INTRODUCTION

Welding began to be used in aviation, when metal replaced wood in aircraft structure. First airplanes used automobile parts and some manufacturing processes (including resistance welding and arc welding) were taken from automobile industry. Welded steel parts were applied in landing gear, wing spars and fuselage beams. But later high-strength aluminum alloys replaced steel to reduce airplane weight. Riveting began to be main assembling process, because of some problems with welding parts made of aluminum.

European countries had powerful metallurgical industry and could produce aluminum for aircraft manufacturing. The Soviet Union had to buy aluminum aboard. In 1930th Soviet engineers developed some aircraft, named “Steel 2”, “Steel 3” and “Steel 6”, using structure parts made of steel. For such aircrafts welding was the main manufacturing process. But in common Al-Cu alloys replaced steels for long time.

At the 1950th supersonic aircraft were developed. Supersonic speed results in heating the airplane skin. Aluminum loses strength if it heated up to high temperature. Heat-resistant materials, like stainless steel and titanium alloy came to replace aluminum. Resistance welding was used instead of riveting as main manufacturing process. For example, a supersonic fighter MiG-25 has 1 400 000 spots made by resistance spot welding, 1300 meters of welds made by resistance seam welding, 400 meters – by TIG welding, 113 – by oxyfuel welding and 32 – by MMA welding.

Later new welding techniques (like inert gas welding and electron-beam welding) became available and new materials with good weldability were developed. In 1986 in Soviet Union three experimental all-welded fighters MiG-29M made of Al-Li alloy. This aircraft would have been in serial production, but in 1990 this project was stopped due to financial problems.

In the USA the electron-beam welding started to use for some sections of supersonic fighters. For example, the welded wing central section of a F-14 *Tomcat* fighter more than 10% lighter than comparable structure assembled by bolting. And welded parts have great reliability. The same technological process used for F-22 *Raptor* fighter.

Lately new welding processes became available like friction stir welding and laser welding. For example, Eclipse Aviation manufactured a small business jet aircraft with the use of friction stir welding. This process easy to atomize and it has number of benefits, especially in mass production.

There are some tends in aeronautics industry:

1. Aircraft should be light and reliable.

To make aircraft lighter and more reliable engineers are finding and utilizing new materials.

2. Aircraft should be chip in manufacturing.

Aircraft manufacturing costs include capital costs, labor costs and equipment operating costs. To reduce cost of aircraft in mass production, fully automatized manufacturing process with low equipment operating costs should be used. So new equipments are being created and new manufacturing processes are being developed.

3. Aircraft should have long operating life.

The design life of modern aircraft is about 30 000…60 000 flight hours. The longer operating life the more profit the company can get. Sometimes companies use specific repairing processes to extend the service life of aircrafts.

4. Aircraft should be fast.

New powerful and economical engines are being designed. It is require using new heat resistance materials and new types of joints. Under high temperature fasteners can to come loose.

5. Aircrafts should not pollute the air.

To reduce carbon dioxide emissions cryogenic engines can be used. An aircraft with cryogenic engines require external fuel tanks to be welded.

Modern aircraft requirements are very high. How do the welding processes meet such requirements?

Advantages and disadvantages of welding as compared with riveting and bolting.

For efficient and economical fabrication, the choice of manufacturing processes should primarily be based on productivity and cost factors, together with material and design requirements considerations. In general case, welding has the following *advantages*.

1. Welding enables weight and material savings.

Methods like bolts or screws require some type of flange or overlap of parts and addition of fasteners. The resulting mechanical assembly is usually heavier than a corresponding weldment. It is very important in aircraft manufacturing.

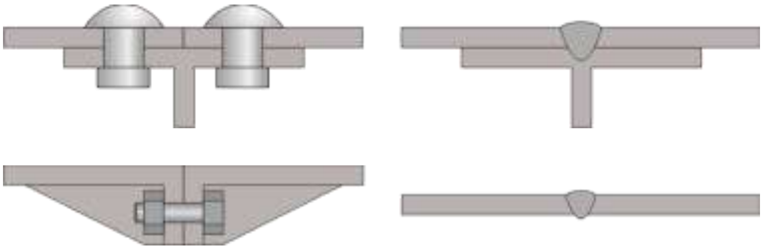

Fig. 1 – Fastened and welded joints

2. Welding is easier to mechanized.

Welding is often continuous process with movable heads or rotated wheels and includes one or several equal moves along parts. The other assembling processes require some operations like drilling, deburring, installing, riveting or screwing.

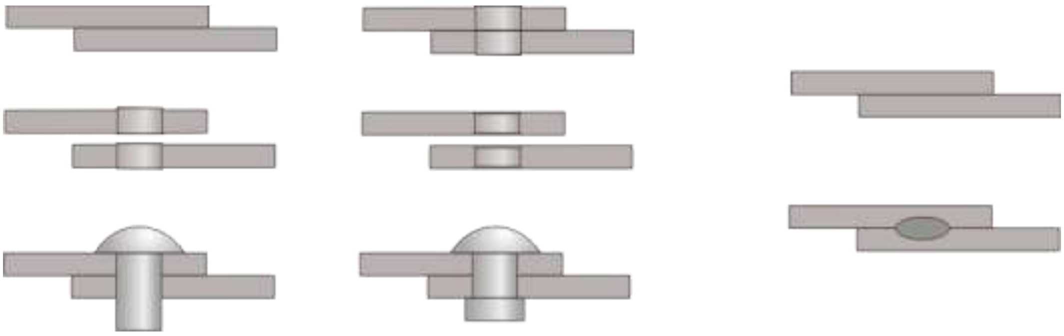

Fig. 2 – Process for riveting and welding

3. Welded joints are easy to renew. Parts with loose rivets need to be replaced, but welded parts can be repaired by welding.

4. Welded joint can be stronger than the parent materials; if a filler material is used that has strength properties superior to those of the parents, and proper welding techniques are used.

5. Welding is not restricted to the factory environment. Portable welding machine equipments are available, so portability of welding machine can be avoided. It can be accomplished in the field.

6. Welding is usually the most economical way to join components in terms of capital and equipment operating costs.

Of cause, welding has some *disadvantages*.

1. The biggest one is that welds often contain defects. Welding requires much more hands-on oversight than other methods, and much stricter manufacturing controls. Some weld defects are difficult to detect. This requires special methods like X-raying to control quality. So in practice welding is less reliable, less predictable than other methods.

2. Welding of very thin sheets is difficult, in some situation rivets or screws are more cost-effective for thin sheet metal.

3. Welding creates a permanent joint, not desirable if parts need to be fixed or replaced later.

4. Most welding operations are performed manually and are expensive in terms of labour cost.

5. Most welding processes, involving the use of high energy, are inherently dangerous.

Specific features of aircraft manufacturing

Compared to the other branches of machine building, the aircraft manufacturing have some following specific features.

Large range and variety of parts of airplane. The airplane frame details differ by their purpose and type; they have many denominations – nomenclature. The number of airplane details is more than hundreds of thousands items, furthermore, a large number of the details of the same type (in particular, fastenings) is used, which gives us the grounds to call the airframes as “multidetail”.

Airplane parts could be very large in sizes, could have complex forms and usual require high accuracy of the surfaces of the parts. Master parts of the aircraft frame and the elements of machine tools have the bicurvature surface with changeable with small and substantial curvature (frameworks of the cockpits, bulkheads, ribs, honeycomb units of the wing-flap system joints, control and standard and pasted equipment, contact breakers, etc.). The length of the aircraft airframe details (E.g., wing panel) are 30 m and larger, and the error of the bypass aerodynamic surfaces has reduced to ±0,5 mm. The design and processing technique of the large capacity details of the complex special form require using the special-purpose NC-machining technique, monitoring devices, special technological means.

High reliability of the parts. All aircraft parts should provide flawless operation within the warranty period provided that working instructions are followed. Parts, joints, sections, assemblies operate under the conditions of changeable cyclic loads. The life of a part is increased by the technological methods of surface reinforcement, and the aircraft reliability is increased at the stage of production through controlling the important details and joints using the nondestructive tests, and also by leading the complex imitation testing of the assemblies and products on special test benches.

High standards to quality of the parts produced. Every part of an aircraft or of its system should be produced according to all technical requirements and conditions set in the design and technological documentation.

Large number of different materials used. For example, to produce the airframe details for an airliner An-148, more than 50 grades of different materials are used, and 70% of the details are made of aluminum alloys, 16% - of polymer composites, 9% - of titanium alloys, 5% - of superstrong alloyed steels.

Stock and work pieces for aircraft parts

Main types of raw pieces for airframe parts to be machined in modern wide-body and heavy cargo aircraft are the following: extruded section bars – 52%, stamped blanks – 31.4%, slubs – 7.5%, tubes – 3.0%, round bars or rods – 2.6%, castings – 2.1%, sheets – 1.1%.

Review of aviation materials.

Aircraft manufacturing use various materials. About 80 percent of these materials are metals. Special metals, which are used in aircraft structure, include the following groups of metal: aluminum alloys, magnesium alloys, titanium alloys, steels, metal composite materials.

Aluminum alloys are primary metals in aircraft frame. Aluminum alloys have low density, relatively high strength, good thermal and electrical conductivity, high corrosion resistance. They retain high strength and ductility at low temperature. Aluminum alloys have good processability for cutting, milling, pressing, forging, rolling. Aluminum aircraft parts of various section shapes easier to fabricate as compared with parts equal in shape but made of steel. All aluminum alloys can be welded by spot welding, some of them – by fusion welding.

Aluminum alloy AlMn1 used as material for no-load aircraft parts like air inlet parts, ducts, fuel tanks, pipelines, covers, panels, which are formed by deep drawing. Parts made of AlMn1 alloy good to weld by argon arc welding, acetylene welding and resistance welding.

Aluminum alloy AlMg2 used for low-load parts, which need to have high corrosion resistance. Parts made of AlMg2 alloy good to weld by spot and seam resistance welding. Argon arc welding perform with AlMg3 filler material. Welds have high ductility and strength more than 0.9 σ_{uts}

(ultimate tensile strength) of base metal. Parts made of AlMg2 alloy can work if temperature in the range -253…+200° C.

Aluminum alloy AlMg6 used for middle-loaded parts. This alloy has the highest strength among Al-Mg alloys (σ_{uts} not less than 310…320 MPa). Parts made of AlMg6 have high corrosion resistance and work as long as 3000 flight hours at temperature in the range -196…+70. The alloy has good weldability for argon arc welding with AlMg6 filler rode and poor weldability for spot welding. Welds have high ductility and strength about 0.9…0.95 σ_{uts} of base metal (for sheets 1…4 mm in the thickness).

Aluminum alloy AlMg1SiCu used for middle-strength parts, which need high corrosion resistance to work at humid conditions or marine environment. Working temperatures are from -253 up to +50. The alloy can be satisfactory welded by almost all types of welding. Weld strength is about 60…70% of base metal, but after heat treatment and aging is 90…95%.

Aluminum alloy AlMg0.7Si used for parts, which need to have high corrosion resistance, good-looking appearance. Working temperatures are from -70 up to +50. The alloy is good to weld by spot and seam welding. Argon arc welding can be used with AlSi5 filler metal. In such case weld strength equals 60…70% of base metal strength.

Aluminum alloy AlCu2Mg1.5Ni is recommended to use for parts, which work at relatively high temperature. Supersonic aircrafts used this alloy as material for frames, ribs, stringers skins, which are continuously work at temperature 150° C. For subsonic aircrafts – for parts, that can be heated up to 175 ° C (parts of deicing system, engine fixture). Also this alloy can be used for jet engine parts, which are heated up to 250° C (impeller, compressor blades, disks, rotor blades).

Aluminum alloy AlMg1CuMnSi can be used instead of AlCu2Mg1.5Ni for all-welded fuselage. Compared to AlMg1SiCu, alloy AlMg1CuMnSi provides higher strength and improved toughness, heat resistance and fatigue properties with equivalent corrosion resistance. The alloy has good ability to fusion and resistance welding.

Aluminum alloy AlCu4Mg1 used for high-load parts of aircraft frame. This alloy has good ability to weld by resistance welding, but poor ability to weld by argon arc or acetylene welding.

Aluminum alloy AlMg5.5Li2 has the strength close to AlCu4Mg1, but less weight and higher coefficient of elasticity. Corrosion resistance of AlMg5.5Li2 alloy is about the same as AlMg6 alloy has. Working temperature is up to +125° C. Good weldability for fusion and resistance welding. Relatively low fatigue properties. This alloy is recommended for low-load aircraft parts, which need to have long lifetime, or for high-loaded parts, which are short time in service.

Aluminum alloy AlZn7Mg2Cu1 used for large-size high-load aircrafts parts, which work at temperature from -196 up to +125° C. The alloy has good ability to forging and high strength (σ_{uts}=450…500 MPa). Welding is not recommended, because of low strength and quick corrosion of welds.

Aluminum alloy AlZn6MgCu is recommended to use for high-load aircrafts parts, which are squeezed. Working temperature is up to +125° C. The alloy has high strength after artificial ageing (σ_{uts}=490…530 MPa), but low corrosion fatigue. Fusion welding is not recommended. Resistance welding limited.

Table 1 – Aluminum alloys used in aviation

ISO	Ukraine (DSTU) Russia (GOST)	USA (AA) Japan (JIS)	Applications
AlMn1	АМц (1440)	3003	Air inlet parts, oil ducts, fuel tanks, pipelines, covers, panels, est.
AlMg2	АМг2 (1520)	5052	Pipelines for oil or fuel, air ducts, tubes, flanges, nipples, welded jars.
AlMg6	АМг6 (1560)		Middle-strength flanges, mouth pieces, fringes, loaded welded fuel tanks.
AlMg1SiCu	АД33 (1330)	6061	Helicopter rotor blade, seaplane wheel hub,

			fringes
AlMg0.7Si	АД31 (1310)	6063	Aircraft cockpit decorations
AlCu2Mg1.5Ni	АК4-1 (1141)	2018	Engine fixture, impeller, compressor blades, disks, rotor blades, parts of deicing system.
AlMg1CuMnSi	1370	6013	All-welded fuselage unit, parts of deicing system
AlCu4Mg1	Д16 (1160)	2024	Stringers, skin, spars, ribs, lower wing panels, supports
AlMg5.5Li2	1420		Can replace AlCu4Mg1 in welded units, high-load aircraft parts with short life time.
AlZn7Mg2Cu1	В93пч		Support arms, longerons, beams, diaphragms
AlZn6MgCu	В95	7075	Upper panels of wing and fuselage, stringers, skin

Titanium alloys are used as material for highly loaded frame parts and parts of different aircraft systems. Titanium has high specific strength and does not lose strength at high temperature up to 450…500° C. Titanium has long operational time and high corrosion resistance. Titanium is chemical inertness and has minimal coefficient of thermal expansion among metals (very good to apply to thin-wall hot air pipelines). Titanium has high melting point and is used to make fire-resisting covering and bulkheads. Some titanium alloys has highest specific strength and used in aircraft armour-plates.

Titanium has some disadvantages. Compared to iron, titanium has low coefficient of elasticity (2 times less). Rigidity requirements often increase cross-section of frame, even if strength is enough. Titanium alloys are expensive and more specific and complex manufacturing processes are required.

Pure titanium has high ductility and good weldability, but relatively low strength. Titanium of high purity used to produce thin-gage sheets, foil for honeycomb panels, low-loaded aircraft parts, which need high corrosion resistance and heat resistance (air conditioning system pipes, ducks, tanks, brackets).

Middle-strength titanium alloys have small quantity of alloying elements in chemical compound like aluminum, manganese, tin, zirconium, molybdenum, vanadium, chrome, tungsten. Such alloys (Ti-2Al-1.5Mn, Ti-2Al-2.5Zr, Ti-6Al-4V) are good to form at high temperature, and they have good strength in hardened state. Middle-strength titanium alloys have good ability to be welded by resistance and inert gas welding. Most titanium parts made of middle-strength titanium alloys.

High-strength titanium alloys have higher quantity of alloying elements in chemical compound (for example, Ti-5Al-5Mo-5V-1.5Cr). The grain structure of the alloys change, it is possible to increase their strength by heat treatment. Ductility and weldability of the alloy decrease. Special conditions are required for forming and welding parts without cracks. High-strength titanium alloys are used for high-loaded aircraft parts, like landing gear, hydraulic rams, high pressure cylinders, rotor blades and so on.

Table 2 – Titanium alloys used in aviation

ISO	Ukraine (DSTU) Russia (GOST)	Applications
Ti	ВТ1-0	Air conditioning system pipes, honeycomb panels, brackets.
Ti-2Al-1.5Mn	ОТ4-1	Fringes, rims, pipelines, fire-resisting bulkheads
Ti-2Al-2.5Zr	ПТ7М	Hot pipelines, ducks.

Ti-6Al-4V	ВТ6С	Cargo cabin floor sheets, hydraulic high pressure accumulator boxes.
Ti-6Al-4.5V	ВТ6	Welded brackets and support arms, engine casing, engine rotor blades.
Ti-5Al-5Mo-5V-1.5Cr	ВТ22	Landing gear parts, hydraulic rams, swivel gland, brackets, guiding bars, jet engine rotor blades, low-pressure compressor disks, armour-plating

Steel parts take about 10% of aircraft weight. Steels have good processability, reliability and low price; steel parts can work at high temperature. In big steel in-process parts, the anisotropy of properties lower compared to in-process parts made of aluminum and titanium alloys. Steels have high ultimate tensile strength and heat and fatigue resistance; wide range of special steels allows to pick up suitable for concrete conditions.

But most steels have specific strength (tensile strength to weight ratio) less than aluminum and titanium alloys. High-strength steels are very sensitive to stress concentration. Also steel have low corrosion resistance and require rust-preventing covering. Therefore steel parts using is decreased in modern aircrafts. But steel continue to be used in aircraft engines, supersonic fighter frames, welded high-loaded parts and so on.

Low-carbon steels are used to manufacture different accessories, no-load clamps, fixation welded and so on. Low-carbon steels have good weldability.

Middle-strength alloyed steels are used for middle-loaded and high-loaded aircraft parts (carriers, frames, brackets), including welded. Such parts completed field tests, show high reliability and long life in operation. Surface hardening like nitriding, carbonitriding are used to increase wear resistance. Most used middle-strength steels are FeC0.3CrMnSi, FeC0.38Cr2MoAl, FeC0.16CrSiNi.

High-strength steels can be harden by heat treatment to σ_{uts}>1400 MPa and used for high-loaded and vital parts like landing gear parts, shock strut piston, wheel spindle, extension flap gear. But such steels are sensitive to stress concentrations and aggressive environment, and that limit range of application. Welding is before heat treatment. Inert gas, submerged and electron-beam welding processes are used. Main high-strength steels used are FeC0.3CrMnSiNi2Mo, FeC0.03Cr18Cd8Mo5Ti.

Austenitic stainless steels like FeC0.08Cr18Ni10Ti, FeC0.08Cr18Ni09Ti are used to manufacture high temperature hydraulic pipelines, different parts, which work at aggressive environment.

Special steels hardened by heat treatment have improved corrosion resistance, resistance to stress concentration (FeC0.07Cr16Ni6), fracture toughness (FeC0.13Cr15Ni4Mo3), heat resistance (FeC0.08Cr15Ni5Cu2Ti). New requirements to increase operation life of military aircraft (fighters, low-flying attack aircrafts) force to use special steels more often due to good corrosion and fatigue resistance. Steel grade option depends on working conditions.

Table 3 – Steels used in aviation

ISO	Ukraine (DSTU) Russia (GOST)	Applications
FeC0.3CrMnSi	30ХГСА	Carriers, frames, brackets.
FeC0.3CrMnSiNi2Mo	30ХГСН2МА	Landing gear parts
FeC0.03Cr18Cd8Mo5Ti	ВКС-170 (03Х18К8М5Т)	Strut piston, wheel spindle, extension flap gear
FeC0.08Cr18Ni10Ti	08Х18Н10Т	Hot air and hydraulic pipelines, ducts, oil jars

FeC0.07Cr16Ni6	CH-2A (07X16H6)	Welded high pressure oxygen balloons, high loaded support arms
FeC0.13Cr15Ni4Mo3	BHC-5 (13X15H4AM3)	Fuselage frames, wing spar, hinge units
FeC0.08Cr15Ni5Cu2Ti	BHC-2 (08X15H5Д2T)	Engine support frames, stringers, skin, fuel tanks

Composite materials became very popular to be used in aircraft structures. According to the matrix material used, composite materials can be polymer matrix composites or metal matrix composites. Polymer matrix composites (PMC) are used in aerospace applications because they have high tensile strength and stiffness, high chemical durability in aggressive environment, relatively low costs.

Metal matrix composites (MMC) combine advantages of structural metal materials and advantages of composites. They are resistant to fire, do not absorb moisture, have higher strength, modulus of elasticity, fracture toughness, impact toughness, better electrical and thermal conductivity and can be operated in wider range of temperatures than polymer matrix composites.

As opposed to PMC, which practically don't have reserve to increase transverse and shear strength, such properties of MMC can be considerably varied. For example, metal matrix composite BKA-1 consisting of aluminum Al99.3 matrix combined with boron fibers has shear strength in the range 80…100 MPa. Using AlMg1SiCu alloy as matrix material allowed increasing shear strength to 120…140 MPa.

MMC are preferable than PMC to produce high stiffness structures. Fatigue failure properties are better for MMC than PMC. At high operational temperatures MMC properties more stable as opposed to PMC. Specific strength can be vary in 15…20% range, the module of elasticity almost don't change.

Significant advantage for MMC structures is high maintainability. Repairing of units made of PMC require special conditions (certain temperature, pressure, humidity), special equipments. To repair MMC units the argon-arc or spot welding can be used.

According to the fiber length composites can be divided on long-fiber reinforced composites and short-fiber reinforced composites.

Long-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibers. Continuous reinforcement uses monofilament wires or fibers such as carbon or silicon carbide fibers, boron or steel filaments. Some grades of long-fiber metal matrix composites presented at the table.

Discontinuous reinforcement uses short fibers, or particles. The most common reinforcing materials in this category are alumina Al_2O_3 and silicon carbide SiC. Short-fiber composites have higher strength, stiffness and wear resistance, lower thermal expansion coefficient. For example, *DURALCAN* composite W6A.15A-T6 (AlMg1SiCu+15%Al_2O_3) has ultimate strength, which is 22% more, and elastic module, which is 20% more than AlMg1SiCu alloy has.

Table 4 – Metal matrix composites used in aviation

Grade of MMC	BKA-1	BKA-2	BKM-1	BKY-1M	KAC-1A
Fiber	Boron	Boron	Boron	Carbon	Steel
Matrix	Al99.3	AlMg1SiCu	MgAl3.5Zn	AlZn7Mg2Cu1	Al99.5
Modulus of elasticity, MPa along the fiber across the fiber	 $22*10^4$ $11*10^4$	 $22*10^4$ $10*10^4$	 $22*10^4$ $10*10^4$	 $24*10^4$ $11*10^4$	 $11.7*10^4$ $9{,}0*10^4$
Tensile strength, MPa along the fiber across the fiber	 1150 100	 1250 180	 1000 90	 1000 50	 1500 280
Shear strength, MPa	60	110	120	60	180
Creep rupture strength, MPa	1040	1050	580	650	840

100 hours base at 150° C.					
Density, kg/m^3	2.6	2.6	2.15	2.35	4.75

Aluminum matrix composites are used for manufacturing pistons, pushrods, brake components, electronic substrates est.

Magnesium matrix composites are used for manufacturing aircraft parts like gearboxes, transmissions, compressors and engine cases.

Titanium matrix composites are used for manufacturing structural components of the F-16 jet's landing gear, turbine engine components (fan blades, actuator pistons, synchronization rings, connecting links, shafts and discs).

Questions

When did welding begin to be used in aviation?
Why did riveting begin to be used as main assembling process?
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Why did Soviet engineer develop aircrafts made of steel in 1930th?
What was the main manufacturing process for such aircrafts?
Why did stainless steels come to replace aluminum at the 1950th?
What types of welding used in MiG-25 fighter manufacturing process?
What Russian fighters would be all-welded?
What advantage to use welded wing central section in F-14 and F-22 fighters?
What type of welding used in Eclipse 500 aircraft manufacturing?
How to meet the requirement?
  Aircraft should be light and reliable
  Aircraft should be chip in manufacturing
  Aircraft should have long operating life
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  Aircrafts should not pollute the air
Why does welding weight and material savings?
Why is welding easier to mechanized?
Why are welded joints easy to renew?
Why can welded joint be stronger than the parent materials?
Why is welding not restricted to the factory environment?
What are disadvantages of welding?
What are advantages of aluminum alloys?
Describe AlMn1 aluminum alloy.
Describe AlMg2 aluminum alloy.
Describe AlMn6 aluminum alloy.
Describe AlMg1SiCu aluminum alloy.
Describe AlMg0.7Si aluminum alloy.
Describe AlCu2Mg1.5Ni aluminum alloy.
Describe AlMg1CuMnSi aluminum alloy.
Describe AlCu4Mg1aluminum alloy.
Describe AlMg5.5Li2 aluminum alloy.
Describe AlZn7Mg2Cu1 aluminum alloy.
Describe AlZn6MgCu aluminum alloy.
What are advantages of titanium alloys?
What are disadvantages of titanium alloys?
What are applications for pure titanium?
Describe middle-strength titanium alloys.
Describe high-strength titanium alloys.
What are advantages of steels?

What are disadvantages of steels?
Describe middle-strength alloyed steels.
Describe high-strength alloyed steels.
Describe special steels.
What are advantages of metal matrix composites?
Describe long-fiber reinforced composites.
Describe short-fiber reinforced composites.
Where are the metal matrix composites used?

WELDING BASICS.

Definition : ***Welding is a materials joining process in which two (or more) parts are coalesced at their contacting surfaces by the suitable application of heat or pressure or both.***

Many welding processes are accomplished by heat alone, with no pressure applied, others by a combination of heat and pressure, and still others by pressure alone with no external heat supplied.

Types of welding processes

There are over 50 different types of welding operations. They use various types or combinations of energy sources to accomplish the coalescence. Energy can be supplied in the form of heat (generated on nearby the faying surfaces or in the bulk) or in the form of mechanical energy (friction, deformation). Type of welding process commonly is defined by type of energy source. For example, arc welding uses electric arc as heat source, which melts faying surfaces of parts to weld them. Oxyfuel gas welding uses flame as heat source, resistance welding uses resistance to electric current, friction welding uses friction to heat up metals and so on.

According to the state of the base metal welding processes can be grouped into fusion welding (liquid state) and solid-state welding processes.

Fusion Welding involves localized melting and use heat to melt the base metals. Filler metal may or may not be added. In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and strength to the welded joint. A fusion welding operation in which no filler metal is added is referred to as an *autogenous* weld. The fusion category comprises the most widely used welding processes and includes such big groups as arc welding and resistance welding (see Fig. 3).

Solid-state Welding refers to joining processes in which coalescence results from application of pressure alone or a combination of heat and pressure. If heat is used, the temperature in the process is below the melting point of the metals being welded. No filler metal is utilized in solid-state processes.

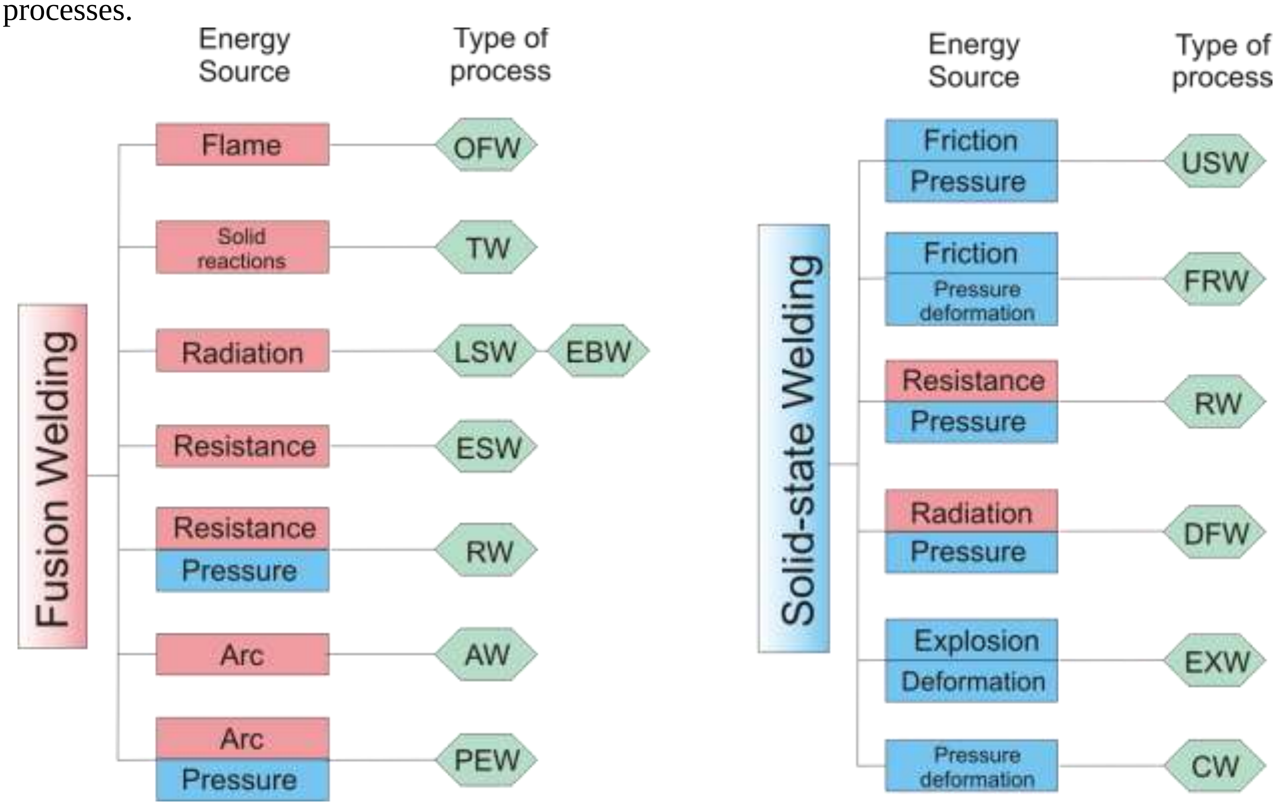


Fig. 3 – Fusion and solid-state welding processes

According to the degree of process mechanization, there are manual, mechanized, semiautomatic, automatic, adaptive control and robotic welding.

Manual welding is a welding process with the torch, gun, or electrode holder held and manipulated by hand. Accessory equipment, such as part motion devices and manually controlled filler material feeders may be used.

Mechanized welding is a welding process with equipment that requires manual adjustment of the equipment controls in response to visual observation of the welding, with the torch, gun, or electrode holder held by a mechanical device.

Adaptive control welding is a welding with a process control system that automatically determines changes in welding conditions and directs the equipment to take appropriate action.

Semiautomatic welding is a manual welding process with equipment that automatically controls one or more of the welding conditions.

Automatic welding is a welding process with equipment that requires only occasional or no observation of the welding, and no manual adjustment of the equipment controls.

Robotic welding is a welding that is performed and controlled by robotic equipment.

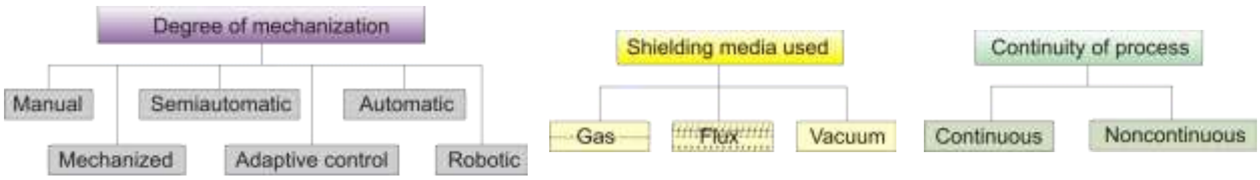


Fig. 4 – Welding classification

According to the shielding media welding process can use gases, fluxes or vacuum to prevent metal oxidation.

According to the continuity of the process there are continuous and discontinuous welding processes.

Types of weld joints

A *welded joint* is that portion of a structure where separate base metal parts are united by welding. The word *weld* is often used to refer to *a welded joint.* For example, a butt weld is a welded butt joint. The word *seam* is often used to refer to a joint, especially in a case of tanks and containers. A weld joint classification based on five basic joint configurations such as a butt joint, corner joint, edge joint, lap joint, and T-joint.

Butt Joints

A butt joint is a joint made by placing two pieces of material edge to edge in the same plane so that there is no overlapping. It is called a *butt joint* because the two edges, when joined, are abutted together. There are two classifications of butt joints: plain butt joint and flange butt joint. The **plain butt joint** is used where the two pieces of the materials to be welded are aligned in approximately the same plane. **Flange butt joints** are welded using folding (edges are turned up 90°), producing a flange height of from one to three times the thickness of the material being welded. The flanges are fused together. Since the flanges supply enough metal to fill the seam, a filler rod is not normally used. This makes welding simpler and allows avoiding burn-through if metal is a light gage, but requires extra labor costs for metal folding.

Weld can be single-side or double side. Single-side welds can be made quick, but double side welds usually stronger, welding currents can be decreased. With double welding, the depths of each weld can vary slightly.

Plain butt join without edge preparation (square butt joint) is simple to prepare, economical to use, and provides satisfactory strength, but is limited by joint thickness. For thicker joints, the edge of each member of the joint must be prepared to a particular geometry to provide accessibility for welding and to ensure the desired weld soundness and strength. The opening or gap at the root of the joint and the included angle of the groove should be selected to require the least weld metal necessary to give needed access and meet strength requirements.

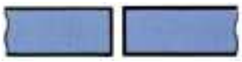
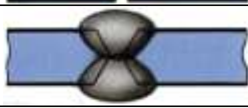
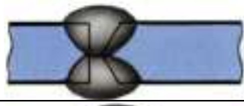
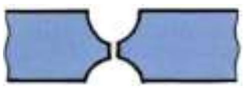
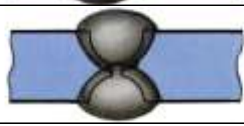
V-grooving or V-beveling are used where adequate penetration cannot be achieved without edge preparation and the metals are to be welded in the horizontal position. V-groove butt joints are common in arc and gas welding processes.

In thick metals, and when welding can be performed from both sides of the work piece, a **X-grooving joint** is used. When welding thicker metals, a X-grooving joint requires less filler material because there are two narrower V-groove joints compared to a wider single V-groove joint. Also the X-grooving helps compensate for warping forces. With a V-joint, stress tends to warp the piece in one direction when the V-joint is filled, but with a X-joint, there are welds on both sides of the material, having opposing stresses, straightening the material.

A **K-groove joint** is a joint where one piece in the joint is beveled and the other surface is perpendicular to the plane of the surface. This reduces labor and filler material costs, but the welds are not symmetrical so it is more difficult to get high quality joint.

U-groove joints can be single or double. Singe U-groove joints have a U formation on one side of the joint, but double U-groove have a U formation on both the top and bottom of the prepared joint. U-joints are the most expensive edge to prepare and weld. They are usually used on thick base metals where a V-groove would be at such an extreme angle, that it would cost too much to fill.

Table 5 – Butt joints

Edge preparation	Type of weld	Edge prepared cross-section	Weld cross-section	Sheet thickness
Flange butt joint	Single-side			1…4
Plain butt joint without preparation	Single-side			1…6
Plain butt joint without preparation	Double-side			3…8
Plain butt joint with V-grooving	Single-side			3…60
Plain butt joint with X-grooving	Double-side			8…120
Plain butt joint with K-grooving	Double-side			8…100
Plain butt joint with U-grooving	Double-side			15…100

Lap Joints

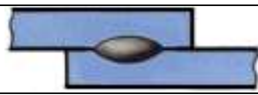
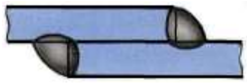
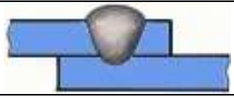
A **lap joint** is a joint made by lapping one base over the other. These joints are widely used in the construction, because it doesn't require parts to fit exactly (and cut faces don’t be perfectly flat and parallel), but a lap joint is not as efficient as a butt joint for distributing load stresses. A butt joint is recommended instead of a lap joint for loaded parts, because they tend to have a much higher tensile strength than lap joints, as the total effective area of the weld is higher. A lap joint is commonly used for nonleaded parts or where the primary load stress will be transverse (perpendicular) to the line of weld, for example, skin-to-rib or skin-to-stringer joints. Lap joints can be used to weld pieces of dissimilar thicknesses.

A lap joint welded by resistance welding commonly requires double side approach and more complex operating control. Advantages are absence of overlapping metal on faces and high productivity of resistance welding.

A **single-side welded lap joint** is used for sheets, plates, and structural shapes where the loading is not severe and one-side approach is available. The same type of joint can be used for telescope splices in steel tubing, and in that application it is better than a butt joint. A double-side welded joint is stronger and more efficient for distributing load stresses.

A **plug weld** is a weld made in a circular hole in one member of a joint fusing that member to another member. Plug welds when done properly tend to be stronger than the original spot welds. One alternative to plug welding is "MIG spot welding". It is similar to plug welding, although a hole is not drilled in the front sheet of metal. Instead the power of the MIG is relied upon to fully melt the top sheet and penetrate into the back sheet.

Table 6 – Lap joints

Type of welding	Type of weld	Edge prepared cross-section	Weld cross-section	Sheet thickness
Resistance welding				0,3…6
Arc or oxyfuel welding	Single-side			1…60
Arc or oxyfuel welding	Double-side			1…60
Arc welding	Plug weld			1…6

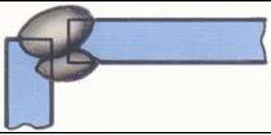
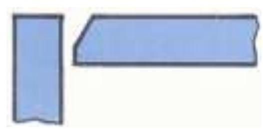
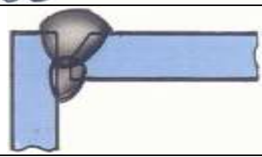
Corner Joints

A corner joint is a joint between two members located approximately at right angles to each other in the form of an L.

Single weld used for lighter-gauge metals. If the joint is subjected only to moderate stresses, the closed type of corner joint is used. This mean the edge at outside corner is melted and fused to form the bead. It is not much adding of filler metal. The open type corner joint is used on heavier sheet. It is made by fusing the two edges at the inside corner and adding enough welding rod to give a well-rounded bead of weld metal on the outside.

If the joint is required to bear a fairly heavy load, an additional weld must be made on the inside corner to provide the necessary strength where a light concave bead has been laid on the inside. It is double side weld. For heavy sheets beveling in used to get complete penetration.

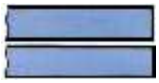
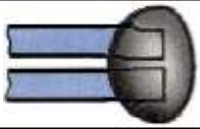
Table 7 – Corner joints

Edge preparation	Type of weld	Edge prepared cross-section	Weld cross-section	Sheet thickness
Square edges	Single-side			1…6
Square edges	Double-side			2…30
Beveled edges	Double-side			3…60

Edge Joints

An edge joint is a form of joint made by placing a surface of one base part on a surface of the other base part in such a manner that the weld will be on the outer surface planes of both parts joined. This type of joint is not used where a high joint strength is required, but it is widely used for fittings composed of two or more pieces of sheet stock where the edges must be fastened together. This use is acceptable because the joint is not subjected to high stresses. Edge joints can be used also for tanks that are not subjected to high pressures. Edge joints are usually made by bending the edges of one or both parts upwards at a 90° angle, placing the two bent ends parallel to each other, or placing one bent end parallel to the upright unbent end and then welding along the outside of the scum formed by the two joined edges.

Table 8 – Edge joints

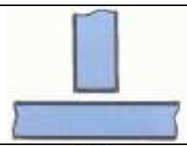
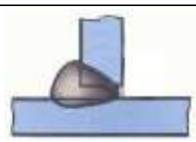
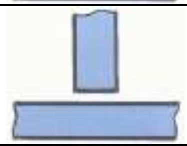
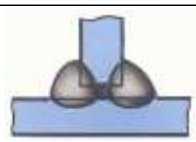
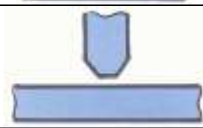
Edge preparation	Type of weld	Edge prepared cross-section	Weld cross-section	Sheet thickness
Square edges	Single-side			2…60

Tee Joints

A tee joint is a form of joint made by placing the edge of one base part on the surface of the other base part so that the surface of the second part extends on either side of the joint in the form of a T. Filler rod is used with tee joints.

A **plain tee joint** is acceptable for most metal thicknesses in aircraft work and also may be used for heavier metals, where the weld can be located so that the load stresses will be transverse (perpendicular) to the longitudinal dimensions of the weld. The only preparation required is cleaning the surface of the horizontal member and the end of the vertical member. The weld is then made from each side with penetration into the intersection. This results in a fillet weld, having a general triangular cross-sectional shape. Any weld that joins two parts that are at right angles to each other may be called a *fillet weld.* Comer joints, lap joints, and edge joints also require fillet welds.

Table 9 – Tee joints

Edge preparation	Type of weld	Edge prepared cross-section	Weld cross-section	Sheet thickness
Square edges	Single-side			1…6
Square edges	Double-side			2…40
Beveled edges	Double-side			8…100

An intermittent fillet weld is one that is not continuous across a joint. Intermittent welding is used when either a continuous weld is not necessary, or when a continuous weld threatens the joint by warping. **Chain intermittent weld** is an intermittent weld on both sides of a joint in which the weld increments on one side are approximately opposite those on the other side. **Staggered intermittent weld** is an intermittent weld on both sides of a joint in which the weld increments on one side are alternated with respect to those on the other side.

Chain intermittent weld   Staggered intermittent weld

Fig. 5 – Intermittent welds

Welding positions

All welding is accomplished in one of four positions: flat, horizontal, vertical and overhead. The limiting angles of the various positions depend somewhat as to whether the weld is a fillet or groove weld.

Flat position is a welding position in which welding is performed from the upper side of the joint and the axis of the weld is approximately horizontal and the weld face lies in approximately horizontal plane. Flat welding is the preferred term; however, the same position is sometimes called downhand. Flat welding is the most preferable welding position. Gravity keeps molten metal in the weldpool. Gas bubbles come to the surface when metal solidifies.

Horizontal position is a welding position in which the weld face lies in approximately vertical plane and the weld axis at the point of welding is approximately horizontal. Used for fillet and groove welds.

Vertical position is a position of welding in which the axis of the weld is approximately vertical and the weld face lies in approximately vertical plane. It is typically more complicated to perform than flat or horizontal welding

Overhead position is a welding position in which welding is performed from the underside of a joint and the face of the weld is approximately horizontal. In this position welding the most complicated. Weld metal flows downward. Welds can have gas cavities because gas bubbles not came to the surface.

Pipe welding is a more complicated process than structural welding and only a minority of certified welders do pipe welding. The angle and the position of the weld constantly changes as the welded works their way around the pipe. In pipe welding four basic positions are used: horizontal rolled, horizontal fixed, vertical and inclined positions.

In *horizontal rolled position*, the pipe is rolled so that the welding is done in the flat position with the pipe rotating under the arc. This position is the most advantageous of all the pipe welding positions. In *horizontal fixed position* the axis of the pipe is horizontal, but the pipe is not turned or rolled during the welding operation; therefore, the welding is more difficult in this position.

When you are welding pipe in the *vertical position*, the pipe is placed in the vertical position so the welding can be done in the horizontal position.

When pipe *inclined position* is used, the axis of the pipe is at a 45-degree angle with the horizontal and the pipe is not rolled. Since the pipe is not rolled, welding has to be done in all the positions — flat, vertical, horizontal, and overhead.

Parts of a weld.

To make a proper weld it is necessary to identify the characteristics of a correct weld. The technician should also be aware of the changes in material characteristics that may take place as a result of the welding operation.

There are five basic parts of a ***groove weld***: face, root, toe, reinforcement and throat. The **face** is the exposed surface of the weld. The **root** is the zone at the bottom, or base, of the weld; in other words, it is the depth that fusion penetrates into the base metal at the joint. The **toe** is the edge formed where the face of the weld meets the base metal; that is, it is the edge of the fusion zone in the base metal on each side of the weld. The **reinforcement** is the quantity of weld metal added above the surface of the base metal (the metal in the parts being joined) to give the weld a greater thickness in cross section. Materials welded by the electric resistance process may not have reinforcement, depending upon the details of the technique used. The **throat** is the distance through the center of the weld from the root to the face. Throat of a groove weld ensure strength of the joint.

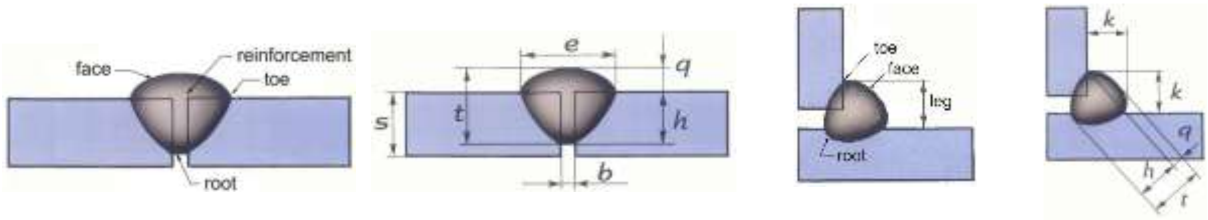


Fig. 6 – Parts of a weld

Weld bead is the metal deposited as the weld is made. In order to have good penetration, the base metal at the joint must be melted throughout its thickness; hence a bead of weld metal should be visible on the underside of a butt joint. A good indication of penetration in the case of a fillet weld is the presence of scale on the lower side.

The three most important proportions of a groove weld are: the depth of penetration, which should be at least one-fourth the thickness of the base metal; the width of the bead which should be between two and three times as great as the thickness of the base metal; and the height of the reinforcement, which should be not less than one-half the thickness of the base metal.

Fillet weld is aesthetically triangular in shape and may have a concave, flat or convex surface depending on the welder's technique. Fillet weld have the same parts as groove weld and one extra dimension – leg of a weld. The **leg** is the dimension of the weld metal extending on each side of the root of the joint. For a fillet weld typically the depth of the throat should be at least as thick as the thickness of metal you are welding.

Heat affected zones in a weldment.

It is common to think of a single-pass weld as consisting of two zones: weld metal and heat affected zone. Careful metallographic examination has shown that a weld can in fact be divided into four regions: **the composite zone**, in which a volume of base metal melted by the superheated filler metal experiences complete mixing to produce an alloy with nominal composition intermediate between that of the base metal and that of the filler metal; **the unmixed zone**, which forms from the stagnant molten boundary layer region at the outer extremities of the composite region. because no mechanical mixing with the filler metal occurs here, the composition of the metal in this region is identical to that of the base metal, except for minor changes produced by diffusion; **the partially melted zone**, which is a region at the fusion boundary where the peak temperatures fall between the liquidus and solidus so that melting is incomplete and **the heat-affected zone**, which is that portion of the base metal where all microstructural changes induced by welding occur in the solid state.

The width of unmixed zone depends on fluid flows in weldpool, commonly is about 100 to 1000 μm thick. Unmixed zone increases if low-temperature heat sources used for fusion welding or dissimilar metals are welded.

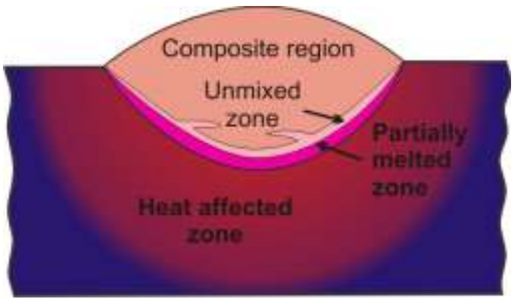


Fig. 7 – Zones of a weld

The width of the partially melted zone can be extended by a phenomenon known as liquation, whereby melting can occur even when the peak temperature is less than the liquidus temperature. For some alloys, solidus-liquidus range can be rather wide.

For example, for AlCu4Mg1 eutectic temperature is 821 K, liquidus temperature – 933 K. Near the weld boundary the metal is heated up to between the eutectic temperature and liquidus temperature during welding. The base metal consists of α matrix and large and small θ particles (Al_2Cu) both within grains and along grain boundaries. If the alloy is heated very slowly to above the solvus temperature, the eutectic can dissolve completely in the α matrix by solid-state diffusion. However, if it is heated rapidly to above solvus temperature, as in welding, the eutectic does not have enough time to dissolve completely in the matrix, because solid-state diffusion takes time.

Consequently, liquation occurs by the eutectic reaction $\alpha+\theta = L_e$, where L_e is the liquid of the eutectic composition. Upon cooling, the eutectic liquid solidifies into the eutectic solid without composition changes and results in eutectic particles and some grain boundary eutectic. Above eutectic temperature liquation intensifies. The α matrix surrounding the eutectic liquid dissolves and the liquid increases in volume. This causes the liquid composition to change from eutectic to hypoeutectic L_{he}. Upon cooling hypoeutectic liquid solidifies first as Cu-depleted α and last as Cu-rich eutectic. This results in a band of Cu-depleted α along the grain boundary eutectic and a ring of Cu-depleted α surrounding each large eutectic particle.

The partially melted zone can suffer from liquation cracking, loss of ductility and hydrogen cracking. Liquation cracking, loss of ductility are particularly severe in heat-treatable aluminum alloys due to wide partially melted zone (wide freezing temperature range and high thermal conductivity), large solidification shrinkage and large thermal contraction. Hydrogen cracking in partially melted zone is typical for maraging steels, austenitic stainless steels and nickel-base superalloys.

The heat-affected zone consists of overheated section, grain-refined (normalized) section, partially grain-refined section, recrystallized section and aging section.

Weld discontinuities.

Discontinuities are interruptions in the desirable physical structure of a weld. A discontinuity constituting a danger to the fitness-for-service of a weld is a defect. By definition, a defect is a condition that must be removed or corrected. The word "defect" should therefore be carefully used, because it implies that a weld is defective and requires corrective measures or rejection. Thus, repairs may be made unnecessarily and solely by implication, without a critical engineering assessment. Consequently, the engineering community now tends to use the word "discontinuity" or "flaw" instead of "defect".

The significance of a weld discontinuity should be viewed in the context of the fitness-for-service of the welded construction. Fitness-for-service is a concept of weld evaluation that seeks a balance among quality, reliability, and economy of welding procedure. Fitness-for-service is not a constant. It varies depending on the service requirements of a particular welded structure, as well as on the properties of the material involved.

The typical welding discontinuities are different types of cracks (hot cracks, cold cracks), gas inclusions (porosity, blow holes, wormholes, gas pockets), non-metallic inclusions (flux or slag shots, rust or mill scale), unacceptable weld profiles (undercut, overlap, underfill, lack of penetration or bridging, burn-through).

Cracks will occur in the weld metal when localized stresses exceed the ultimate strength of the metal. The crack sensitivity of the base material may be associated with its chemistry and/or its susceptibility to the formation of elements which will reduce its ductility. Cracks are usually classified into one of two types: hot cracks and cold cracks.

Hot cracks, also known as solidification cracks, occur immediately after welds are completed and sometimes while the welds are being made, propagate between the grains of the material. They normally appear in straight lines along the centreline of the weld bead, but may occasionally appear as transverse cracking. Solidification cracks in the final crater may have a branching appearance. Hot cracks in steel are often caused by sulphur and phosphorus, are more likely to occur in higher carbon steels. In aluminum alloys they are caused by liquation phenomena. To diminish the probability of this type of cracking, excess material restraint should be avoided, and a proper filler material should be utilized.

Cold cracks develop after solidification of the weld as a result of stresses and propagate both between grains and through grains. Cold cracks in steel are sometimes called delayed cracks and are often associated with hydrogen embrittlement. Other causes include a hard brittle structure which is susceptible to cracking and tensile stresses acting on the welded joint. Cold cracking is limited to steels and is associated with the formation of martensite as the weld cools. The cracking occurs in the heat-affected zone of the base material. To reduce the amount of distortion and residual stresses, the amount of heat input should be limited, and the welding sequence used should not be from one end directly to the other, but rather in segments.

Another way to classify cracks is the crack location (see Fig. 8): toe cracks, underbead cracks, face cracks, root cracks, throat cracks, longitudinal and transverse cracks, crater cracks, heat-effected zone cracks and weld interface cracks.

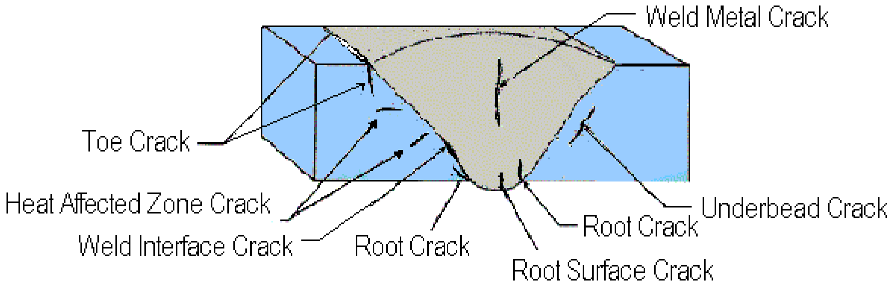


Fig. 8 – Types of cracks

The underlying cause for **gas inclusions** is the entrapment of gas within the solidified weld. Excessive gaseous content is present, when molten metal cooling too rapidly. A gas pocket in the weld metal resulting from the hot metal solidifying without all of the gases having escaped to the surface. The main reason for the presence of gases in the weldpool are dirty base material, moisture on joint surface or electrode, high sulphur content in the workpiece or electrode, insufficient or improper shielding during the welding process, or incorrect welding conditions or techniques (too short of an arc, or wrong welding current or polarity). Base material that is contaminated with hydrocarbons such as oil, grease or paint, will be susceptible to porosity during the welding process. Moisture in the form of water or hydrated oxides on base material and/or welding electrodes can introduce hydrogen into the welding process and cause major porosity problems during welding. Nitrogen and oxygen absorption in the weld pool usually originates from poor gas shielding. As little as 1% air entrainment in the shielding gas will cause distributed porosity and greater than 1.5% results in gross surface breaking pores. Leaks in the gas line, too high a gas flow rate, draughts and excessive turbulence in the weld pool are frequent causes of distributed porosity.

Wormholes are elongated pores which produce a herring bone appearance on the radiograph. Wormholes are indicative of a large amount of gas being formed which is then trapped in the solidifying weld metal. Entrapment is more likely in crevices such as the gap beneath the vertical member of a horizontal-vertical, T joint which is fillet welded on both sides.

Non-metallic inclusions can be either isolated or cumulative. Cumulative inclusions occur when there is slag or flux in the weld. Slag forms from the use of a flux, which is why this type of defect usually occurs in welding processes that use flux, such as shielded metal arc welding, flux-cored arc welding, and submerged arc welding, but it can also occur in gas metal arc welding. This defect usually occurs in welds that require multiple passes and there is poor overlap between the welds. The poor overlap does not allow the slag from the previous weld to melt out and rise to the top of the new weld bead. It can also occur if the previous weld left an undercut or an uneven surface profile. To prevent slag inclusions the slag should be cleaned from the weld bead between passes via grinding, wire brushing, or chipping. Isolated inclusions occur when rust or mill scale is present on the base metal.

Unacceptable weld profiles can cause problems associated with a reduction in base material thickness, a reduction in the affective weld size, or provide stress concentrations on the weld or plate surface. These types of weld discontinuities can often seriously detract from the overall performance of a welded component in service.

Undercut is a groove melted into the base metal adjacent to the weld toe, or weld root, and left unfilled by weld metal. One reason for this type of defect is excessive current, causing the edges of the joint to melt and drain into the weld; this leaves a drain-like impression along the length of the weld. Another reason is if a poor technique is used that does not deposit enough filler metal along the edges of the weld. A third reason is using an incorrect filler metal, because it will create greater temperature gradients between the center of the weld and the edges. Other causes include too small of an electrode angle, a dampened electrode, excessive arc length, and slow speed.

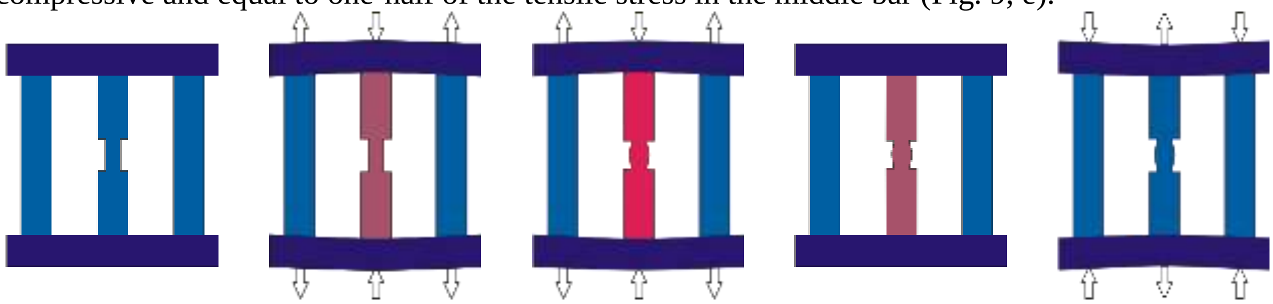
Overlap is the protrusion of weld metal beyond the weld toe or weld root. This condition can occur in fillet welds and butt joints and can produce notches at the toe of the weld that are undesirable due to their resultant stress concentration under load. This discontinuity can be caused by incorrect welding techniques or insufficient current settings.

Underfill is the extension of a weld face or root surface of a weld below the adjacent surface of the base metal. Underfill results from the failure of a welder to completely fill the weld joint.

Incomplete penetration forms channels and crevices in the root of the weld which can cause serious issues in pipes because corrosive substances can settle in these areas. These types of defects occur when the welding procedures are not adhered to; possible causes include the current setting, arc length, electrode angle, and electrode manipulation. Lack of fusion results from too little heat input and / or too rapid traverse of the welding torch .Excess penetration arises from to high a heat input and / or too slow transverse of the welding torch. Excess penetration - *burning through* - is more of a problem with thin sheet as a higher level of skill is needed to balance heat input and torch traverse when welding thin metal.

Welding residual stresses and distortions

Residual stresses and distortions are developed due to heating and cooling to the high temperatures under constrain. To understand this mechanism let us consider three bar arrangement. Three metal bars connected to two rigid blocks. Initially all bars at room temperature (Fig. 9, a). The middle bar alone is heated up and expands. Its thermal expansion is restrained by side bars. Consequently, compressive stresses are produced in the middle bar and they increase with increasing temperature (Fig. 9, b) until the yield stress in compression is reached. At yield stress plastic deformation occurs (Fig. 9, c). When the heating stops and the middle bar is allowed to cool off, the compressive stresses drop rapidly. Because of plastic deformation occurred the middle bar become shorter, so stresses reduce to zero at temperature higher then room temperature (Fig. 9, d). Following thermal contraction is restrained by the side bars, tensile stresses are produced in the middle bar and increase with decreasing temperature until the yield stress in tension is reached. Therefore, a residual tensile stress equal to the yield stress at room temperature is set up in the middle bar when it cools down to room temperature. The residual stresses in the side bars are compressive and equal to one-half of the tensile stress in the middle bar (Fig. 9, e).



a) b) c) d) e)

Fig. 9 – Three bar arrangement heating and cooling steps.

Roughly speaking, the weld metal and adjacent base metal are analogous to the middle bar, and the areas farther away from the weld metal are analogous to the two side bars. This is because the expansion and contraction of the weld metal and the adjacent base metal are restrained by the areas farther away from the weld metal. After cooling to the room temperature, residual tensile stresses exist in the weld metal and the adjacent base metal, while residual compressive stresses exist in the areas farther away from the weld metal.

Residual stresses can cause problems such as hydrogen-induced cracking and stress corrosion cracking. Postweld heat treatment is often used to reduce residual stresses. Other techniques such as preheat, peening, and vibration have also been used for stress relief.

Because of solidification shrinkage and thermal contraction of the weld metal during welding, the workpiece has a tendency to distort. The welded workpiece can shrink in the longitudinal and transverse direction. Upward angular distortion usually occurs when the weld is made from the top of the workpiece alone. The weld tends to be wider at the top than at the bottom, causing more solidification shrinkage and thermal contraction at the top of the weld than at the bottom. Consequently, the resultant angular distortion is upward. Angular distortion increases with workpiece thickness because of increasing amount of the weld metal and hence increasing solidification shrinkage and thermal contraction.

When fillet welds between a flat sheet at the bottom and a vertical sheet on the top shrink (double-side tee joint), they pull the flat sheet toward the vertical one and cause upward distortion in the flat sheet.

Several techniques can be used to reduce weld distortions. Reducing the volume of the weld metal can reduce the amount of angular distortion and lateral shrinkage. The use of electron or laser beam welding can minimize angular distortion. Balancing welding by using a X-groove joint in preference to a V-groove joint can help reduce angular distortion. Placing welds about the neutral axis also helps reduce distortion. Presetting is achieved by estimating the amount of distortion likely to occur during welding and then assembling the job with members preset to compensate for the distortion. Elastic prespringing can reduce angular changes after the removal of the restraint. Pre-heating, thermal management during welding, and postweld heating can also reduce angular distortion.

Questions

Tell the definition of “welding”.
In what form can energy be supplied?
How is the type of welding defined?
How can the welding processes be grouped according to the state of base metal?
Describe fusion welding processes.
What is autogeneus weld?
Describe solid-state welding processes.
What types of welding are there according to the degree of process mechanization?
What is manual welding?
What is mechanized welding?
What is adaptive control welding?
What is semiautomatic welding?
What is automatic welding?
What is robotic welding?
What shielding media can be used?
What are processes according to the continuity?
What is a welded joint?
What is a seam?
Tell five basic joint configurations.
What is a butt joint?
What is a flange butt joint?
Compare single-side and double-side welds.
What advantages does a square plain butt joint have?
Describe edge preparation for butt joint.
What is a lap joint?
What is a plug weld?
What is a corner joint?
What is an edge joint?

What is a tee joint?
What is a fillet weld?
Tell me main positions of welding.
Why is the flat position the most preferable?
Describe horizontal and vertical positions.
Why welding in overhead position the most complicated.
What is a weld face?
What is a weld root?
What is a weld toe?
What is a weld reinforcement?
What is a weld throat?
What is a weld bead?
What is a weld leg?
Describe the composite region of a weld.
Describe the unmixed zone of a weld.
Describe partially melted zone in a weldment.
Describe heat affected zone.

What is discontinuity?
What is fitness-for-service of the welded construction?
What are typical welding discontinuities?
When do cracks occur in the weld?
When do hot cracks occur?
What are causes of cold cracking?
What are types of cracks according to the crack location?
What is the main cause for gas inclusions?
What is the main reason for the presence of gases in the weldpool?
What is a wormhole in a weld?
How do the cumulative and isolated inclusions occur?
How to prevent slag inclusions?
What is a undercut?
What is a overlap?
What is a undelfill?
What does a lack of fusion result from?
Why are residual stresses and distortions developed?
Describe the main stages of the heating and cooling process.
What problems can the residual stresses cause?
How to reduce residual stresses?
How does upward angular distortion occur?
How to reduce weld distortions?

THEME 2: FUSION WELDING

Definition: ***Fusion welding is a any welding process what uses fusion to make a weld.***

Types of fusion welding include: arc welding (carbon arc welding, gas shielded metal arc welding, submerged arc welding, atomic hydrogen arc welding, gas tungsten arc welding, gas metal arc welding, plasma arc welding), gas welding (oxyfuel welding), high-energy beam welding (electron beam welding, laser beam welding).

Arc welding basics

Arc welding refers to a group of welding processes in which heating of the metals is accomplished by an electric arc. Some arc welding operations also apply pressure during the process, and most utilize a filler metal.

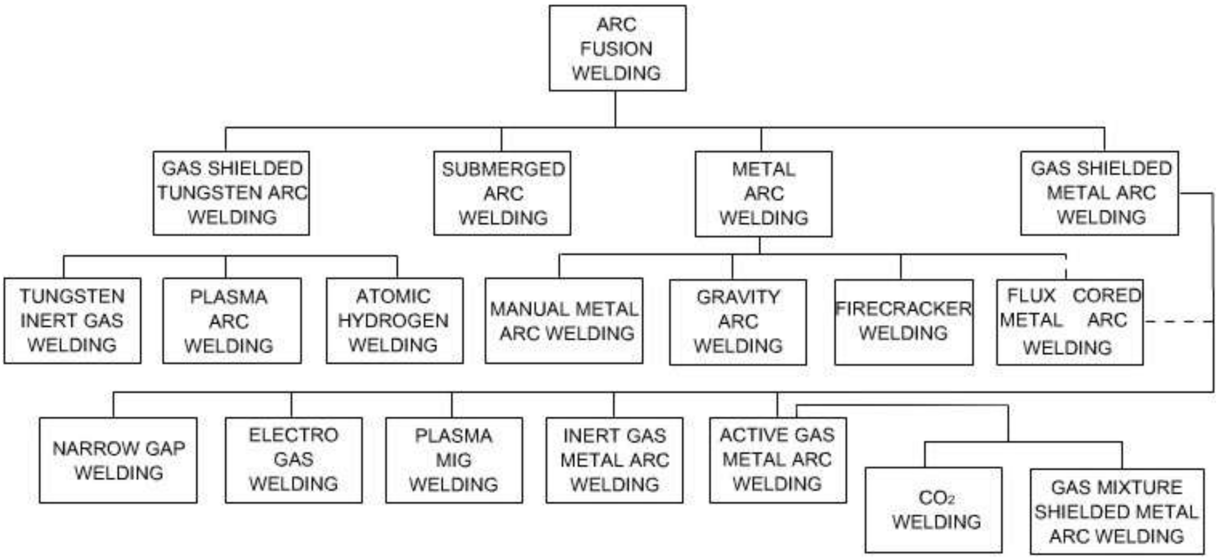


Fig. 10 – Arc welding classification

Welding arc

A welding arc is a sustained electrical discharge through high conducting plasma. It produces sufficient thermal energy which is useful for joining metals by fusion. There are three characteristic regions of electric arc: cathode spot, anode spot and plasma column. The cathode is the negatively charged electrode. The cathode spot is the source of electrons or an electron emitter and accept positive charge from arc column. The anode is the positively charged electrode. The anode spot attracts electrons. Plasma column is an ionized gas in the space between the cathode and anode. The arc column is electrically conductive and neutral, i.e. the number of positive and negative charges in a given volume balanced.

The arc discharge requires a flow of electrons from the cathode through the arc column to the anode. There are two cases of electron discharge at the cathode: thermionic emission and nonthermionic emission.

Thermionic emission results from joule heating (resistance) of the cathode by the imposed welding current until the electron energy at the cathode tip exceeds the work function (energy required to strip off an electron). This case applies to the general case if metal electrode charged negative. Metal electrodes have to be heated to very high temperature to achieve thermionic emission. The lower work function the electrode material has, the lower temperature of the thermionic emission. Thermionic emission creates a cloud of electrons, called a space charge, around the cathode. If a second electrode at a higher potential is nearby (the workpiece, in this case), then the electrons will flow to it, thus establishing the arc.

Table 10 – Work function of same materials

Metal		K	Na	Ba	Ca	Fe
Work function, eV	Pure	2,02	2,29	2,39	3,34	4,74
	Oxide	0,46	1,8	1,59	1,7	3,53

Table 11 – Work function of tungsten alloys

Metal	W	W-ThO$_2$	W-LaO$_2$	W-ZrO$_2$	W- CeO$_2$
Work function, eV	5,52	2,7	2,7	1,6	1,5

Nonthermionic, or field, **emission** creates an electron discharge with a very high electric field, typically exceeding 10^9 V/m. This intense electric field "pulls electrons out" of a relatively cold or unheated cathode. This would not appear to be applicable to welding until one considers that for reverse polarity, a condensation of positive ions from the arc column can build up in a very thin (1 nm) layer over the cathode surface, creating a very high localized electric field even though the cathode voltage drop may only amount to several volts.

Analysis of the arc discharge is separated into electrode regions and the arc column. The electrode regions are confined to very small distances from the electrode surfaces, have very high electrical and thermal fields, and have much higher current density, because of the contraction of the arc to a small spot. As a result, electrode regions for both the cathode and the anode are difficult to analyze. The arc column, on the other hand, is relatively easy to analyze, but is important primarily as a means to deduce arc characteristics at the electrodes.

The cathode and anode are similar in several aspects. Both exhibit a voltage drop caused by a space charge that covers a very thin region over their surfaces ($10^{-5}…10^{-7}$ the thickness), and the arc is significantly contracted on the surfaces. The relative magnitude of these drops depends on welding parameters and electrode material. For manual metal arc, cathode voltage drop U_{cth} is about 10…16 V, and anode voltage drop U_{an} is about 6…8 V.

The arc column voltage U_{pc} is proportional to the arc length L_a and arc potential gradient E_{pc}. The potential gradient in the arc column is relatively low: from 0.2 to 10 V/mm and depends on plasma compound.

The total arc voltage $\boldsymbol{U_a=U_{cth}+U_{an}+U_{pc}}$ **.**

The volt-amperage curve of an arc takes on a nonlinear and consists of three parts (see Fig. 11). At low current range (less than 50 A) the curve has a negative slope. This is because low current do not generate heat enough to ensure stable conditions for gas ionizing. The more current the higher conductivity of arc column, therefore arc voltage decreases. The conductivity of the arc increases at a greater rate than simple proportionality to current. When the temperature is high enough to sustain plasma, the arc voltage become stable. The middle part of the curve is flat. The more amperage the more diameters of arc column and electrode spots. Then the electrode spot covers all surface of electrode tip, and density of electric current rises the arc voltage slightly increases too. The curve has a positive slope.

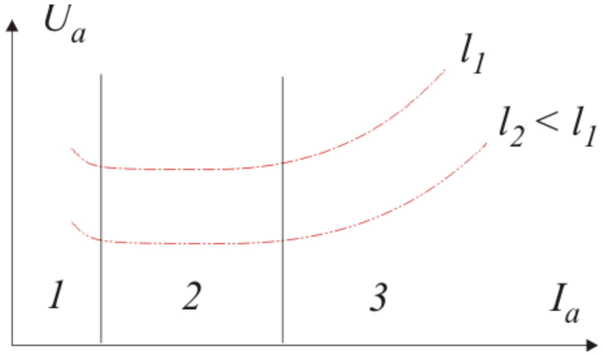


Fig. 11 – Voltage-amperage curves of arcs

Polarity

An electrical circuit has a negative and a positive pole. Direct current flows in one direction, resulting in a constant polarity. If the electrode is the negative pole and workpiece is the positive pole of the welding arc, it is **straight polarity** (DCSP – direct current straight polarity or DCEN – direct current electrode negative). The arrangement of direct current arc welding leads in which the electrode is the positive pole and the workpiece is the negative pole of the welding called **reverse polarity** (DCRP - direct current reverse polarity or DCEP – direct current electrode positive).

Due to the fact that the cathode loses some heat through the electron work function, the temperature is more at anode spot then at cathode spot. For example, upon shielded metal welding is about 43% of total heat generated at anode spot, 36% - at cathode spot, and 21% - in arc column. Therefore **DCSP** provides the deepest penetration for given amperage and is used when welding tight-fit joints. The technician should be aware that this process develops the most heat. **DCRP** results in faster melt-off of the electrode, faster deposition rate and less splatter but lessened penetration. Thinner materials and joints with wide gaps are most frequently welded with DCRP power.

With **alternative current (AC)**, the order in which the leads from the power source are connected will make no difference. Alternating current flows half the time in one direction and half the time in the other, changing its polarity 100 times per second with 50-hertz current.

The **cathode cleaning action**, which is one of the principal reasons to use DCRP or AC, results from stripping away the oxide film at the emitting sites by very small and intense jets of metal vapor and debris. It becomes obvious that a practical implication of the short lifetime of these cathode spots is a generally unstable arc that is due to the necessity of continual movement of the cathode spot to undepleted regions of oxide film. The cathode cleaning action is widely used in welding aluminum and magnesium alloys.

Arc blow

Arc blow is the deflection of an arc from its normal path because of magnetic forces. Arc blow, when it occurs, is encountered principally with direct current welding of magnetic materials (iron and nickel). It can be encountered with alternating current under some conditions, but these cases are rare, and the intensity of the arc blow is always much less severe. Direct current flowing through the electrode and base metal sets up magnetic fields around the electrode which tend to deflect the arc to the side at times, but usually the arc is deflected either forward or backward along the joint.

Back blow is encountered when welding toward the workpiece connection near the end of the joint or into a corner. Forward blow is encountered when welding away from the lead at the start of the joint. In general, arc blow is the result of two basic conditions: 1. the change of direction of the current flow as it enters the work and is conducted toward the work lead; 2. the asymmetric arrangement of magnetic material around the arc, a condition that normally exists when welding is done near the end of ferromagnetic materials.

Although arc blow cannot always be eliminated, it can be controlled or reduced to an acceptable level through a knowledge of the above two conditions. Except in cases where arc blow is unusually severe, certain corrective steps may be taken to eliminate it or at least to reduce its severity. Some or all of the following steps may be necessary:

- place the workpiece lead connections as close as possible to the joints to be welded;
- set the position of electrode so that the arc force counteracts the arc blow;
- use the arc as short as possible;
- wrap the workpiece lead around the workpiece in the direction that sets up a magnetic field which will counteract the magnetic field causing the arc blow;
- weld toward a heavy tack or runoff tab;
- reduce the welding current if possible;
- change to AC, if possible.

Arc welding power sources

The primary function of an arc welding power source is to provide sufficient power to melt the join and fillet metal, to sustain the welding arc. There are four basic types of arc power source: AC transformer; DC rectifier; invertors; DC generator.

AC transformers are quite simple to use and service and cheap, but very inefficient and have high power consumption. Bulky equipment, thus occupies large floor space. Welding at low currents is not possible.

DC rectifiers are controlled electronically, for example by thyristors. DC rectifiers have higher efficiency, better quality of weld and lower open circuit voltage.

A new generation of power sources called **inverters** is available. These use transistors to convert mains AC (50Hz) to a high frequency AC (over 500 Hz) before transforming down to a voltage suitable for welding and then rectifying to DC. Because high frequency transformers can be relatively small, principal advantages of inverter power sources are undoubtedly their size and weight when the source must be portable. The high frequency inverter-based welding machines are typically more efficient and provide better control of variable functional parameters than non-inverter welding machines.

Welding power supplies may also use **generators** to convert mechanical energy into electrical energy. Most designs are usually driven by an internal combustion engine. The output of the generator can be direct current or even a higher frequency AC current and can be used for implementing TIG welders.

One of the most important characteristic of arc power source is static volt-ampere characteristic.

Typical volt-ampere output curves for a conventional **constant-current** power source are shown in Fig. 12a. It is sometimes called a “drooping” because of the substantial downward (negative) slope of the curves. The power source might have open circuit voltage adjustment in addition to output current control. A change in either control will change the slope of the volt-ampere curve.

With constant current curve a increase in arc voltage would result in a decrease in current but the change in current is relatively small. Therefore, with a consumable electrode welding process, electrode melting rate would remain fairly constant with a change in arc length.

The point of intersection between the arc characteristic and the power unit load characteristic is referred to as the *working point*. The working point at any particular time represents the welding current and voltage at that time.

In shielded metal arc welding, the flatter volt-ampere curve would give a skilled welder the opportunity to vary the current substantially by changing the arc length. This could be useful for out-of-position welding because it would enable the welder to control the electrode melting rate and molten pool size. Generally, however, less skilled welders would prefer the current to stay constant if the arc length should change.

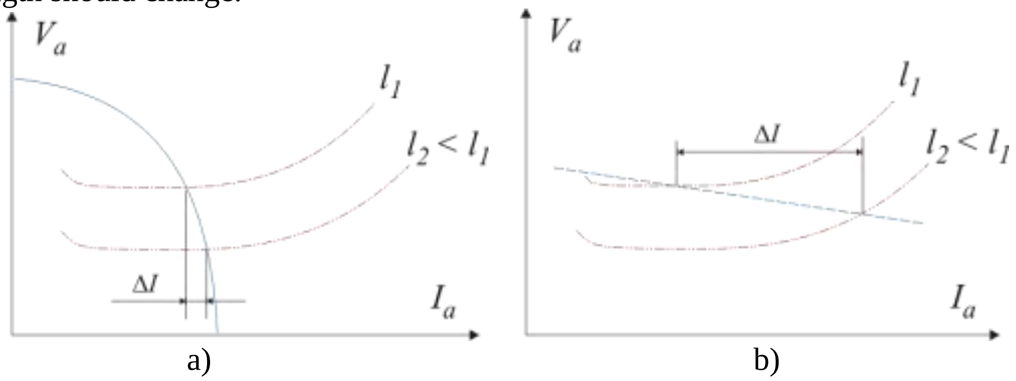


Fig. 12 – Volt-amp static characteristics

A typical volt-ampere curve for a **constant-voltage** power source is shown in Fig. 12b. This power source does not have true constant-voltage output. It has a slightly downward (negative) slope because internal electrical impedance in the welding circuit causes a minor voltage drop in the output. Changing that impedance will alter the slope of the volt-ampere curve.

With constant voltage curve an increase or decrease in voltage produces a large change in amperage. This characteristic is suitable for constant-feed electrode processes, such as gas metal arc, submerged arc, and flux cored arc welding, in order to maintain a constant arc length. A slight change in arc length (voltage) will cause a fairly large change in welding current. This will automatically increase or decrease the electrode melting rate to regain the desired arc length (voltage). This effect has been called ***self regulation***. Adjustments are sometimes provided with constant-voltage power sources to change or modify the slope or shape of the volt-ampere curve.

Questions

What is a fusion welding?
What types of fusion welding do you know?
What is arc welding?
What types of arc welding do you know?
What is a welding arc?
Describe cathode spot, anode spot, plasma column.
What does thermionic emission result from?
Explain principles of nonthermionic emission.
How to calculate total arc voltage?
Describe voltage-amperage curves of an arc.
What advantages does the straight polarity have?
What advantages does the reverse polarity have?
What advantages does the alternative current have?
What is a cathode cleaning action?
What is arc blow?
What causes of arc blow do you know?
How to prevent or reduce arc blow?
What are advantages of AC transformers?
What are advantages of DC rectifies?
What are advantages of inverters?
What are advantages of DC generators?
Describe typical volt-ampere output curve for the constant-current power source.
Describe typical volt-ampere output curve for the constant-voltage power source.
What is a working point?
Why do less skilled welders prefer the constant-current output?
Explain self regulation effect.

Carbon arc welding

Carbon arc welding is an arc welding process with the use of nonconsumable carbon or graphite electrode. It was the first arc welding process ever developed. The inventor of carbon-arc welding was Russian, Nikolay Benardos, who developed this method in 1881 and patented it later under the name *Elektrogefest* ("Electric Hephaestus").

Carbon electrodes are rods 6…18 mm in diameter, 250…700 mm in length. Electrode tip are sharpened to the angle 50…70 for welding ferrous metal and to 20…40 for welding of non ferrous metals. Carbon arc welding can be performed with direct current straight polarity (electrode negative) only. If reverse polarity the welding arc is not stable, weld may has poor profile, metal added is carbonized, carbon electrode is overheated and has intensive degradation. Welding arc is sensitive to air drafts or arc blow.

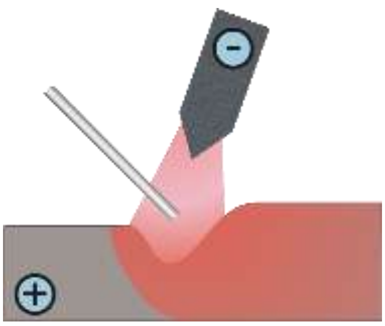


Fig. 13 – Carbon arc welding

Welding without filler metal is the most used and simplest technique. Edge joints are preferable, but close type of corner joint and tight-fit lap joints are welded too. This technique has high welding rate, but the weld has poor mechanical properties.

Carbon arc welding can be used for light gage metal. In this case the weld has better appearances then the weld made by shielded metal welding and good mechanical properties. Welding with filler metal is recommended for thin steel sheets 0.3…1.0 mm in the thickness. This technique can be also used for casting patch work and for nonferrous metals welding. Aluminum is welded using fluxes to prevent oxidation. Fluxes are the same as for oxyfuel welding. Aluminum alloys welded by CAW are Al99, AlMn1, AlMg2 up to 5 mm in the thickness. Copper welding up to 15 mm in the thickness are welded by CAW.

Table 12 – Welding conditions for carbon arc welding of steel

Type of joint	Metal thickness, mm	Current, A	Electrode diameter, mm	Welding rate, m/h
Single-side butt joint	2	200	10	20
	3	300	12	20
Single-side corner joint	2	150	10	20
	3	250	10	15
Edge joint	1	130	10	30
	2	200	10	40

Table 13 - Welding conditions for arc welding with graphite electrodes

Metal thickness, mm	Electrode diameter, mm	Current, A	Welding rate, m/h
1,5	5	90–100	45
2	6	125–135	40
2,5	6–8	100–250	35
3	6–8	250–275	33

Electrode current capacity can be increased if graphite electrodes are used. Graphite is a soft steel-gray hexagonally crystallized allotrope of carbon, has better electric conductivity and wear resistance. Welding current can be increased in 2…3 times if graphite electrodes are used.

But the common disadvantages of the process are poor shielding, carbonizing of the weld metal. The field of applications is limited to no-load non-critical parts. TIG process should be used to improve metal fused shielding and weld properties.

Questions

Who developed carbon arc welding?

Describe carbon electrodes used in CAW process.

What polarity does the CAW process use?

Describe field of application for CAW.

What disadvantages does the CAW process have?

Manual metal arc welding

In 1891 a Russian mining engineer Nicolay Slavyanov obtained a patent for arc welding with bare metal electrodes. He use this technique for casting patch work and sometimes to repair heavy sections parts, like shafts, gear components, flywheels.

Approximately 1900, Strohmenger introduced a coated metal electrode in Great Britain. There was a thin coating of clay or lime, but it provided a more stable arc. In 1904-1907 a Swedish ship engineer Oscar Kjellberg improved arc welding process and obtained a patent for overhead welding and special covered electrode. Stick electrodes were produced by dipping short lengths of bare iron wire in thick mixtures of carbonates and silicates, and allowing the coating to dry. Arc welding with covered electrode was used first for repairing works in shipbuilding later as manufacturing process.

World War I brought a tremendous demand for armament production and welding was pressed into service. The repair of sabotaged German ships in New York Harbor highlighted the first important use welding because the German merchant marines tried to destroy the ships boilers on 109 ships. A team of engineers from a railroad company was tasked to the repair. Later, 500 000 troops were delivered to the European War in France using these repaired ships.

During WW I American's industry was called upon to produce war and transport ships in quantity and with speed. President Woodrow Wilson founded Emergency Fleet Corp to build ships using welding as main manufacturing process. This time because of a gas shortage in England, the use electric arc welding to manufacture bombs, mines, and torpedoes became the primary fabrication method. In Germany, a Dutchman, Anthony Fokker, began using welding in the production of fuselages in German fighter planes.

After WW I, the Treaty of Versailles limited the Germans from designing and building ships in excess of 10 000 tons for armored ships and cruisers not to exceed 6 000 tons. Welding was an experimental production option, but the Germans used it to develop the next stage of warships by saving weight whereby the ship could then carry more armament or armor plating in selected areas.

During the 1920s, various types of welding electrodes were developed. There was considerable controversy during the 1920s about the advantage of the heavy-coated rods versus light-coated rods. The heavy-coated electrodes, which were made by extruding, were developed by A.O. Smith Company. By 1930, covered electrodes were widely used.

Now shielded metal arc welding (SMAW) is one of the simplest and widespread processes.

Principals of operation

Shielded metal arc welding is shown in **Ошибка! Источник ссылки не найден.**. The electric arc 4 struck between the shielded electrode 8 and base metal 10. Arc heat fuses a portion of the tip of the electrode, its coating and base metal. The molten metal forms a weldpool 9 and tends to flow away from the arc. While the droplet 6 is forming, some forces act on the droplet: gravity G, surface tension $F_{s.t}$, electrodynamic force $F_{e.d}$. Additional forces, which can have an effect, are plasma blow $F_{p.b}$, vapor reaction force $F_{v.r}$. Molten metal droplets from electrode core 7 are transferred to weldpool through arc space. Electrode covering 5 fuses, generates shielding gas and makes liquid slag film on droplet 5 and weldpool surface 3. Weldpool metal cools, solidifies and forms weld 1. Slag solidifies and makes solid coverage 2 on top of the weld to protect it during cooling. The slag coverage needs to be removed after the welding.

The main components of the welding station are: power source, electrode holder and cables, welder protection, fume extraction. Tools required include: a wire brush to clean the joint area adjacent to the weld (and the weld itself after slag removal); a chipping hammer to remove slag from the weld deposit; and, when removing slag, a pair of clear lens goggles or a face shield to protect the eyes (lenses should be shatter-proof and noninflammable).

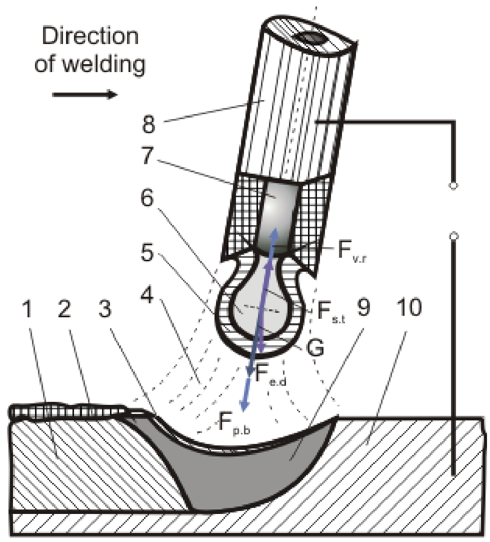


Fig. 14 – Scheme of shielded metal arc welding

Types of stick electrodes

Rutile electrodes are easy to strike and use, give excellent slag detachability, fine bead appearance. Spatter loses are negligible, the welding speed is moderate. Rutile electrodes are relatively insensitive to moisture. The weld metal has tensile properties, which are as high as, or some what higher then weld metal from basic electrodes but have lower elongation and notch toughness. Rutile electrodes can be recommended for welding mild steel having a nominal tensile strength 440N/mm^2.

Acid electrodes are easier to strike than basic electrodes but more difficult to strike and restrike than rutile electrodes. The welding speed is moderate. The weld beads are smooth and shiny. The slag is inflated and easy to remove. The weld metal has a lower yield stress and tensile strength compared with those from rutile electrodes but has higher elongation and impact toughness.

Basic electrodes have moderate welding speed in the flat position but are faster than other type of electrodes when welding vertically upwards. Amount of weld metal deposited per electrode is greater than for other types of electrodes. The slag is normally not quite as easy to remove as the slag from acid or rutile type of electrodes, but risk of slag inclusions is smaller The weld metal from basic electrodes has low hydrogen content and good toughness even at low temperatures. Basic electrodes are less likely to give either hot cracks or cold cracks compared to other type of electrodes. The higher the hardenability of steel to be welded, the greater the necessity to use basic electrodes.

Cellulosic electrodes are recommended for all position welding where the mechanical properties of the deposit are of the greatest importance and radiographic requirements are must to meet. Vertical and over head welding require often one size larger electrode in comparison to electrodes with other types of coating. Cellulose electrodes are extremely good for vertical down welding. Mild steel can be welded without preheating.

Advantages

1. Simple, portable and inexpensive equipment.

Almost all types of arc welding power source can be used (AC transformers, DC rectifiers, inventors, DC generators). Wide range of equipment for SMAW offered at the market can satisfy all consumer needs. Total cost of equipment for welding station can be below 1500$. Fuel-powered DC generators are suitable for remote works.

2. Wide range of joints and positions are applicable.

The process is universal and can be used to manufacture, maintenance and repair. Range of metal thicknesses welded relatively wide (in comparison with carbon or tungsten inert gas welding) and can be easily increased by application suitable electrodes and edge preparation. This process is really good for inexpensive welding of heavy sections in construction of steel structures. The welding positions is not limited to flat position. Due to the forces acting the electrode molten metal can be easily transferred to weldpool in vertical and overhead positions. Variety of electrodes at the market allows to pick up suitable for metal welded, weld strength required, welding rate required, polarity used and so on.

Disadvantages and limitations

1. The process is discontinuous due to limited length of electrodes;

The welder needs to change the used-up electrode and insert new quite often. This decreases work rate. The part of electrode can not be used, so this decreases consumables efficiency. At the termination of the weld there is weld discontinuity called crater. Craters have severe problems with stress concentrations and cracks. Discontinuous process also results in more residual stresses.

2. Relatively low work rate (compared to automated metal arc welding processes like submerged arc welding, gas metal arc welding)

3. Require skilled worker (hard to master);

Good welders must be able to select the correct size and type electrode for each job. They must know which machine use for the job and be able to set the current and voltage controls properly. They must be able to manipulate the electrode and arc to make a good weld under varying conditions. In addition, welders must have knowledge of job preparation, positioning the work, distortion, and many other factors that enter into the final result of a good weld.

4. Weld may contain slag inclusions.

Slag shields weld metal from oxidation, prevents porosity and gas cavity in the weld, but due to intensive agitation of fused metal, some pieces of slag can freeze in the weld.

5. SMAW limited to ferrous materials.

Actually nonferrous materials (like aluminum, copper, nickel alloys) are also possible to weld by stick electrodes, but require very aggressive fluxes in covering to be used and shielding poorer then in inert gases, so it rarely used.

Applications

Shielded metal arc welding is one of the simplest and widespread processes. Currently, about 50 percent of all industrial welding is performed by this process. SMAW is commonly used in general construction, shipbuilding, and pipelines, as well as for maintenance work, since the equipment is portable and can be easily maintained. It is especially useful for work in the field where portable fuel-powered generators can be used as the power supply.

SMAW best suites for steel parts thicknesses of 3…19 mm, although this range can be easy extended by using appropriate edge preparation and technique. Now flux-cored welding replaces stick welding in many applications except outdoor works.

Process variations

Gravity arc welding serves as an automated version of the traditional shielded metal arc welding process, employing an electrode holder attached to an inclined bar along the length of the weld. Once started, the process continues until the electrode is spent, allowing the operator to manage multiple gravity welding systems. The electrodes employed are coated heavily in flux and are typically not less than 0.7 m in length and about 6 mm thick. As in manual SMAW, a constant current welding power supply is used, with either direct current straight polarity or alternating current.

Firecracker welding is an automatic method for making butt and fillet welds, A flux-coated electrode is laid horizontally above a close-fitting corner or butt joint. An arc is struck at one end of the electrode, which then burns along the length of the electrode. The electrode is held in place by either copper blocks, clamps or adhesive tape. Firecracker welding allows a weld the entire length of an electrode to be welded in one pass, without pausing. Extra-long electrodes may be used to increase the length that may be welded in one pass. The process is also suitable for use in areas with limited access. Once started it continues automatically, without needing enough space for a skilled welder with sight of the weld. One drawback is that the size of the bead deposited is limited by the cross-section of the electrode, as there is no scope for manually weaving the arc to deposit more rod in less weld length. For this reason, the flux coating often contains iron powder, to give additional deposition. The rod coating is generally the same as for manual arc, with no change being required.

Underwater welding is welding process with the welder in the water with no physical barrier between the water and the welding arc. Although it is a complex metallurgical process, underwater welding closely resembles welding in air in that the welding arc and molten metal are shielded from the environment (water) by gas and slag produced by decomposition of flux coated electrodes. Underwater welding has been used during the installation of new offshore drilling structures, sub-sea pipelines and hot taps, docks and harbor facilities, and for modifications and additions to underwater structures. However, underwater welding is most often required for repairs to existing structures.

Questions

Who obtained a patent for overhead welding and special covered electrode?
What were the first uses for SMAW process?
Describe SMAW process. What are the main components of the welding station?
What are advantages and field of application for rutile electrodes?
What are advantages and field of application for acid electrodes?
What are advantages and field of application for basic electrodes?
What are advantages and field of application for cellulosic electrodes?
Describe gravity arc welding. Describe firecracker welding.
Recount advantages of SMAW process. Describe fields of application for SMAW process.
Recount disadvantages and limitations of SMAW process.

Arc stud welding

Arc stud welding is an arc welding process that uses an arc between a metal stud, or similar part, and the other workpiece. The process is used without filler metal, with or without shielding gas or flux, with or without partial shielding from a ceramic or graphite ferrule surrounding the stud, and with the application of pressure after the faying surfaces are sufficiently heated.

In arc stud welding, the base end of the stud is joined to the other work part by heating the stud and the work with an arc drawn between the two. When the surfaces to be joined are properly heated, they are brought together under low pressure. Stud welding guns are used to hold the studs and move them in proper sequence during welding. There are two basic power supplies used to create the arc for welding studs. One type uses d-c power sources similar to those used for shielded metal arc welding (SMAW). The other type uses a capacitor storage bank to supply the arc power. The stud arc welding processes using these two types of power sources are known as arc stud welding and capacitor discharge stud welding, respectively

Arc stud welding, the more widely used of the two major stud welding processes, is similar in many respects to manual SMAW. The heat necessary for welding of studs is developed by a DC arc between the stud (electrode) and the plate (work) to which the stud is to be welded. Welding time and the plunging of the stud into the molten weld pool to complete the weld are controlled automatically. The stud, which is held in a stud welding gun, is positioned by the operator, who then actuates the unit by pressing a switch. The weld is completed quickly, usually in less than a second. This process generally uses a ceramic arc shield, called a ferrule. It surrounds the stud to contain the molten metal and shield the arc.

Capacitor discharge stud welding derives its heat from an arc produced by the rapid discharge of electrical energy stored in a bank of capacitors. During or immediately following the electrical discharge, pressure is applied to the stud, plunging its base into the molten pool of the workpiece. The arc may be established either by rapid resistance heating, and vaporization of a projection on the stud weld base (arc time: 3…6 milliseconds), or by drawing an arc as the stud is lifted away from the workpiece (arc time: 6…15 milliseconds). The capacitor discharge process does not require a shielding ceramic ferrule because of the short arc duration and small amount of molten metal expelled from the joint. It is suited for applications requiring small to medium studs.

Because arc stud welding time cycles are very short, heat input to the base metal is very small compared to conventional arc welding. Consequently, the weld metal and heat-affected zones are very narrow. Distortion of the base metal at stud locations is minimal.

Studs can be welded at the appropriate time during construction or fabrication without access to the back side of the base member. Drilling, tapping, or riveting for installation is not required. Small studs can be welded to thin sections by the capacitor discharge method. Studs have been welded to sheet as thin as 0.75 mm without melt-through. They have been joined to certain materials (stainless steel, for example) in thicknesses down to 0.25 mm. Because the depth of melting is very shallow, capacitor discharge welds can be made without damage to a refinished opposite side. No subsequent cleaning or finishing is required.

Arc stud welding has been widely accepted by all the metalworking industries. Specifically, stud welding is used extensively in the following fields: automotive, boiler and building and bridge construction, farm and industrial equipment manufacture, railroads, and shipbuilding. Defense industry applications include missile containers, armored vehicles, and tanks. The process can be used on parts that have had the face surface painted, plated, polished, or coated with ceramic or plastic, because postweld cleaning or finishing operations on the side of the base metal opposite to the stud attachment are eliminated.

Questions:

What is arc stud welding?

Describe arc stud welding process.

What the difference between arc stud and capacitor discharge stud welding?

Describe advantages and limitations of the process.

Describe field of applications for stud welding.

Submerged-arc welding

Minerals were used for welding from the beginning. Nicolay Benardos used fine crushed limestones to increase arc stability and prevent heat scale. Nicolay Slavyanov used broken glass for arc casting metal drossing.

In 1920th, automatic welding with bare electrode wire was introduced. Later granular flux placed on workpiece surface began to use for fused metal shielding. In 1935 the patent for submerged arc welding was obtained in USA. The process was developed in USSR and widely used in tank building industry in 1942.

Principles of operation

Submerged arc welding used continuously-fed wire electrode 2. The consumable electrode is a coil of bare round wire 1.5-10 mm in diameter, and is fed automatically through a tube (welding gun). Electric arc 1 struck under granular flux 3 in gas cavity 5, which is generated by vapor and gas emission ne in area close to electric arc. Gas cavity is bounded above by molten flux and below by weldpool. As the process goes the pressure of gases increases and tears the molten flux film off to release some portion of gas. This intermittently repeats.

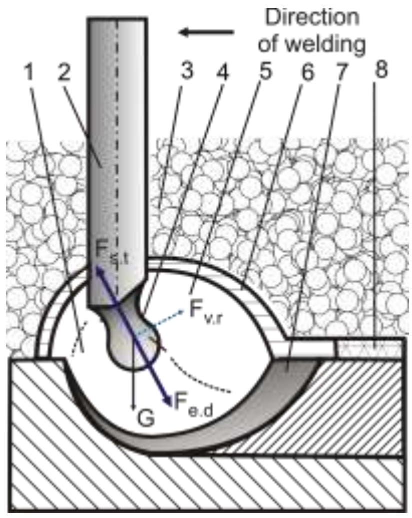


Fig. 15 – Scheme of Submerged Arc Welding

Arc is located near front side of weldpool. Some forces acting to the droplet formed trying to departure the droplet off or to keep from departing. These forces are gravity *G*, surface tension $F_{s.t}$, electrodynamic force $F_{e.d}$, vapor reaction $F_{v.r.}$. Vapor backpressure reaction force the detached droplet fly to rear side of weldpool. Arc pressure forces molten metal in weldpool to rear part also. Under arc there is the molten metal film. The thinner the film the more heat from arc is conducted to unfused base metal.

The process uses a granular flux to generate protective gases and slag, and to add alloying elements to the weld pool. The flux is fed into the weld zone by gravity flow through a nozzle. Prior to welding, a layer of flux powder is placed on the workpiece surface.

SAW is usually operated as a fully-mechanized or automatic process, but it can be semi-automatic. If semiautomatic the electrode travel is automatic (spool feed), where as the welding holder travel is manual. But this process rare used now. For automatic welding both electrode feed rate and holder travel is automatic.

Process variables

Because the operator cannot see the weld pool, greater reliance must be placed on welding settings. Process variables are welding current, arc voltage and welding speed, electrode size, electrode work angle, electrode stick out, depth of flux, polarity. All affect bead shape, depth of penetration and mechanical properties of the deposited weld metal.

Welding current is the most influential parameter because it affects bead shape, controls the rate at which electrode is melted and therefore also controls the deposition rate, heat affected zone, the depth of penetration, and the amount of base metal melted.

If the current is too high at a given welding speed, the depth of fusion or penetration will also be too high so that the resulting weld may tend to melt through the metal being joined. High current also leads to waste of electrodes in the form of excessive reinforcement and produces digging arc and undercut. This overwelding increases weld shrinkage and causes greater distortion.

Bead width increases with welding current until a critical value is reached and then starts decreasing if the polarity used is DCSP. When DCRP polarity is employed bead width increases with the increase in current for entire range. Heat affected zone also increases with the increase in welding current. If the current is too low, inadequate penetration or incomplete fusion may result. Too low current also leads to unstable arc and overlapping.

Arc voltage varies with the length of the arc between the electrode and molten weld metal. With the increase in arc length, the arc voltage increases. The voltage principally determines the shape of the weld bead cross section and its external appearance. Increasing the welding voltage with constant current and welding speed produces flatter, wider, less penetrated weld beads and tends to reduce the porosity caused by rust or scale on steel. Higher voltage also bridges an excessive root opening when fit-up is poor. Increase in arc voltage also increases the size of droplets and hence decreases the number of droplets. The time of the movement of droplet transfer also increases. Further increase in voltage increases the possibility of breaking the arc and disrupting the normal welding process. Increase in voltage also enhances flux consumption which increases pick up or loss of the alloying elements and therefore affects the mechanical and metallurgical properties of the weld metal.

Excessively high voltage produces a wide bead shape that is subject to cracking, increases undercut and creates difficulty in removing slag. Lowering the voltage produces stiffer arc, which improves penetration in a deep weld groove and resists arc blow. An excessively low voltage produces a narrow bead and causes difficult slag removal along the bead edges.

Welding speed is the linear rate at which an arc is moved along the weld joint. With any combination of welding voltage and welding current, the effect of changing the welding speed confirms to a general pattern. If the welding speed is increased, power or heat input per unit length of weld is decreased and less filler metal is applied per unit length of the weld, resulting in less weld reinforcement. Thus, the weld bead becomes smaller.

Weld penetration is affected more by welding speed than any variable other than current. This is true except for excessively slow speeds when the molten weld pool is beneath the welding electrode. Then the penetrating force of the arc is cushioned by the molten pool. Excessive speed any cause undercutting, porosity, arc blow, uneven bead shape, cracking and higher slag inclusion in the weld metal. Higher welding speed results in less heat affected zone and finer grains.

Within limits, welding speed can be adjusted to control weld size and penetration. Relatively slow welding speed provides time for gases to escape from the molten metal, thus reducing porosity. An excessive slow speed produces a convex bead shape which is subject to cracking and excessive arc exposure which is uncomfortable for the operator. Too low welding speed may also result in a large molten pool that flows around the arc, resulting in rough bead, slag inclusions and burn through of the weld plate. The welding speed did not affect the metal deposition rate significantly.

Electrode size affects the weld bead shape and the depth of penetration at fixed current. Electrode size also influences the deposition rate. At any given current, a small diameter electrode will have a higher current density and a higher deposition rate than a larger electrode. However, a larger diameter electrode can carry more current than a smaller electrode, and produce a higher deposition rate at higher amperage. For the same values of current, arc voltage and welding speed, an increase in electrode diameter results in a slight increase in the spread of the bead

Electrode work angle. The electrode may be held perpendicular to the workpiece or, tilted forward or backward with respect to the weld pool. As the arc stream tends to align itself along the axis of the electrode, the weld pool shape is different in each case, and so is the shape of the weld bead. It is observed that in forehand welding, molten metal flows under the arc, the depth of penetration and reinforcement are reduced while the width of the weld increases, whereas in backhand welding the pressure of the arc scoops the molten metal from beneath the arc, the depth of penetration and height of reinforcement increases while the width of the weld is reduced. The electrode in perpendicular position results in bead geometry in between those obtained in the above two cases.

The distance between the current pick-up tip and the arc root, called **electrode stick out**, has a considerable effect on the weld bead geometry. Normally the distance between the contact tip and the work is 25-40 mm. The increase in melting rate of the electrode as a result of increase in electrode stickout is proportionate to current density and stick-out. This effect is particularly more significant with smaller diameter electrode since electrode heating is caused by the electrode electric resistance, which increases with the decrease in the electrode diameter. The depth of penetration decreases with the increase in electrode stick-out. Heat affected zone decreased with the increase in stick- out.

The **depth of** the layer of the granular **flux** influences the appearance and soundness of the finished weld as well as welding action. If the granular flux layer is too shallow, the arc will not be entirely submerged in flux. Flashing and spattering will occur. Apart from injurious to the eyes of the operator, this may lead to poor appearance of weld and it may also be porous. If the flux layer is too thick, the arc will be too confined and a rough ropelike appearing weld will result and the weld bead may be narrow and humped. The gases generated during welding may not be able to escape, and the surface of the molten weld metal becomes irregularly distorted. Optimum depth of flux can be established by slowly increasing the flow of flux until the welding arc is submerged and flashing no longer occurs. The gases will then puff up quietly around the electrode, sometimes igniting

Polarity. The amount of heat generated at the electrode and work piece, deposition rate, bead geometry and mechanical properties are affected by polarity. The change in polarity from DCEP to DCEN changes the amount of heat generated at electrode and the work piece and, hence the metal depositing rate, weld bead geometry and mechanical properties of the weld metal. DCSP polarity produced higher deposition rate and reinforcement than with DCRP polarity in submerged arc welding. DCSP produce higher yield strength, ultimate tensile strength and hardness of the weld metal as compared to DCRP

SAW can be operated using either a DC or an AC power source. DC is supplied by a transformer-rectifier and AC is supplied by a transformer. Current for a single wire ranges from as low as 200A (1.6mm diameter wire) to as high as 1000A (6.0 mm diameter wire). In practice, most welding is carried out on thick plate where a single wire (4.0 mm diameter) is normally used over a more limited range of 600 to 900A, with a twin wire system operating between 800 and 1200A.

In DC operation, the electrode is normally connected to the positive terminal. Electrode negative (DCEN) polarity can be used to increase deposition rate but depth of penetration is reduced by between 20 and 25%. For this reason, DCEN is used for surfacing applications where parent metal dilution is important.

The power source has a 'constant voltage' output characteristic which produces a self-regulating arc. For a given diameter of wire, welding current is controlled by wire feed speed and arc length is determined by voltage setting.

Fluxes for submerged arc welding

Fluxes used in SAW are granular fusible minerals containing oxides of manganese, silicon, titanium, aluminium, calcium, zirconium, magnesium and other compounds such as calcium fluoride. It is specially formulated to be compatible with a given electrode wire type so that the combination of flux and wire yields desired mechanical properties.

All fluxes react with the weld pool to produce the weld metal chemical composition and mechanical properties. The flux is often instrumental in achieving high deposition rates and producing the type of weld quality that characterizes the submerged arc welding process. It is common practice to refer to fluxes as 'active' if they add manganese and silicon to the weld, the amount of manganese and silicon added is influenced by the arc voltage and the welding current level. The main types of flux for SAW are: fused, bonded and mechanically mixed.

Mechanically mixed fluxes are achieved by mixing some compounds to get the desired properties. These mixed fluxes have the advantage of using readily available materials or commercial fluxes for mixture in higher critical situations. Disadvantages of mixed fluxes are: segregation during shipping, storage and handling, segregation in flux feeding and recovery systems, and inconsistent mixtures from one mix to the next.

Fused fluxes are produced by mixing the ingredients, then melting them in an electric furnace to form a chemical homogeneous product, cooled and ground to the required particle size. Fused fluxes offer these advantages: 1) Less moisture pickup than other flux manufacturing methods and

2) Recycling through flux recovery systems without losing particle sizing or composition. A disadvantage of fused fluxes is the difficulty in adding deoxidizers and alloys during manufacture. This problem stems from the high temperature used during manufacture. Smooth stable arcs, with welding currents up to 2000A and consistent weld metal properties, are the main attraction of these fluxes.

Bonded fluxes produced by drying the ingredients, then bonding them with a low melting point compound such as a sodium silicate. Most bonded fluxes contain metallic deoxidisers which help to prevent weld porosity. Bonded fluxes offer these advantages: 1) Easy addition of deoxidizers and alloying elements (fused fluxes achieve this with great difficulty because of separation or loss), 2) Allows a thicker flux layer when welding and 3) Can be identified by color. The disadvantages of bonded fluxes are that they absorb moisture like Shielded Metal Arc electrode coatings and they can change in flux composition from segregation or loss of fine particle size. These fluxes are effective over rust and mill scale.

Advantages of the process

1. High welding productivity.

The SAW process provides very high welding productivity, depositing 4-10 times the amount of weld metal per hour as the MMA process. The quality of the weld is very high, with good toughness, ductility, and uniformity of properties.

2. Good conditions for welder.

The thick layer of flux completely covers the molten metal and prevents spatter and sparks — and without the intense radiation and fumes of the MMA process. There is no visible arc light, welding is spatter-free and there is no need for fume extraction. The welder must wear gloves, but other than tinted safety glasses, face shields generally are unnecessary.

3. High thermal efficiency.

The flux also acts as a thermal insulator, allowing deep penetration of heat into the workpiece. As the arc is completely covered by the flux layer, heat loss is extremely low. This produces a thermal efficiency as high as 60% (compared with 25% for manual metal arc).

Limitations

1. Process is mostly specific to ferrous metals

Although submerged welding of aluminum alloys is possible, problems with caustic flux negate the environmental and safety advantages of SAW and require a different process.

2. Commonly limited to welds in flat position.

Because the flux is fed by gravity, the SAW process is performed in a flat or horizontal position with backup piece. Circular welds can be made on pipes, provided that they are rotated during welding.

Applications

SAW is ideally suited for longitudinal and circumferential butt and fillet welds. However, because of high fluidity of the weld pool, molten slag and loose flux layer, welding is generally carried out on butt joints in the flat position and fillet joints in both the flat and horizontal-vertical positions. For circumferential joints, the workpiece is rotated under a fixed welding head with welding taking place in the flat position.

Depending on material thickness, either single-pass, two-pass or multipass weld procedures can be carried out. There is virtually no restriction on the material thickness, provided a suitable joint preparation is adopted. Most commonly welded materials are carbon-manganese steels, low alloy steels and stainless steels, although the process is capable of welding some non-ferrous materials with judicious choice of electrode filler wire and flux combinations.

Questions

Describe principles of SAW operation.

What are types of SAW processes according to the degree of mechanization?

What are SAW process variables?
How does welding current influence to the weld geometry?
How does arc voltage influence to the process?
How does welding speed influence to the weld geometry?
How does electrode size influence to the process?
How does electrode work angle influence to the weld geometry?
How does electrode stick out influence to the process?
How does depth of granular flux influence to the process?
Which polarity is used for SAW process?
Which output does a SAW power source have?
What minerals do the SAW fluxes contain?
What does it mean – "active flux"?
Describe mechanically mixed fluxes.
Describe fused flaxes
Describe bonded fluxes.
Recount the advantages of the process
Recount limitations of the process.
Describe field of applications for SAW.

Atomic hydrogen welding

Invented by Dr. Irving Langmuir, assistant director of the Schenectady laboratory, in 1926 with General Electric Co. Used extensively to weld nonferrous metals before Second World War, but was replaced by tungsten inert gas welding later.

Hydrogen in contact with a tungsten wire heated by an electric current at low pressure, is dissociated into atoms:H_2 <=> 2H. This splitting of the hydrogen molecule is attended by the absorption of a large amount of energy, about 422 kJ per gram molecule. The atomic hydrogen so formed is chemically very active. Langmuir also showed that atomic hydrogen is formed when an electric arc between tungsten electrodes is allowed to burn in hydrogen at atmospheric pressure.

The atomic hydrogen was blown out of the arc by a jet of molecular hydrogen directed across the arc, and formed an intensely hot flame, which is capable of melting tungsten (flame average temperature is about 4000^{o}C). When the hydrogen strikes a relatively cold surface (i.e., the weld zone), it recombines into its diatomic form releasing the energy associated with the formation of that bond. The energy in AHW can be varied easily by changing the distance between the arc stream and the workpiece surface.

The welding torch consists of two inclined tungsten electrodes 1 across which an AC arc is struck. Annular nozzles 2 around the electrodes carry hydrogen gas. The gas streams 3 converge forming a fan shaped flame. Fillet rods 4 may or may not be used. A transformer with an open circuit voltage of 300…800 V is required to strike and maintain the arc in hydrogen.

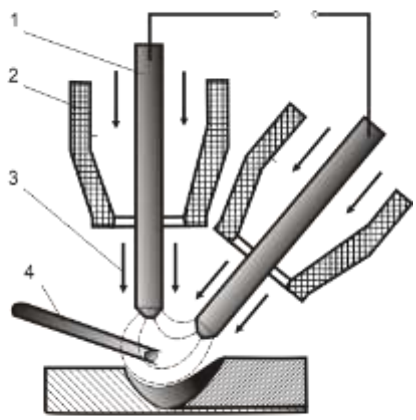


Fig. 16 – Scheme of atomic hydrogen arc welding

Advantages of the process

1. Relatively good shielding.

Separate flux is not required. The hydrogen envelop itself prevents oxidation of the metal and the tungsten electrode. It reduces the risk of nitrogen pickup. Because of the powerful reducing action of the atomic hydrogen, alloys can be melted without surface oxidation. Metals can be melted without contamination with carbon, oxygen or nitrogen.

2. High heat concentration.

Because of the high thermal conductivity of hydrogen, the plasma channel in the arc is constricted, offering very high energy concentration. As a result welding is faster, heat affected zone is smaller, less residual stresses and distortions. Atomic hydogen welding was of particular use for such jobs as surfacing dies, where the high flame temperature enabled a thin surface layer to be deposited on the thick base metal.

3. Work piece do not form a part of the electric circuit.

Hence, problems like striking the arc and maintaining the arc column are eliminated. Welding of nonconductive materials is possible.

Disadvantages and limitations

1. The process is potential dangerous.

Atomic hydrogen welding with high open circuit voltage (300…800 V) is very dangerous for welders because of risk of electric shock. Hydrogen is highly flammable. It reacts violently with air, oxygen, halogens. Heating may cause violent combustion or explosion. Because hydrogen is also colorless and odorless it is also hard to detect leaks that may occur.

2. The process costs slightly more than other processes.
3. Hydrogen generates porosity in aluminum welds

Applications

The process was used for welding thin parts made of steel or nonferrous metals, but was replaced by inert gas welding.

Questions

Who invented atomic hydrogen welding?
How to dissociate hydrogen into atoms?
What happens then hydrogen strikes a cold surface?
Describe the welding torch for AHW.
Recount advantages of the process.
Recount disadvantages and limitations of the process.

Gas tungsten arc welding

Gas tungsten arc welding (GTAW), commonly known as tungsten inert gas (TIG) welding or wolfram inert gas (WIG) welding, is an arc welding process that uses a nonconsumable tungsten electrode to produce the weld.

Russell Meredith, working for Northrop Aircraft, was the first to produce a system that was a true production tool applying for a patent in January 1941 (US Patent 2,274,631.) He was concerned about meeting a critical national need of welding light weight aircraft materials. In the first line of the patent it states: “My invention relates to welding magnesium and its alloys - so relatively low melting point materials may be efficiently welded by an electric arc.” He goes on to say that airplanes are being made of lighter materials and a more efficient method of joining these materials is needed.

Since the early days of the invention, numerous improvements have been made to the process and equipment. Welding power sources have been developed specifically for the process. Water-cooled and gas-cooled torches were developed. The tungsten electrode has been alloyed with small amounts of active elements to increase its emissivity; this has improved arc starting, arc stability, and electrode life.

Process description

The process uses tungsten (or tungsten alloy) electrode 3 fixed in copper collet 4, which cools the electrode and conducts electric current from power supply.

Shielding gas 1 is fed through the torch 2 and ceramic nozzle 5 to protect the electrode, molten weld pool, and

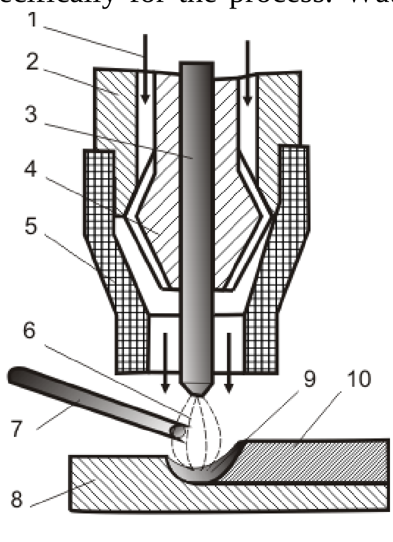


Fig. 17 – Schematic view of GTAW process

solidifying weld metal from contamination by the atmosphere.

The electric arc is produced by the passage of current through the conductive, ionized shielding gas. The arc is established between the tip of the electrode and the work. Heat generated by the arc melts the base metal 8. Once the arc and weld pool 9 are established, the torch is moved along the joint and the arc progressively melts the faying surfaces. Filler wire 7, if used, is usually added to the leading edge of the weld pool to fill the joint. Some welds, known as autogenous welds, do not require filler metal.

Potential problems with the process include:

1. Tungsten inclusions can occur if the electrode is allowed to contact the weld pool;
2. Contamination of the weld metal can occur if proper shielding of the filler metal by the gas stream is not maintained;
3. There is low tolerance for contaminants on filler or base metals;
4. Possible contamination or porosity can be caused by coolant leakage from water-cooled torches;
5. Arc blow or arc deflection, as with other processes.

Process Variables

The primary variables in GTAW are polarity, welding current, arc voltage, travel speed. The amount of energy produced by the arc is proportional to the current and voltage. The amount transferred per unit length of weld is inversely proportional to the travel speed. However, because all of these variables interact strongly, it is impossible to treat them as truly independent variables when establishing welding procedures for fabricating specific joints.

The process can be used with either direct or alternating current, the choice depending largely on the metal to be welded. *Direct current straight polarity* offers the advantages of deep penetration and fast welding speeds, especially when helium is used as the shield. *Alternating current* provides a cathode cleaning action which removes refractory oxides from the surfaces of aluminum and magnesium during the portion of the AC wave that the electrode is positive. *Direct current reverse polarity* is rarely used because it causes electrode overheating.

Welding current controls the weld penetration, the effect being directly proportional, if not somewhat exponential.

Arc voltage is a strongly dependent variable, affected by arc length. Arc length is important with this process because it affects the width of the weld pool; pool width is proportional to arc length. Therefore, in most applications other than those involving sheet, the desired arc length is as short as possible. Of course, recognition needs to be given to the possibility of short circuiting the electrode to the pool or filler wire if the arc is too short. However, with mechanized welding, using a helium shield, and DCSP power, and a relatively high current, it is possible to submerge the electrode tip below the plate surface to produce deeply penetrating but narrow welds at high speeds. This technique has been called *buried arc* and was used for crew cabin welding of shuttle “Buran”.

Travel speed affects both the width and penetration of a weld. However, its effect on width is more pronounced than that on penetration. Travel speed is important because of its effect on cost. In some applications, travel speed is defined as an objective, with the other variables selected to achieve the desired weld configuration at that speed.

Power Supplies

Constant-current type power sources are used for GTAW. Power required for both AC and DC welding can be supplied by transformer-rectifier power supplies or from rotating AC or DC generators. Advances in semiconductor electronics have made transformer-rectifier power sources popular for both shop and field GTAW, but rotating-type power sources continue to be widely used in the field. GTAW power sources typically have either drooping or nearly true constant-current static output characteristics.

A *drooping* volt-ampere characteristic is typical of magnetically controlled power source designs including the moving coil, moving shunt, moving core reactor or magnetic amplifier designs and also rotating power source designs. A *truly constant-current* output is available from electronically controlled power sources. The drooping characteristic is advantageous for manual welding where a remote foot pedal current control is not available at the site of welding. With a drooping characteristic, the welder may vary the current level slightly by changing the arc length.

In most of the **magnetically controlled power sources**, the current-level control is accomplished in the AC portion of the power source. As a result, these power sources are not typically used to provide pulsed current because of their slow dynamic response. Those power sources which use a moving component for current control cannot readily be remotely controlled with a foot pedal, while the others typically can.

The advantages of magnetically controlled power sources are that they are simple to operate, require little maintenance in adverse industrial environments, and are relatively inexpensive. The disadvantages are that they are large in size and weight and have a lower efficiency compared to electronically controlled power sources. Also, most magnetic-control techniques are open-loop, which limits repeatability, accuracy, and response.

An essentially constant-current volt-ampere characteristic can be provided by **electronically controlled power sources**, such as the series linear regulator, silicon controlled rectifier, secondary switcher, and inverter designs. The advantages of electronically controlled power sources are that they offer rapid dynamic response, provide variable current waveform output, have excellent repeatability, and offer remote control. The disadvantages are that they are more complex to operate and maintain and are relatively expensive.

The tungsten electrodes for GTAW

The GTAW process relies on tungsten's hardness and high-temperature resistance to carry the welding current to the arc. Tungsten has the highest melting point of any metal, 3 410 °C. Tungsten nonconsumable electrodes come in a variety of sizes and lengths and are composed of either pure tungsten or an alloy of tungsten and other rare-earth elements and oxides. Choosing an electrode for GTAW depends on the base material type and thickness and whether you weld with alternating current or direct current. Each electrode is color-coded to eliminate confusion over its type. The color appears at the tip of the electrode.

Pure tungsten electrodes are general purpose electrodes and contain 99.50 percent tungsten, have the highest consumption rate of all electrodes, and typically are less expensive than their alloyed counterparts.

These electrodes form a clean, balled tip when heated and provide great arc stability for AC welding with a balanced wave. Pure tungsten also provides good arc stability for AC sine wave welding, especially on aluminum and magnesium. It is not typically used for DC welding because it does not provide the strong arc starts associated with thoriated or ceriated electrodes.

Thoriated tungsten electrodes contain a minimum of 97.30 percent tungsten and 1.70 to 2.20 percent thorium and are called 2 percent thoriated. They were designed for DCRP applications and can withstand higher temperatures while providing many of the benefits of other alloys. Thoriated electrodes are the most commonly used electrodes today and are preferred for their longevity and ease of use. Thorium increases the electron emission qualities of the electrode, which improves arc starts and allows for a higher current-carrying capacity. This electrode operates far below its melting temperature, which results in a considerably lower rate of consumption and eliminates arc wandering for greater stability. Compared with other electrodes, thoriated electrodes deposit less tungsten into the weld puddle, so they cause less weld contamination.

These electrodes are used mainly for specialty AC welding (such as thin-gauge aluminum and material) and DC welding, either electrode negative or straight polarity, on carbon steel, stainless steel, nickel, and titanium.

During manufacturing, thorium is evenly dispersed throughout the electrode, which helps the tungsten maintain its sharpened edge — the ideal electrode shape for welding thin steel — after grinding. Thorium is somewhat radioactive; therefore, you must always follow the manufacturer's warnings, instructions for its use.

Ceriated tungsten electrodes contain a minimum of 97.30 percent tungsten and 1.80 to 2.20 percent cerium and are referred to as 2 percent ceriated. These electrodes perform best in DC welding at low current settings but can be used proficiently in AC processes. With its excellent arc starts at low amperages, ceriated tungsten has become popular in such applications as orbital tube and pipe fabricating, thin sheet metal work, and jobs involving small and delicate parts. Like thorium, it is best used to weld carbon steel, stainless steel, nickel alloys, and titanium, and in some cases it can replace 2 percent thoriated electrodes. Ceriated tungsten has slightly different electrical characteristics than thorium, but most welders can't tell the difference.

Using ceriated electrodes at higher amperages is not recommended because higher amperages cause the oxides to migrate quickly to the heat at the tip, removing the oxide content and nullifying its process benefits.

Lanthanated tungsten electrodes contain a minimum of 97.80 percent tungsten and 1.30 percent to 1.70 percent lanthanum, or lanthana, and are known as 1.5 percent lanthanated. These electrodes have excellent arc starting, a low burnoff rate, good arc stability, and excellent reignition characteristics—many of the same advantages as ceriated electrodes. Lanthanated electrodes also share the conductivity characteristics of 2 percent thoriated tungsten. In some cases, 1.5 percent lanthanated can replace 2 percent thoriated without having to make significant welding program changes.

Lanthanated tungsten electrodes are ideal if you want to optimize your welding capabilities. They work well on AC or DC electrode negative with a pointed end, or they can be balled for use with AC sine wave power sources. Lanthanated tungsten maintains a sharpened point well, which is an advantage for welding steel and stainless steel on DC or AC from square wave power sources.

Unlike thoriated tungsten, these electrodes are suitable for AC welding and, like ceriated electrodes, allow the arc to be started and maintained at lower voltages. Compared with pure tungsten, the addition of 1.5 percent lanthana increases the maximum current-carrying capacity by approximately 50 percent for a given electrode size.

Zirconiated tungsten electrodes contain a minimum of 99.10 percent tungsten and 0.15 to 0.40 percent zirconium. A zirconiated tungsten electrode produces an extremely stable arc and resists tungsten spitting. It is ideal for AC welding because it retains a balled tip and has a high resistance to contamination. Its current-carrying capability is equal to or greater than that of thoriated tungsten. Under no circumstances is zirconiated recommended for DC welding.

Rare-earth tungsten electrodes contain unspecified additives of rare-earth oxides or hybrid combinations of different oxides, but manufacturers are required to identify each additive and its percentage on the package. Depending on the additives, desired results can include a stable arc in both AC and DC processes, greater longevity than thoriated tungsten, the ability to use a smaller-diameter electrode for the same job, use of a higher current for a similar-sized electrode, and less tungsten spitting.

Electrode tip preparation

After selecting a type of electrode, the next step is to select an end preparation. The three choices are balled, pointed, and truncated.

A **balled tip** generally is used on pure tungsten and zirconiated electrodes and is suggested for use with the AC process on sine wave and conventional square wave GTAW machines. To ball the end of the tungsten properly, simply apply the AC amperage recommended for a given electrode diameter, and a ball will form on the end of the electrode. The diameter of the balled end should not exceed 1.5 times the diameter of the electrode. A larger sphere at the tip of the electrode can reduce arc stability. It also can fall off and contaminate the weld.

A **pointed and**/or **truncated tip** (for pure tungsten, ceriated, lanthanated, and thoriated types) should be used for inverter AC and DC welding processes. To grind the tungsten properly, use a grinding wheel specially designated for tungsten grinding to prevent contamination and one that is made of diamond to resist tungsten's hardness.

Grind the tungsten straight on the wheel versus at a 90-degree angle to ensure that the grind marks run the length of the electrode. Doing so reduces the presence of ridges on the tungsten that could create arc wandering or melt into the weld puddle, causing contamination.

Generally, you will want to grind the taper on the tungsten to a distance of no more than 2.5 times the electrode diameter. Grinding the tungsten to a taper eases the transition of arc starting and creates a more focused arc for better welding performance.

When welding with low current on thin material, it is best to grind the tungsten to a point. A pointed tip allows the welding current to transfer in a focused arc and helps prevent thin metals, such as aluminum, from becoming distorted. Using pointed tungsten for higher-current applications is not recommended, because the higher current can blow off the tip of the tungsten and cause weld puddle contamination.

For higher-current applications, it is best to grind a truncated tip. To achieve this shape, first grind the tungsten to a taper as explained previously, then grind a flat land on the end of the tungsten. This flat land helps prevent the tungsten from being transferred across the arc. It also prevents a ball from forming.

Shielding Gases

Shielding gas is directed by the torch to the arc zone and weld pool to protect the electrode and the molten weld metal from atmospheric contamination. Backup purge gas can also be used to protect the underside of the weld and its adjacent base metal surfaces from oxidation during welding. In some materials, gas backup reduces root cracking and porosity in the weld.

Argon and helium, or mixtures of the two, are the most common types of inert gas used for shielding. Argon-hydrogen mixtures are used for special applications.

Welding grade **argon** is refined to a minimum purity of 99.95%. This is acceptable for GTAW of most metals. But some reactive and refractory metals require a minimum purity of 99.997%. Often, such metals are fabricated in special chambers.

Argon is approximately one and one-third times as heavy as air and ten times heavier than helium. Argon, after leaving the torch nozzle, forms a blanket over the weld area, which has *good cross-draft resistance.* Helium, because it is lighter, tends to rise around the nozzle. Experimental work has consistently shown that to produce equivalent shielding effectiveness, *the flow of helium must be two to three times more that of argon.* The same general relationship is true for mixtures of argon and helium, particularly those high in helium content.

The other influential characteristic is that of arc stability. Both gases provide excellent stability with direct current power. *With alternating current power*, which is used extensively for welding aluminum and magnesium, *argon provides much better arc stability and the highly desirable cleaning action,* which makes argon superior to helium in this respect.

As well argon is used more extensively than helium because of the following advantages:

1. Smoother, quieter arc action.
2. Lower cost and greater availability.
3. Reduced penetration.

The reduced penetration of an argon shielded arc is particularly helpful when manual welding of thin material. The same characteristic is advantageous in vertical or overhead welding, since the tendency for the molten metal to sag or run is decreased.

For given values of welding current and arc length, **helium** transfers more heat into the work than argon. The greater heating power of the helium arc can be advantageous for joining metals of high thermal conductivity and for high-speed mechanized applications. Also, helium is used more often than argon for welding heavy plate. Mixtures of argon and helium are useful when some balance between the characteristics of both is desired.

Argon-hydrogen mixtures are employed in special cases, such as mechanized welding of light-gauge stainless steel tubing, where the hydrogen does not cause adverse metallurgical effects such as porosity and hydrogen-induced cracking. Increased welding speeds can be achieved in almost direct proportion to the amount of hydrogen added to argon because of the increased arc voltage.

However, the amount of hydrogen that can be added varies with the metal thickness and type of joint for each particular application. Excessive hydrogen will cause porosity. Argon-hydrogen mixtures are limited to use on stainless steel, nickel-copper, and nickel-base alloys.

Advantages of the process

1. Weld more metals and alloys than any other process.

This process is used for wide range of metals and its alloys: all grades of steel, including heat resistance steels, stainless steels, most of aluminum alloys, magnesium, titanium, nickel, copper, bronze. Welding of dissimilar materials is also possible.

2. Good for precision works.

The most frequently cited advantage of a TIG welder is its control. Heat and amperage are precisely controlled and changed. The welding mechanism itself is very thin and pen-like, so although dexterity is needed, the welder has superior welding control. This helps produce high-quality welding work, especially when there are intricate curves or designs in the base metal.

3. Create high quality, clean welds.

Welds made by GTAW have very good appearance. Mechanical properties are good too if proper filler metal was used. Welding methods like SMAW, SAW leave slag when they are finished. This wastes time, because the welder has to clean away the slag to make a presentable product or welding job. TIG welding is very clean and leaves no slag at all, so the welder can concentrate on welding instead of cleaning up the metal.

Disadvantages of the process

1. Low deposition rate

Manual GTAW process takes time to do the weld, and there are two way to solve this problem: a) to automize the process or b) to use GMAW process.

2. Require high skill to master.

Applications

The process is widely used in aeronautic industry, chemistry and nuclear industry.

In 60th GTAW was used to joint upper and lower steel wing panels of American experimental bomber B-70. In 80th automatic GTAW process was used to make ribbed titanium panels for a Su-27 fighter.

GTAW was used together with GMAW to weld the AlCu4MnSi and AlCu6Mn aluminum alloy in the fuel and oxidizer tanks in the Saturn V rocket. Messerschmitt Bölkow Blohm in Germany currently uses GMAW for the nozzle extensions of Inconel 600 in the Ariane launch vehicles. Most of the welds performed on commercial aircraft are done on ducting and tubing using GTAW. This process is also used in heat exchanger cores, louvers and exhaust housings for jet engines, both commercial and military in stainless steel and Inconel. GTA plug welds are also used in the stainless steel vanes of the Patriot missile.

The Low Stress No-Distortion (LSND) technique has been developed at the Beijing Aeronautical Manufacturing Technology Research Institute in China. It has been applied to jet engine cases of heat resistant alloys and rocket fuel tanks of aluminum alloys. In this technique, a heat sink trails behind the welding arc in such a way that their thermal fields interact, significantly reducing the residual stresses and distortions created by the GTAW process.

Attempts to replace riveting by GTA welding of stringers to the skin plate have not been successful yet due to serious distortion problems.

Questions

Who was the first to apply GTAW process for welding magnesium?
Describe the process.
What is a autogenous welds?
What potential problems does the process have?
Which polarity is used for GTAW process.
How does welding current influence to weld penetration?
How does arc length influence to weld width?
What is a buried arc?
How does travel speed affect the weld geometry?

Which type of power sources are used for GTAW?
Describe magnetically controlled power sources.
What are advantages and disadvantages of magnetically controlled power sources?
Describe electronically controlled power sources.
What are advantages and disadvantages of electronically controlled power sources?
What are advantages and disadvantages to use pure tungsten electrodes?
What are advantages and disadvantages to use thoriated tungsten electrodes?
What are advantages and disadvantages to use ceriated tungsten electrodes?
What are advantages and disadvantages to use lanthanated tungsten electrodes?
What are advantages and disadvantages to use zirconiated tungsten electrodes?
What are there forms of electrode tip prepared?
How to ball electrode tip?
How to make pointed or truncated tip?
What is better pointed or truncated tip?
What shielded gasses are used in GTAW?
What benefits does the argon have as shielding gas?
What benefits does the helium have as shielding gas?
What benefits does the argon-hydrogen mixture have as shielding media?
Recount advantages of the process.
Recount disadvantages of the process.
Describe field of applications for GTAW.

Gas metal arc welding

Gas metal-arc welding (GMAW) or MIG/MAG welding simplistically appears to be the same process as TIG, except that the electrode is consumable and fed through the torch automatically. The basic concept of GMAW was commercially available in 1949. Its primary application was for welding aluminum.

Electrode wire *3* is continuously fed through copper contact tube *1* to the workpiece. Welding arc *4*, which is struck between base metal 6 and electrode wire, digs into the base metal and creates weldpool. Molten metal flows to the rear part of weldpool and solidifies, forming weld *5*. Molten metal and weld are shielded by gas, which is supplied to the weld area through gas nozzle *2*.

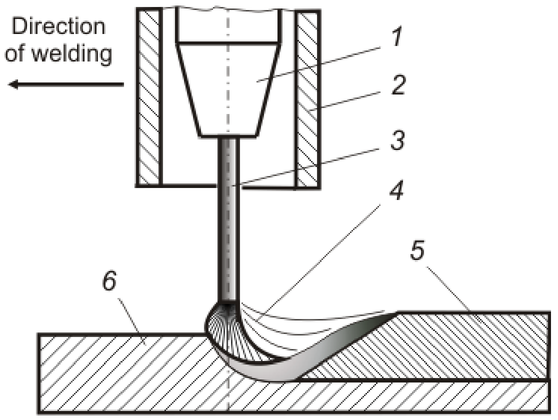


Fig. 18 – Scheme of GMAW

Typically, GMAW requires the use DCRP with constant voltage supply. With a constant voltage the power controller will automatically maintain the amperage at a level that will melt the electrode. The setup used for the power supply depends upon the type of arc desired. The short-circuit mode require less voltage (16-20 V) and result in less heat, less fluidity of the molten metal droplets, and more splatter. For short arcs the slope of the power source should be set on a "flat" setting.

Process variables

The process variables, which affect weld geometry, are polarity (DCSP or DCRP), welding current, arc voltage (arc length), travel speed, wire feed rate, electrode extension (stick-out), electrode diameter, shielding gas composition and flow rate. Also influence to the weld penetration and bead geometry the weld joint position and electrode orientation (trail or lead angle). These variables are not completely independent, and changing one generally requires changing one or more of the others to produce the desired results.

Polarity. The vast majority of GMAW applications use direct current *reverse polarity*. This condition yields a stable arc, smooth metal transfer, relatively low spatter, good weld bead characteristics, and greatest depth of penetration for a wide range of welding currents.

Direct current *straight polarity* is seldom used because axial spray transfer is not possible without modifications that have had little commercial acceptance. DCSP has a distinct advantage of high melting rates that cannot be exploited because the transfer is globular. With steels, the transfer can be improved by adding a minimum of 5% oxygen to the argon shield (requiring special alloys to compensate for oxidation losses). But the deposition rates drop, eliminating the only real advantage of changing polarity. However, because of the high deposition rate and reduced penetration, DCSP has found some use in surfacing applications.

Attempts to use *alternating current* with the GMAW process have generally been unsuccessful. The cyclic wave form creates arc instability due to the tendency of the arc to extinguish as the current passes through the zero point. Although special wire surface treatments have been developed to overcome this problem, the expense of applying them has made the technique uneconomical.

When all other variables are held constant, the **welding current** varies with the electrode feed speed or melting rate in a nonlinear relation, As the electrode feed speed is varied, the welding amperage will vary in a like manner if a constant-voltage power source is used.

With all other variables held constant, an increase in welding current (electrode feed speed) will result in: an increase in the depth and width of the weld penetration; an increase in the deposition rate; an increase in the size of the weld bead.

With GMAW, **arc length** is a critical variable that must be carefully controlled. For example, in the spray-arc mode with argon shielding, an arc that is too short experiences momentary short circuits. They cause pressure fluctuations which pump air into the arc stream, producing porosity or embitterment due to absorbed nitrogen. Should the arc be too long, it tends to wander, affecting both the penetration and surface bead profiles. A long arc can also disrupt the gas shield.

With all variables held constant, **arc voltage** is directly related to arc length. Even though the arc length is the variable of interest and the variable that should be controlled, the voltage is more easily monitored. Because of this, the arc voltage is specified in the welding procedure.

The **electrode extension** is the distance between the end of the contact tube and the end of the electrode. An increase in the electrode extension results in an increase in its electrical resistance. Resistance heating in turn causes the electrode temperature to rise, and results in a small increase in electrode melting rate. Overall, the increased electrical resistance produces a greater voltage drop from the contact tube to the work. This is sensed by the power source, which compensates by decreasing the current. That immediately reduces the electrode melting rate, which then lets the electrode shorten the physical arc length. Thus, unless there is an increase in the voltage at the welding machine, the filler metal will be deposited as a narrow, high-crowned weld bead.

The desirable electrode extension is generally from 6 to 12 mm for short circuiting transfer and from 12 to 25 mm for other types of metal transfer.

The selection of electrode wire for GMAW is similar to that of other bare filler rod. The recommendations of the equipment and wire manufacturers should always be followed. Some filler metals are very similar to the base metals (for example, for welding steels the 08S2 wire is used), whereas others, such as the electrode wire for 6061 aluminum, is quite different. Commonly standards writing societies publish filler metal specifications for specific applications. For example, the Aerospace Materials Specifications are written by SAE, and are intended for aerospace applications.

Shielding Gases

As with other welding processes, such as gas metal arc welding, shielding gases are necessary to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. The gas also transfers heat from the tungsten electrode to the metal, and it helps start and maintain a stable arc.

The selection of a shielding gas depends on several factors, including the type of material being welded, joint design, and desired final weld appearance. **Argon** is the most commonly used shielding gas, since the arc is easier to initiate and the wider variation to the arc length are possible. Because argon is heavier than air, the gas envelope does not dissipate as quickly as that of helium. Argon is more economical than helium. When used with alternating current, the use of argon results in high weld quality and good appearance.

Another common shielding gas, **helium**, is most often used to increase the weld penetration in a joint, to increase the welding speed, and to weld conductive metals like copper and aluminum. A significant disadvantage is the difficulty of striking an arc with helium gas, and the decreased weld quality associated with a varying arc length.

Argon-helium mixtures are also frequently utilized in inert gas welding, since they can increase control of the heat input while maintaining the benefits of using argon. Normally, the mixtures are made with primarily helium (often about 75% or higher), with the remainder being argon. These mixtures increase the speed and quality of the AC welding of aluminum, and also make it easier to strike an arc. Another shielding gas mixture, argon-hydrogen, is used in the mechanized welding of light gauge stainless steel, but because hydrogen can cause porosity, its uses are limited.

Small additions of **hydrogen** can be used to increase heat input and welding speed in the same manner as helium, but it is much cheaper. Because of the risk of cracks, hydrogen can only be used for welding of austenitic stainless steel. It actively reduces the oxides.

Pure carbon dioxide ($C0_2$) can be used for welding with short circuits. It is a cheap gas, it has good properties for welding of galvanised steel and gives better safety against lack of fusion than argon based gases. Drawbacks are a higher amount of spatter and the fact that the gas cannot be used for spray metal transfer.

Oxygen is also used as a small addition (2…5%) to stabilise the arc and to improve metal transfer at low currents.

Metal transfer

There are four general metal transfer mode: global, short-circuiting, spray.

Globular transfer is often considered the most undesirable, because of its tendency to produce high heat, a poor weld surface, and spatter. The method was originally developed as a cost efficient way to weld steel, because this variation uses carbon dioxide, a less expensive shielding gas than argon. Pulsed-arc welding involves the use of high-amperage pulsations during the process in order to reduce the average current. However, highly specialized power supplies are required and extensive operator training is required.

Short-circuiting transfer is used in welding steel, when carbon dioxide shields the weld, the electrode wire is smaller, and the current is lower than for the globular method. As a result of the lower current, the heat input for the short-arc variation is reduced, making it possible to weld thinner materials while decreasing the amount of distortion and residual stress in the weld area.

Spray transfer is best suited for welding aluminum and stainless steel while employing an inert shielding gas and a relatively thick electrode. Molten metal droplets (with diameters smaller than the electrode diameter) are rapidly passed along the stable electric arc from the electrode to the workpiece, essentially eliminating spatter and resulting in a high-quality weld finish. High amounts of voltage and current are necessary, which means that the process involves high heat input and a large weld area and heat-affected zone.

Pulse-spray transfer mode is based on the principles of spray transfer but uses a pulsing current to melt the filler wire and allow one small molten droplet to fall with each pulse. The pulses allow the average current to be lower, decreasing the overall heat input and thereby decreasing the size of the weld pool and heat-affected zone while making it possible to weld thin work pieces. The pulse provides a stable arc and no spatter, since no short-circuiting takes place. This also makes the process suitable for nearly all metals, and thicker electrode wire can be used as well. The smaller weld pool gives the variation greater versatility, making it possible to weld in all positions. It generates lower heat input and can be used to weld thin work pieces, as well as nonferrous materials. Most spray type GMAW is done in the flat or horizontal positions, while at low-energy levels, pulsed and short circuiting GMAW can be used in all positions. Fillet welds made in the flat position with spray transfer are usually more uniform, less likely to have unequal legs and convex profiles, and are less susceptible to undercutting than similar welds made in the horizontal position.

To overcome the pull of gravity on the weld metal in the vertical and overhead positions of welding, small diameter electrodes are usually used, with either short circuiting metal transfer or spray transfer with pulsed direct current. Electrode diameters of 1.1 mm and smaller are best suited for out-of-position welding. The low-heat input allows the molten pool to freeze quickly. Downward welding progression is usually effective on sheet metal in the vertical position.

Process variations

Pulsed spray welding is variation of the GMAW process in which the current is pulsed to obtain the advantages of the spray mode of metal transfer at average currents equal to or less than the globular-to-spray transition current.

Since arc force and deposition rate are exponentially dependent on current, operation above the transition current often makes the arc forces uncontrollable in the vertical and overhead positions. By reducing the average current with pulsing, the arc force and deposition rates can both be reduced, allowing welds to be made in all positions and in thin sections.

With solid wires, another advantage of pulsed power welding is that larger diameter wires, i.e., 1.6mm can be used. Although deposition rates are generally no greater than those with smaller diameter wires, the advantage is in the lower cost per unit of metal deposited. There is also an increase in deposition efficiency because of reduced spatter loss.

With metal cored wires, pulsed power produces an arc that is less sensitive to changes in electrode extension (stick-out) and voltage compared to solid wires. Thus, the process is more tolerant of operator guidance fluctuations. Pulsed power also minimizes spatter from an operation already low in spatter generation.

Advantages of the process

1. Welding most commercial metals and alloys
2. High efficiency of the process

GMAW overcomes the restriction of limited electrode length encountered with shielded metal arc welding.

3. Welding can be done in all positions
4. Create high quality, clean welds

Limitations

1. The welding arc sensitive to air drafts

GTAW was the main welding process used for the construction of the fuel and oxidizer tanks for the Saturn V rocket (AlCu6Mn aluminum alloy for the first stage). One of the current applications of GMAW is in the automatic welding of the vanes of the Patriot missile (stainless steel).

Questions

When was the GMAW developed?
Describe GMAW.
Which polarity is used for GMAW?
How does feed rate influence to welding current?
What are shielded gases used in GMAW process?
Describe globular transfer.
Describe short-circuit transfer.
Describe spray transfer.
Describe pulse-spray transfer.
Describe pulse spray welding.

Plasma arc welding

The first practical plasma arc metal-working tool was a cutting torch introduced in 1955. This device was similar to a gas tungsten arc welding torch in that it used a tungsten electrode and a “plasma” gas. However, the electrode was recessed in the torch, and the arc was constricted by passing it through an orifice in the torch nozzle. The usual circuitry for gas tungsten arc welding was supplemented in the plasma arc cutting torch with a pilot arc circuit for arc initiation.

Principles of operation

Tungsten electrode 5 is located within a constricting copper nozzle 2 having a small orifice 3 at the tip. A pilot arc called non-transferred is initiated between the electrode and nozzle. Then welding arc is initiated between the electrode and the metal 1 to be welded. By forcing the plasma gas and arc through a constricting orifice, the torch delivers a high concentration of heat to a small area. With high performance welding equipment, the plasma process produces exceptionally high quality welds.

Shielding gas is normally argon, which assists in shielding the molten weld puddle thus minimizing oxidation of the weld. The torch also uses a plasma gas which can be an inert gas like argon, helium or an active gas like nitrogen, water vapors. Active gases commonly give hot arc, but electrode life is short.

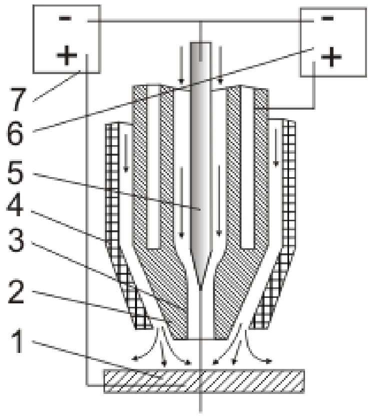


Fig. 19 – Plasma welding torch

Table 14 – Plasma temperature for different gases

Gas	N_2	Ar	He	H_2O
T_{pl}, ℃	80000	15000	20000	50000

Plasma-arc welding are classified as ***transfer*** and ***nontransfer***. Transfer plasma arc welding include the workpiece as part of the electric circuit. Nontransfer PAW do not. The function of the orifice, found in the torch, is to direct and accelerate the plasma gas toward the workpiece. In the nontransfer application the nozzle also acts as the cathode for the electric circuit.

Power efficiency depends on type of the process. If nontransfer plasma welding a lot of heat sinks to watercooled copper nozzle, so the power efficiency as low as 0.3…0.5, but if transfer plasma welding the power efficiency is 0.7…0.9.

Process variables

The process variables which influence to weld penetration and depth-to-width ratio are: plasma current, orifice diameter, plasma gas composition and flow rate.

Plasma jet can cause turbulence in the weld puddle, what results in increasing depth of weld penetration. The less diameter of orifice and the more gas flow rate the higher speed of plasma jet. But very high flow rates may remove the melted metal from a groove. Therefore, the high energy densities, small orifice diameters and high jet velocities are used for cutting. For welding, a low plasma jet velocity is necessary to prevent expulsion of the molten metal from the groove.

Plasma arc welding is normally done with direct current straight polarity, pure tungsten or tungsten alloy electrodes, argon plasma gas and a transferred arc. Current range for plasma arc welding is from 0.1 to 500 amperes, depending on the torch size and material thickness. Steel, stainless steel, nickel base alloys and titanium alloys can be welded with DCSP.

Direct current reverse polarity is used to a limited extent for welding aluminum and magnesium to make use of the surface oxide removal feature (cleaning affect) of this polarity. Arc current is usually limited to a maximum of 100 amperes to prevent rapid degradation of the electrode.

Sine wave alternating current with continuous high-frequency stabilization can also be used for welding aluminum and magnesium, but the maximum is still limited to about 100 amperes. Surface oxide removal occurs during the positive half cycles of alternating current. Square-wave alternating current with unbalanced positive and negative current half cycles, also called variable polarity plasma arc, is highly efficient for welding aluminum and magnesium alloys and permits use of higher average weld current than sine wave ac. This is possible because the duration of the negative portion is considerably longer than the positive portion, thus developing most of the heat at the work, where it is needed. The short positive pulse is sufficient for removing surface oxides and does not cause excessive heating of the electrode.

Three operating modes can be produced by varying bore diameter and plasma gas flow rate:

Microplasma welding. Microplasma was traditionally used for welding thin sheets (down to 0.1 mm thickness), and wire and mesh sections. The needle-like stiff arc minimises arc wander and distortion. Although the equivalent TIG arc is more diffuse, the newer transistorised (TIG) power sources can produce a very stable arc at low current levels.

Melt-in medium current welding. When used in the melt mode this is an alternative to conventional TIG. The advantages are deeper penetration (from higher plasma gas flow), and greater tolerance to surface contamination including coatings (the electrode is within the body of the torch). The major disadvantage lies in the bulkiness of the torch, making manual welding more difficult. In mechanised welding, greater attention must be paid to maintenance of the torch to ensure consistent performance.

Keyhole welding. Higher current density arc is used, which produces a small hole completely through the joint being welded. This has several advantages which can be exploited: deep penetration and high welding speeds. Compared with the TIG arc, it can penetrate plate thicknesses up to l0mm, but when welding using a single pass technique, it is more usual to limit the thickness to 6mm. The normal method is to use the keyhole mode with filler to ensure smooth weld bead profile (with no undercut). For thicknesses up to 15mm, a V-groove joint preparation is used with a 6mm root face. A two-pass technique is employed and here, the first pass is autogenous with the second pass being made in melt mode with filler wire addition. If the arc moves too rapidly, the result will be cutting instead of welding.

Advantages of the process

1. Low weld contamination with tungsten.

This is especially advantageous in welding materials that out gas when welded and contaminate the unprotected TIG electrode.

2. High arc stability.

Plasma arc welding has forgiveness in arc length changes due to arc shape and even heat distribution. Arc column has greater directional stability. This results in the arc stand off distances not being as critical as in TIG.

3. Good for precision works.

Low amperage arc welding (as low as 0.05A) allows welding of miniature components. The arc transfer is gentle and consistent so it provides for welding of thin sheet and fine wire, where the harsh TIG arc start would damage the part to be welded. Welding time can be very short.

4. High energy concentration.

Energy concentration is greater than other arc processes have, what results in: high welding speed, lower currents used for the same penetration; less weld distortions, narrower beads (higher depth-to-width ratio) for a given penetration.

Limitations:

1. Heavy welding torch.

Manual plasma welding torches are generally more difficult to manipulate than a comparable GTAW torch.

2. The process is very sensitive to joint misalignment.

Due to the narrow constricted arc, the process has little tolerance for joint misalignment.

Applications

PAW is used for the welding of the Space Shuttle Advanced Solid Rocket Motor made of FeC0.3Ni7Co4Cr steel by Lockheed. Variable-polarity PAW process used for welding thicker sections of alloy aluminum, specifically for the external fuel tank of the space shuttle.

Questions

When was the first practical plasma tool introduced?
Describe operation of plasma welding.
What is better to use as plasma gas: inert gases or active gases?
What is the difference between transfer and non transfer plasma arc welding?
What are process variables for plasma arc weldin?
How orifice diameter and gas flow rate influence to depth of penetration?
Which polarity is used for plasma arc welding?
Describe microplasma welding.
Describe melt-in medium current welding.
Describe keyhole welding.
What are advantages of plasma arc welding?
What are limitations of plasma arc welding?
Where are the PAW used?

Oxyfuel welding

Oxyfuel or gas welding is a group of welding processes that produces coalescence of workpieces by heating them with an oxyfuel gas flame.

Gas welding is a versatile method, using simple and relatively cheap equipment. It is suitable for repair and erection work, for welding pipes, tubes and structures with a wall thickness of 6 mm in materials particularly prone to cracking, such as cast iron and non-ferrous metals. It is also widely used for cladding and hardfacing. The heat is generated by the combustion of acetylene in oxygen, which gives a flame temperature of about 3 100 °C. This is lower than the temperature of an electric arc, and the heat is also less concentrated. The flame is directed onto the surfaces of the joint, which melt, after which filler material can be added as necessary. The melt pool is protected from air by the reducing zone and the outer zone of the flame. The flame should therefore be removed slowly when the weld is completed.

The less concentrated flame results in slower cooling, which is an advantage, when welding steels that have a tendency to harden. Although it does make the method relatively slow, with higher heat input and the added risk of thermal stresses and distortion. In addition to welding, gas flames are also often used for cutting, and are very useful for heating and flame straightening.

Table 15

Gas	Density, kg/m^3	Calorific value. MJ/kg	Flame temperature, °C	Combustion velocity, m/s
Acetylene	1.07	48.2	3 100	13.1
Propane	2.00	46.4	2 825	3.7
Hydrogen	0.08	120	2 525	8.9

Gas flames

The basic requirement for a good weld is that the size and type of the flame should be suited to the type of work. The size of the flame depends on the size of the torch nozzle and on the pressure of the gases flowing through it. This pressure should be maintained within certain limits. If it exceeds the normal pressure, there will be a considerable jet effect and the flame will become 'hard'. Below the correct pressure, the jet effect will be reduced and the flame will be 'soft'. Depending on their chemical effect on the melt pool, there are three different types of flames: carburising, neutral, and oxidising.

The **neutral flame** is used most. It is easily recognised by the three clearly distinguished combustion zones. The inner zone, the cone, is a mixing zone and glows white. Acetylene is burning here, to form carbon monoxide and hydrogen which produce a colourless tongue around the cone. This second zone is chemically reducing, and so it reduces any metal oxides and keeps the melt pool clean. The outer, blue zone of the flame is where carbon monoxide and hydrogen are burning with oxygen from the air, forming the final combustion products of carbon dioxide and water vapour. It prevents oxygen in the air from coming into contact with the molten metal, and so acts as a shielding gas.

If the proportion of acetylene in a neutral flame is increased, there is insufficient oxygen to burn the surplus acetylene in the core zone. The acetylene therefore continues to the second zone, where it appears as a highly luminous yellow-white flame. To some extent, the length of second zone indicates the amount of excess acetylene.

If the quantity of oxygen in the weakly reducing flame is further increased, the flame changes to an **oxidising flame**. The core length is reduced, and the flame takes on a violet tinge with low luminosity.

Most ferrous and nonferrous metals can be oxyfuel gas welded. Oxyacetylene supplies the heat intensity and flame atmosphere necessary for welding carbon steel, cast iron, and other ferrous, copper, and nickel alloys. Aluminum can also be welded by the oxyacetylene process.

Oxyfuel gas welding of steel is done almost exclusively with an oxyacetylene flame. Hydrogen, natural gas, propane are used as fuel gases in welding metals with lower melting temperatures, such as aluminum, magnesium, copper alloys.

Table 16

Base metal	Flame type	Flux type
Aluminums	Slightly reducing	Borax
Brasses	Slightly oxidizing	Borax
Bronzes	Slightly oxidizing	Borax
Copper	Neutral	
Copper nickel	Reducing	
Cast iron	Neutral	Borax
Low-carbon steel	Neutral	
Low-alloy steel	Slightly reducing	
Stainless steel	Slightly reducing	
High-carbon steel	Reducing	

Equipment

The principal function of OFW equipment is to supply the oxyfuel gas mixture to the welding tip at the correct rate of flow, exit velocity, and mixture ratio. The rate of gas flow affects the quantity of metal melted; the pressure and velocity affect the manipulation of the weld pool and the rate of heating; and the ratio of oxygen to fuel gas determines the flame temperature and the atmosphere, which must be chemically suited to the metal being welded.

Main elements in an OFW system include gas storage cylinders, pressure regulators, hoses, torches, and accessories.

Compressed gas cylinders and storage tanks are used as on-site supply sources for gases. Cylinders are designed for specific gases and are not generally interchangeable. Sizes and threading of cylinder connections for oxygen, for example, differ from those for acetylene, hydrogen, and other gases. Only the appropriate fittings can be used for delivery of compressed gas. Users should not tamper with valves or safety devices on cylinders.

Pressure regulators reduce the supply gas pressure to a desired delivery pressure. They are designed for specific gases and are not generally interchangeable. In operation, gas enters the inlet side of the regulator at cylinder pressure and emerges from the outlet side at the desired delivery pressure. Regulators are made for various ranges of inlet and outlet pressure. They can be adjusted within their delivery pressure range by turning an adjusting screw. Although some regulators do not have gages and are preset to deliver at a specific and constant pressure, most are equipped with two pressure gages. The one on the outlet side permits the operator to read the adjusted delivery pressure; the one on the inlet side indicates the pressure in the cylinder.

Welding torches control the operating characteristics of the welding flame and enable the flame to be manipulated during welding. The choice of torch size and style depends on the work to be performed. Aircraft welding torches, for example, are small and light to permit ease of handling. Most torch styles permit one of several sizes of welding tips or a cutting attachment to be added. Two general types of welding torches are available: equal-pressure (also called high-pressure) and injector (or low-pressure).

In *equal-pressure* torches, gases are at approximately the same pressure and are mixed by directing the fuel gas into the oxygen stream. In the *injector* torch, low-pressure fuel gas is aspirated by directing it into a high-velocity stream of oxygen. A nozzle system based on the flow principles of the venturi tube is used. Injector torches are useful when fuel gases are supplied at pressures too low to produce a flame of adequate combustion intensity. Supplying oxygen at desired pressure is not usually difficult.

Welding tips are replaceable nozzles that control gas flow through the diameter of the exit orifice. Tips of various orifice diameters are usually available for any welding torch. Small-diameter tips produce small flames for welding thin sections; large-diameter tips are required for heavier work. Welding tips are made with a smooth bore at the exit end to ensure laminar flow and a uniform flame.

Accessories essential to OFW include a friction lighter for igniting the torch; welder's goggles, gloves, and protective clothing; and related safety devices.

Methods of welding

Two different methods of welding are used when gas welding: forehand and backhand.

The flame in **forehand welding** is directed away from the finished weld, while in backhand welding it is directed towards it. Thin sheet metal (less than 3 mm) is normally carried out using forehand welding. This method is generally used for non-ferrous metals, although thicker materials can also be **backhand** welded.

Steel over 3 mm thick should be backhand welded, as the size of the melt pool is so large, when welding thick materials, that the gases and slag cannot escape from the pool without assistance. Backhand welding is faster than forehand welding, and so the workpiece is subjected to high temperature for a shorter time. As a result, backhand welding thick materials have a finer crystalline structure and retain their toughness better than would have been the case if they had been forehand welded.

Advantages of the process

1. Good control over weldpool.

Due to the fact that the process is slow, welder has good control of melting and can see at all times that he has the desired pear-shaped opening in the bottom of the melt pool.

Pipes and tubes often have to be welded in very confined spaces. In such cases, gas welding is often preferable, bearing in mind the less bulky protective equipment required (goggles, as against a normal arc welding helmet or visor, and compact torch) to perform the work.

2. Portable equipment.

The equipment is easy to transport and requires no electricity supply.

Disadvantages

1. Heat affected zone is relatively big.

The size of the HAZ can be reduced by surrounding the weld area with damp (fireproof) material.

2. Low welding efficiency.

The process productivity lower compared to the arc welding processes.

Applications

Gas welding is very suitable for welding pipes, tubes, gas bottles, heat exchangers and boilers. It is both effective and economic, especially for small bore pipes, than trying to weld them by arc welding. Aircraft structures are welded by gas welding to control carbon content. Other applications include welding of cast iron or high-carbon steels which tend to harden. Slow heating and cooling can avoid the risk of hardening. Also it is universal process; the same equipment can be used for brazing and cutting.

Questions

What is the temperature of acetylene flame?
How the weldpool is shielded in oxyfuel welding?
Why heat input in oxyfuel welding is higher than in arc welding?
What gasses can be used in oxyfuel welding as fuel?
What is “hard” flame? What is “soft” flame?
Describe neutral flame.
Describe carburizing flame.
Describe oxidising flame.
What metals can be welded by oxyfuel welding?
What metals require fluxes to be used?
What is a principal function of OFW equipment?
What do main elements in an OFW system include?
Describe compressed gas cylinders.
Describe pressure regulators.
What is the difference between equal-pressure torch and injector torch?
How to choose welding torch for oxyfuel welding?
Describe forehand welding.
Describe backhand welding.
Recount the process advantages.
Recount the process disadvantages.
Describe the field of application for oxyfuel welding.

Electron beam welding

Electron beam welding (EBW) is a welding process that produces coalescence with a concentrated beam, composed primarily of high-velocity electrons, impinging on the joint.

In 1954 confidential research carried out by Jacques Andre Stohr for the French nuclear industry (published 1957) is often cited as the first reported demonstration of keyhole EB welding, using 15kV equipment, although the aspect ratio of the welds was 'only' twice that of GTAW at the time. Similar results were obtained independently by Walter Wyman in the USA and reported in 1958. Also by 1958 much deeper penetrations were achieved by Karl Heinz Steigerwald using Zeiss equipment in Zircaloy. Commercial high voltage EBW systems were built e.g. by Zeiss in the early 1960s. Low voltage EBW equipment and other variants such as non-vacuum EBW equipment also became widespread in the 1960s. Higher power EBW systems (~100kW rated) were developed in the 1970s and single pass welding of ~200mm thickness material using a horizontal electron beam was first demonstrated at this time at The Welding Institute in the UK.

Principles of Operation

The electron beam is formed under high-vacuum conditions by employing a electron gun *1*. A cathode assembly consists of a heated cathode *9* (emitter of electrons) that is maintained at some high negative potential; and an anode *10*, a ground potential electrode through which the electron flow passes in the form of a collimated beam. The hot cathode emitter is made from a high-emission material, such as tungsten or tantalum. The cathode is heated by filament *2* to the required emitting temperature of about 2500 °C.

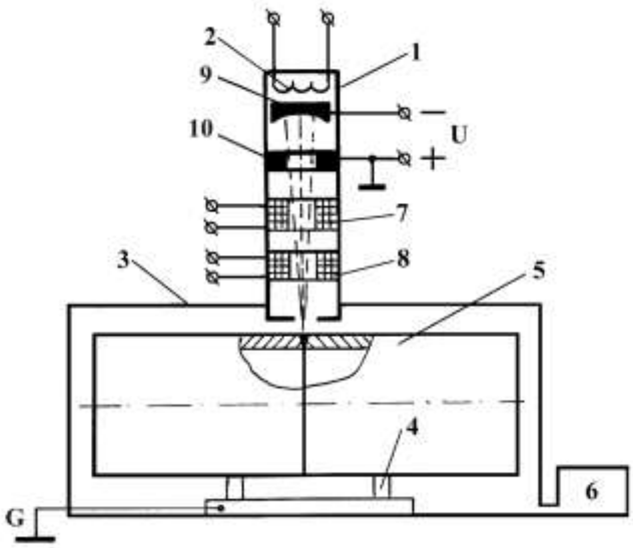


Fig. 20 – Schematic view of welding post.

Electrons emitted from the surface of the cathode are accelerated to a high velocity and shaped into a collimated beam by the electrostatic field geometry generated from the cathode/anode configuration employed, thus producing a steady stream of electrons.

Once the electrons exit the anode, they receive the maximum energy input allowable from the operating voltage *U* being applied to the gun. Electrons then pass down through the electron beam column assembly and into the field of an electromagnetic focusing coil *7* (a magnetic lens). This focusing lens reduces the diameter of the electron beam, as it continues in its passage, and focuses the stream of electrons down to a much smaller beam cross section in the plane of the workpiece. This reduction in beam diameter increases the energy density, producing a very small, high-intensity beam spot at the workpiece. In addition, an electromagnetic deflection coil *8* (positioned below the magnetic lens) can be employed to "bend" the beam, thus providing the flexibility to move the focused beam spot.

When the high-velocity electrons impinge on a joint, their kinetic energy is converted into heat $Q = \frac{m_e V_e^2}{2} n$, where m_e – electron mass, V_e – electron velocity, n – number of electrons. A part of the impinging electrons is emitted in the form of heat radiation, secondary electrons and X-rays.

Typically, high-vacuum EBW beams can be focused down to spot sizes in the range of 0.25 to 1.3 mm in diameter, with a power density of about 10^7 W/cm^2. This high level of beam spot intensity generates temperatures of approximately 14 000 °C. The density of energy (or heat) is so great that vaporization of the metal (or ceramic) usually occurs, creating a cavity called a keyhole. This keyhole allows exceptionally deep penetration, for a relatively narrow width. The depth-to-width ratio can be as high as 10…50 and depends on power density and operating voltage. Weld depths of up to 150 mm (steel materials) and of up to 400 mm (aluminium materials) can be obtained.

The vapor cavity is surrounded by a liquid shell which closes behind the beam (in the direction opposite beam travel) to produce a liquid pool by capillary action. The weld and joint are formed on solidification. A vacuum is required to prevent scattering and dispersion of the beam. This vacuum provides shielding to the molten weld pool and surrounding base metal.

There are three basic modes of electron beam welding: high vacuum (EBW-HV), medium vacuum (EBW-MV), and nonvacuum (EBW-NV). The principal difference between these process modes is the ambient pressure at which welding is done.

Under **high vacuum welding** the workpiece is inside a vacuum chamber in an ambient pressure ranging from 0.13 to 0.30 MPa. This imposes an evacuation time penalty to create the “high purity” environment.

Medium vacuum welding are done inside a vacuum chamber in an pressure ranging from 0.3…3300 MPa. The medium vacuum welding machine retains most of the advantages of high vacuum welding, with shorter chamber evacuation times, resulting in higher production rates.

Nonvacuum EB welding is used to weld workpieces at atmospheric pressure, but a vacuum is still required to produce the electron beam. Although nonvacuum EB welding incurs no pumpdown time penalty, it is not suitable for all applications because the welds it produces are generally wider and shallower than equal power EB welds produced in a vacuum.

Equipment

High vacuum, medium vacuum, and nonvacuum EBW equipment employs an electron beam gun column assembly, one or more vacuum pumping systems, and a power supply. Although nonvacuum work does not need to be placed in a chamber, a vacuum environment is necessary for the electron beam gun column.

Electron-beam welding equipment comes in two basic designs: the *low-voltage system*, which uses accelerating voltages in the 15 to 60 kV range; and the *high-voltage system*, with accelerating voltages in the 100 to 200 kV range. Beam powers up to 100 kW are available with both high-voltage and low-voltage equipment.

Nonvacuum electron beam welding performed directly in air requires beam accelerating voltages greater than 150 kV. High vacuum and medium vacuum welding can also be performed with so-called low-voltage equipment. Because high-voltage gun columns are generally fairly large, they are usually mounted on the exterior of the welding chamber, and are either fixed in position or provided with a limited amount of tilting or translational motion, or both. Low-voltage gun columns are usually small.

An **electron beam gun** generates, accelerates, and collimates the electrons into a directed beam. The gun components can logically be divided into two categories: (1) elements that generate free electrons (the emitter portion), and (2) a rod- or disc-type filament indirectly heated by an auxiliary source, such as electron bombardment or induction heating. The specific emitter design chosen will affect the characteristics of the final beam spot produced on the work.

The **electron gun power source** used for an electron beam welding machine is an assembly of at least one main power supply and one or more auxiliary power supplies. It produces high-voltage power for the gun arid auxiliary power for the emitter and beam control.

Vacuum pumping systems are required to evacuate the electron beam gun chamber, the work chamber for high and medium vacuum modes, and the orifice assembly used on the beam exit portion of the gun column assemblies for medium vacuum and nonvacuum welding. Two basic types of vacuum pumps are used: one is a mechanical piston or vane-type, and the other is an oil-diffusion-type pump used to reduce the: pressure.

Work chambers of low-voltage systems are usually made of carbon steel plate. The thickness of the plate is designed to provide adequate X-ray protection and the structural strength necessary to withstand atmospheric pressure. Lead shielding may be required in certain areas to ensure total radiation tightness of the system.

Advantages

1. High heat concentration.

The power density is by 100 to 1000 times higher than in arc welding methods. The heat input per unit length for a given depth of penetration can be much lower than with arc welding; the resulting narrow weld zone has low distortion, and fewer deleterious thermal effects. Electron beam weldments exhibit a high depth-to-width ratio. This feature allows for single-pass welding of thick joints. Reasonably square butt joints in both thick and relatively thin plates can be welded in one pass without the addition of filler metal. Full penetration, single-pass welds can be produced with nearly parallel sides, and exhibiting nearly symmetrical shrinkage.

Rapid travel speeds are possible because of the high melting rates associated with this concentrated heat source. This reduces welding time and increases productivity. Dissimilar metals and metals with high thermal conductivity, such as copper, can be welded.

2. Good shielding.

Welding in vacuum leads to a purity of the welded seam and to the minimisation of weld defects. No slag inclusions, no tungsten inclusions, no porosity.A high vacuum minimizes contamination of the metal by oxygen and nitrogen. Vacuum uses to permit welding of refractory metals, reactive metals, and combinations of many dissimilar metals that are not joinable by arc welding processes.

3. High energy efficiency of the process

EBW is extremely efficient because it directly converts electrical energy into beam output energy. Kinetic energy of electrons can be transformed into heat with efficiency as high as 95…98%. Actually total energy conversion efficiency of EBW is approximately 65%, which is slightly higher than conventional welding processes and much higher than other types laser-beam welding.

4. Process has some unique capabilities.

Hermetic closures can be welded with the high or medium vacuum modes of operation while retaining a vacuum inside the component. The beam of electrons can be magnetically deflected to produce various shaped welds. The ability to project the beam over a distance of several feet in vacuum often allows welds to be made in otherwise inaccessible locations.

Limitations

1. High capital costs

Capital costs are substantially higher than those of arc welding equipment. However, depending on the volume of parts to be produced, the final per-piece cost attainable with EBW can be highly competitive.

2. High requirements for joint preparation.

Preparation for welds with high depth-to-width ratio requires precision machining of the joint edges, exacting joint alignment, and good fit-up. In addition, the joint gap must be minimized to take advantage of the small size of the electron beam. However, these precise part preparation requirements are not mandatory if high depth-to-width ratio welds are not needed.

3. Long time to evacuate the work chamber (if used)

For high and medium vacuum welding, work chamber size must be large enough to accommodate the assembly operation. The time needed to evacuate the chamber will influence production costs. With the nonvacuum mode of electron beam welding, the restriction on work distance from the bottom of the electron beam gun column to the work will limit the product design in areas directly adjacent to the weld joint.

4. High sensitivity to magnetic fields.

Because the electron beam is deflected by magnetic fields, nonmagnetic or properly degaussed metals should be used for tooling and fixturing close to the beam path.

5. Additional safety precautions.

The three primary potential dangers associated with electron beam equipment are electric shock, x-radiation, fumes and gases. High-voltage equipment can cause *electric shock*. With all modes of EBW, *radiation* shielding must be maintained to ensure that there is no exposure of personnel to the x-radiation generated by EB welding. Adequate ventilation is required with nonvacuum EBW, to ensure proper removal of ozone and other *noxious gases* formed during this mode of EB welding.

Applications

The application of EBW to the welding of titanium components for military aircraft has been expanding constantly. Pylon posts and wing components in Ti-6Al-4V for the F15 fighter have been EB welded by McDonnell Douglas since the mid 70’s. The wing boxes that hold the variable geometry wings in the fighters Tornado, and F14 “Tomcat”, are also Ti-6Al-4V EB welded. Progress in control systems and in the implementation of computers for automation made a significant difference in the EBW of titanium alloys for military aircraft. This new technology enables continuous one-pass welds over curved lines and surfaces, and through varying thicknesses.

Critical titanium structural components are being EB welded this way for the Eurofighter (attachment of the wings and fin to the fuselage) and Boeing’s F-22 (aft fuselage).

The F-22 is the first airplane in 60 years to feature a welded fuselage. Prior fuselages were made of riveted aluminum. The recent application of titanium castings in the F-22 presented welding problems that delayed the start of production by at least five months.

A remarkable application of EBW is in the construction of the oxygen and fuel tanks of the Russian Energia rocket. Due to the large size of the tanks, the vacuum is created locally, and sealed with ferroelectric liquids.

Laser beam welding

A welding process that produces coalescence with the heat from a laser beam impinging on the joint. The word “LASER” is an acronym for Light Amplification by Stimulated Emission of Radiation. In 1917, Albert Einstein established the theoretical foundations for the laser in the paper “On the Quantum Theory of Radiation”. In 1957, Charles Townes and Arthur Schawlow, (the USA) began a serious study of the infrared laser. In 1958, Alexander Prokhorov (the USSR) independently proposed using an open resonator (an essential laser-device component), the first published appearance of this idea. On May 16, 1960, Theodore Maiman operated the first functioning laser, ahead of several research teams, including those of Charles Townes, Arthur Schawlow and Gordon Gould. Maiman's functional laser used a solid-state flashlamp-pumped synthetic ruby crystal to produce red laser light, at 694 nanometres wavelength.

Principals of operation

The generation of a laser beam is essentially a three step process that occurs almost instantaneously.

1. Spontaneous emission.

The pump source provides energy to the medium, exciting the laser medium atoms such that electrons held with in the atoms are elevated temporarily to higher energy states. The electrons held in this excited state cannot remain there indefinitely and drop down to a lower energy level. In this process, the electron looses the excess energy gained from the pump energy by emitting a photon.

2. Stimulated emission.

The photons emitted by spontaneous emission eventually strike other electrons in the higher energy states. The incoming photon knocks the electron from the excited state to a lower energy level creating another photon. These two photons are coherent meaning they are in phase, of the same wavelength, and traveling in the same direction.

3. Amplification.

The photons are emitted in all directions, however some travel along the laser medium to strike the resonator mirrors to be reflected back through the medium. The resonator mirrors define the preferential amplification direction for stimulated emission. In order for the amplification to occur there must be a greater percentage of atoms in the excited state than the lower energy levels.

Equipment

Laser beam welding system includes laser head, beam delivery, and focusing head. Laser head consists of laser media in resonator, pump source, cooling system. The two types of lasers commonly used are solid-state lasers and gas lasers.

The **solid-state lasers** uses one of several solid laser media, including synthetic ruby and chromium in aluminum oxide, neodymium in glass (Nd:glass), and the most common type, crystal composed of yttrium aluminum garnet doped with neodymium (Nd:YAG).

The common design of solid-state LBW head is the following. Inside elliptical case *6* with inner reflective surface the resonator is located at one focus, and flash lamp *5* is located at another focus. The resonator consists of a laser rod *1* approximately 20 mm in diameter and 200 mm long, and the ends are ground flat, and reflective mirrors. The cavity mirror *2* is 100% reflective, the output mirror *3* is partial reflective. The resonator is pumped by a flash lamps containing xenon or krypton. When flashed, a pulse of light lasting about two milliseconds is emitted by the laser. The light is transmitted to focusing head *7* by beam delivery system *4*, which is usually mirror or optical fiber. Typical power output for ruby lasers is 10…20 W, while the Nd:YAG laser outputs up to 6 kW.

Solid-state lasers operate at wavelengths on the order of 1 micrometer, much shorter than gas lasers, and as a result require that operators wear special eyewear or use special screens to prevent retina damage. Sometimes whole plant should be designed as a closed production cell with windows made of special materials. Nd:YAG lasers can operate in both pulsed and continuous mode, but the other types are limited to pulsed mode.

Gas lasers use high-voltage, low-current power sources to supply the energy needed to excite the gas mixture used as a lasing medium. These lasers can operate in both continuous and pulsed mode, and the wavelength of the laser beam is 10.6 μm. Fiber optic cable absorbs and is destroyed by this wavelength, so a rigid lens and mirror delivery system is used. Power outputs for gas lasers can be much higher than solid-state lasers, reaching 25 kW.

The **focusing head** consists of optics which focuses the laser light emitted by the fiber onto the material being welded. Longer focal length lenses produce larger spot diameters while shorter focal length lenses produce smaller weld spots.

The laser can weld a wide range of steels, nickels alloys, titanium, some aluminum alloys and even copper, however there are materials that are better suited to laser welding and some that are difficult or impossible to laser weld. The material characteristics specific to laser welding are: the materials reflectivity, the effect of the high thermal cycling and the vaporization of volatile alloying elements.

Low-carbon steels are readily weldable, but when the carbon content exceeds 0.25% martensitic transformation may cause brittle welds and cracking. Pulsed welding helps minimize the tendency for cracking. Fully killed or semi-killed are preferable.

Aluminum alloys are rather difficult to weld due to the high initial surface reflections of 10.6 μm radiation emitted by CO_2 lasers. Surface coating often reduces this problem. Another critical factor involving laser welding is the vaporization of alloying elements such as magnesium. Suppression of the plasma with a properly designed shielded gas nozzle can be used to avoid the loss of alloying elements. The other alternative is to use filler metal. Although the welding of aluminum is difficult with LBW, it has already been demonstrated that, with proper precautions, welds having tensile strength equivalent to the parent materials can be obtained.

Titanium alloys and other refractory alloys can be welded in this way, but an inert atmosphere is always required to prevent oxidation.

Welding modes

There are two distinctly different modes of energy transfer in laser welding which are commonly referred to as conduction mode welding and keyhole mode welding. It is the power density incident on the material surface, as well as the material properties, which ultimately determine which mode is present for a given weld.

Conduction mode welding is performed at low energy density forming a weld nugget that is shallow and wide. The laser beam does not produce sufficient vaporization pressure to displace the weld pool, form a cavity, and allow the beam to emerge directly at the root of the weld. Instead, the incident beam energy on the weld pool surface is transferred to the root of the weld solely by conductive and convective heat flow in the molten metal. For a given weld diameter, conduction limited welding has a maximum penetration value at which no further penetration can be obtained without creating a cavity. The maximum aspect ratio for conduction mode welding is between 0.5 and 1.0. Conduction mode welding can be obtained either with continuous wave lasers or with pulsed power lasers and with either low or high power. Selection of parameters and focusing optics that result in small vapor plumes and the absence of spatter are necessary to insure conduction mode welding.

Keyhole mode welding occurs when the power density of the beam is about 10^6 W/cm^2 or greater. The material at the interaction point melts and vaporizes. The vapor recoil pressure, surface tension, and other phenomenon create a deep cavity. This cavity is a high-pressure region surrounded by walls of molten metal. As the workpiece moves relative to the beam, the cavity is sustained, and the molten metal flows from the front edge of the cavity around the sides of the cavity in a direction opposite to the travel direction, and solidifies at the trailing edge forming a narrow fusion zone or weld.

Process variations

Hybrid welding refers to a combination of two welding methods, laser welding and an arc welding method such as GTAW, GMAW or plasma welding. Combining a laser with GMAW welding, which wire provides molten material that fills the joint and thus reduces the requirements for exact positioning of the two parts that would otherwise be required for laser welding alone. In addition, when welding fillet joints, this combination provides reinforcement of the joint. This also reduces the risk of undercutting, which can easily occur with laser welding, and which unfortunately seriously reduces fatigue strength. However, in comparison with ordinary GMAW welding, the welding speed is considerably higher, welding arc is more stable, single pass penetration is deeper; residual stresses and distortion are lower, due to use of the laser. Hot cracking (e.g. in some higher strength Al alloys) can be avoided, and internal porosity content reduced, with respect to laser welds.

Advantages

1. High heat concentration

Heat input can be is close to the minimum required to fuse the weld metal; thus, metallurgical effects in heat-affected zones are reduced, and heat-induced workpiece distortion is minimized. Aspect ratios (depth-to-width ratios) on the order of 10 are attainable when the weld is made by forming a cavity in the metal, as in keyhole welding.

2. Good for precision works.

The laser beam can be focused on a small area, permitting the joining of small, closely spaced components with tiny welds. Welds in thin material and on small diameter wires are less susceptible to burn-back than is the case with arc welding

3. High work efficiency

Single pass laser welding procedures have been qualified in materials of up to 32 mm thick, thus allowing the time to weld thick sections to be reduced and the need for filler wire (and elaborate joint preparation) to be eliminated. The laser can be readily mechanized or automated, high-speed welding, including numerical and computer control. Rapid starting and stopping is available. No electrodes are required; welding is performed with freedom from electrode contamination, indentation, or damage from high resistance welding currents. Because LBW is a non-contact process, distortion is minimized and tool wear is essentially eliminated.

4. Good energy transmission capabilities.

A laser beam can be transmitted an appreciable distance through the atmosphere or optical fiber without serious attenuation or optical degradation because of its coherent nature. Laser beams are readily focused, aligned, and directed by optical elements. Thus the laser can be located at a convenient distance from the workpiece, and redirected around tooling and obstacles in the workpiece. This permits welding in areas not easily accessible with other means of welding. The workpiece can be located and hermetically welded in an enclosure that is evacuated or that contains a controlled atmosphere. The beam can be transmitted to more than one work station, using beam switching optics, thus allowing beam time sharing.

A wide variety of materials can be welded, including various combinations of different type materials. Metals with dissimilar physical properties, such as electrical resistance, can be welded.

Laser welds are not influenced by the presence of magnetic fields, as are arc and electron beam welds; they also tend to follow the weld joint through to the root of the workpiece, even when the beam and joint are not perfectly aligned. No vacuum or X-ray shielding is required.

Limitations

1. High capital costs

Capital cost for laser welding devices is almost 10 times more expensive than comparable power arc welding systems. When performing moderate-to-high power laser welding, an appropriate plasma control device must be employed to ensure that weld reproducibility is achieved. When the capital cost of laser-beam welding is compared to electron-beam welding, laser-beam welding becomes the more cost-effective of the two processes because novacuum enclosure is necessary for laser-beam welding.

2. Good joint fit-up required.

Joints must be accurately positioned laterally under the beam and at a controlled position with respect to the beam focal point. When weld surfaces must be forced together mechanically, the clamping mechanisms must ensure that the final position of the joint is accurately aligned with the beam impingement point.

3. Low energy efficiency.

Lasers tend to have fairly low energy conversion efficiency, generally less than 10%. The high reflectivity and high thermal conductivity of some materials, such as aluminum and copper alloys, can affect their weldability with lasers.

4. Single-pass welding practically limited.

The maximum joint thickness that can be laser beam welded is somewhat limited. Thus weld penetrations much greater than 19 mm are not presently considered to be practical production LBW applications.

Applications

LBW can deliver the most concentrated heat sources for welding, with the advantages of higher accuracy and weld quality and smaller distortions. This process is used for welding and drilling of jet engine components made of heat resistant alloys. Laser-processed combustors are used in the Pratt & Whitney jet engines JT9D, PW4000, PW2037 and F-100-PW-22019.

Laser beam welding will replace riveting in the joining of stringers to the skin plate in the Airbus 318 and 3XX aircraft. Significant savings are expected to be made by replacing riveted joints by LBW. Riveting is estimated to consume 40% of the total manufacturing man-hours of the aircraft structure.

Questions

When the electron beam welding was developed?
Describe EB welding gun operation.
How to control (to focus, to direct) electron beam?
How to calculate quantity of heat generated in workpiece?
What is a keyhole?
What depth-to- width ratio can be reached in EBW?
Describe high vacuum EB welding.
Describe medium vacuum EB welding.
Describe nonvacuum EB welding.
What are the main EBW equipment designs?
What is accelerating voltage for nonvacuum welding?
Describe main functions of electron beam gun.
Describe main functions of electron gun power source.
Describe main functions of vacuum pumping system.
Describe main functions of EB work chambers.
Recount advantages of electron beam welding.
Recount disadvantages and limitations of electron beam welding.
Describe field of application for EBW process.
What does the word “laser” mean?
When the laser systems were developed?
Describe spontaneous emission in laser medium.
Describe stimulated emission in laser medium.

Describe amplification of laser beam.
What does the laser beam welding system include?
Describe design of solid state laser head
What wavelength do solid state lasers operate?
What wavelength do gas lasers operate?
Describe design of gas laser head.
Describe abilities to weld steels and aluminum by lasers.
Describe conduction mode welding.
Describe keyhole mode welding.
Describe hybrid welding.
Recount advantages of the process.
Recount disadvantages and limitations of the process.
Describe range of applications for laser beam welding.

Resistance welding

Definition: ***Resistance welding is a group of welding processes that produces coalescence of the faying surfaces with the heat obtained from resistance of the workpieces to the flow of the welding current in a circuit of which the workpieces are a part, and by the application of pressure.***

The principle of resistance welding was discovered by the English physicist, James Joule, in 1856. In his experiments he buried a bundle of wire in charcoal and welded the wires by heating them with an electric current. This is believed to be the first application of heating by internal resistance for welding metal.

Elihu Thompson develops the process for practical applications. During a lecture at the Franklin Institute he reversed a Ruhmkorff coil by sending a Leyden jar discharge through its fine wire. The primary of such coil (which was of heavy wire) had its terminals disengaged and put lightly into contact. It was found on the discharge of the condenser through the fine wire that these heavy primary wires stuck together permanently. The current, which was one of extremely high voltage and small flow, had been transformed down, producing in the primary a current of only a few volts, but of great strength in amperes, so that the instantaneous local heating of the ends of the primary coil, which were in contact, brought them to the point of fusion, and union took place. 1877 Thompson invented a small low-pressure resistance welding machine. For several years, little was done with this development, but in the 1880s the resistance welding was introduced commercially.

Resistance welding is used primarily in the mass production industries where long production runs and consistent conditions can be maintained. Welding is performed with operators who normally load and unload the welding machine and operate the switch for initiating the weld operation. The automotive industry is the major user of the resistance welding processes, followed by the appliance industry. Resistance welding is used by many industries manufacturing a variety of products made of thinner gauge metals. Resistance welding is also used in the steel industry for manufacturing pipe, tubing and smaller structural sections. Resistance welding has the advantage of producing a high volume of work at high speeds and does not require filler materials. Resistance welds are reproducible and high-quality welds are normal.

There are five main resistance-welding processes. These are spot, seam, projection welding, upset and flash welding.

Heat Generation

Three factors involved in making a resistance weld are the amount of current that passes through the work, the pressure that the electrodes transfer to the work, and the time the current flows through the work.

Heat is generated by the passage of electrical current through a resistance circuit. The force applied before, during, and after the current flow forces the heated parts together so that coalescence will occur. Pressure is required throughout the entire welding cycle to assure a continuous electrical circuit through the work.

Heat energy generated in the column of the metal (Joule's law)

$$H = I^2 \cdot R \cdot t,$$

where H - heat energy, in joules; I - current, in amperes; R - resistance, in ohms; t - time of current flow, in seconds.

The total resistance $R = 2R_e + 2R_{ew} + R_{w1} + R_{w2} + R_{w1w2}$, where R_e - resistance of the electrode, R_{ew} – electrode - workpiece contact resistance, R_{w1} and R_{w2} - resistance of the workpieces to be welded and R_{w1w2} – workpiece - workpiece contact resistance (faying surfaces). In the processes, where squeezing pressure is high, contact resistance R_{w1w2} is low, so resistance of the workpieces makes the main contribution.

The resistance of the workpiece $R_w = \rho L / S$ where ρ - resistivity constant, which depends on material welded and temperature; L - length of the current flow path; S - square of workpiece (square of the column of the metal between the electrodes for sheet working).

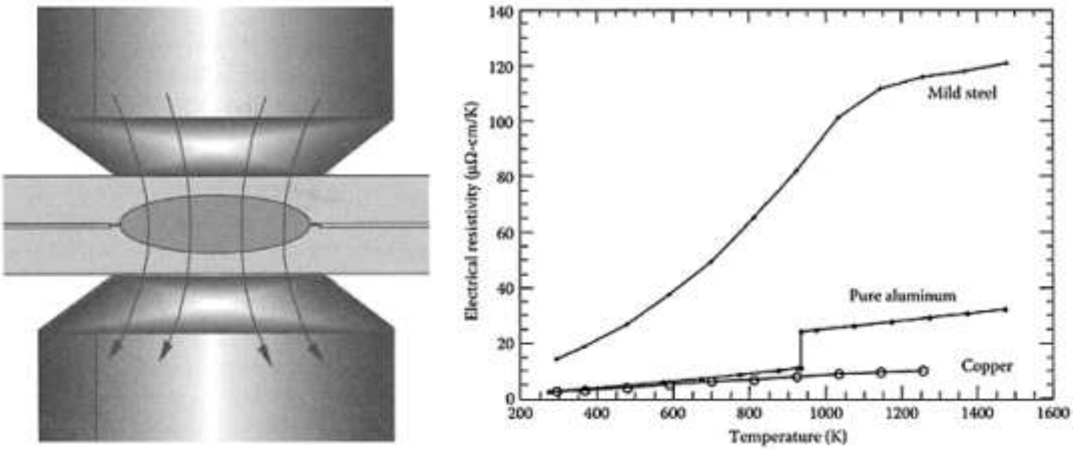


Fig. 21 – Workpiece resistance to electric current

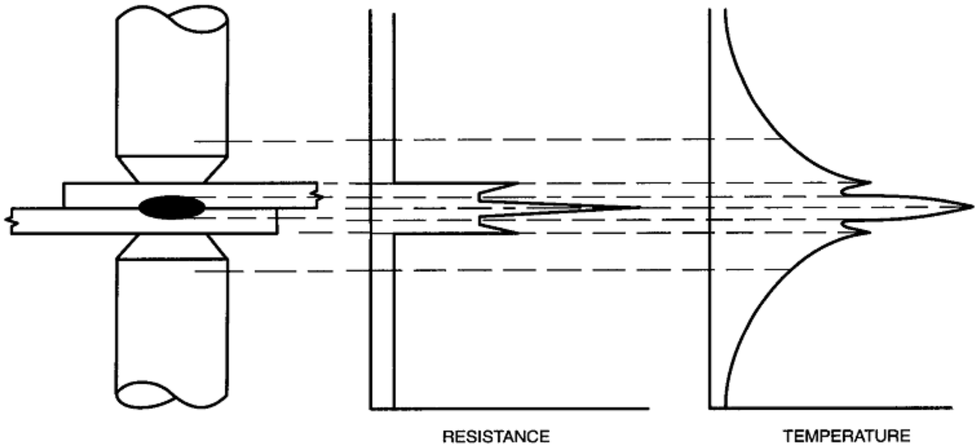


Fig. 22 – Temperature distribution in spot welded joint

Welding heat is proportional to the square of the welding current. If the current is doubled, the heat generated is quadrupled. Welding heat is proportional to the total time of current flow, thus, if current is doubled, the time can be reduced considerably. The welding heat generated is directly proportional to the resistance. The actual temperature rise at the joint depends on the specific heat and the thermal conductivity of the metal to be joined. Thus because they have high thermal conductivity, metals such as aluminium and copper require high heat concentrations. The heat losses should be held to a minimum. It is an advantage to shorten welding tire and short welding time. Mechanical pressure which forces the parts together helps refine the grain structure of the weld.

The contact resistance between the electrodes and the workpiece R_{ew}, and particularly the contact resistance between the two pieces of metal to be joined R_{w1w2}, is considerably higher than the resistance of the conducting path through the metal. Minor unevennesses in the surface of the metal means that the current is concentrated to a few contact points, with the result that the heating is greatest at these points. Changing the clamping force can modify the contact resistance and thus also the heating.

As welding starts, the contact resistances are very high. The initial passage of current breaks through the surface layers, so that the contact resistances drop rapidly. Most of the heat formed at the contact between the electrodes and the workpiece is conducted away through the water-cooled electrodes. However, this is not the case with the heat developed in the contact resistance between the two workpiece sheets, so the temperature here rises until the melting temperature of the metal is reached, while the surfaces continue to be pressed together by the clamping force, so that a weld nugget forms in the contact area.

An Al_2O_3 layer, which is inherent to aluminum sheets, plays an important role in affecting the contact resistance at both the electrode-sheet and sheet-sheet interfaces. The layer at the as-fabricated state is usually not uniform or may be broken under an electrode force during welding. As a ceramic, Al_2O_3 is highly insulating with a high melting temperature. A non-uniform or broken Al_2O_3 layer on a sheet surface results in uneven distribution of electric current, with very high electric current density at low resistance locations, and produces significantly localized heating or even melting on the surfaces. A stable welding process with uniform weld nuggets can be achieved if the sheet-sheet contact resistance is controlled between 20 and 50 μOhm. Such contact resistance can only be achieved if the sheet surface is properly treated.

The workpieces are generally in the secondary circuit of a transformer. The transformer converts high-voltage, low-current power to low-voltage, high-current power. The magnitude of the current in resistance welding operations may be as high as 100 000 A, although the voltage is typically only 0.5…10 V.

Under the copper electrodes, which are cooling by the water, surfaces of the welding parts are cooling in consequence of heat sink; therefore maximum temperature in the column of the metal take place in the middle, between the electrodes, where the metal are melted and are formed the so-called weld nugget.

Components of the welding machine

Resistance welding operations are automatic and require specialized machinery. Many are now operated by programmable computer control. Current control is completely automatic once the welding operator initiates the weld. Resistance welding equipment utilizes programmers for controlling current, time cycles, pressure, and movement. Welding programs for resistance welding can become quite complex.

The three main components of the welding machine are the Control, Transformer, and Secondary Conductor.

Control. Resistance welds are made very quickly; however, each process has its own time cycle. The purpose of the weld control is to accurately time the functions involved in resistance welding. The various functions that are timed are Squeeze, Weld, Hold, and Off.

Squeeze time allows the weld heads to come together and generate the appropriate amount of pressure prior to welding. *Welding time* is the amount of time that the transformer is actually applying electricity to the weld area. This is when the metals are being heated enough to melt and fuse together. During the *Hold Time*, electrode force is still applied, even after the weld current has ceased. During this period, the weld nugget cools and the metals are forged under the force of the electrodes. The continuing electrode force helps keep the weld intact until it solidifies, cools, and the weld nugget reaches its maximum strength. *Off time* is used when the machine is in repeat mode. It specifies an amount of time in between weld initiations. These functions are timed in cycles. In Europe, the mains frequency is 50 Hz, which means that one cycle takes 1/50 = 0.02 s. In the US, typically, there are 60 cycles per second, so 1 cycle is one sixtieth of a second.

The control actually turns the different valves and switches on and off to run the machine. The control will include a small valve transformer, which supplies 115V to the solenoid valve that controls the pneumatic cylinder. There is also a switch to run the transformer. This switch may be a set of "ignitron tubes", or a set of thyristors, more commonly called SCR's (Silicon Controlled Rectifiers). Most companies are quickly moving away from the ignitron tube firing because of environmental concerns and accuracy. Ignitron tubes date to the 1930's. SCR's were introduced in the early 1960's. Both units are water cooled.

Controls can get very complicated. They may be able to run multiple valves and multiple transformers from one control.

Transformer consists of a primary winding, secondary winding, and a magnetic core, onto which the two windings are placed. Without getting into the physics involved, as a voltage and current are applied to the primary winding, a subsequent voltage and current is induced in the secondary winding. Typically, we will take a primary voltage of 230V or 460V at up to ~800 amps, apply it to a primary winding and induce a secondary voltage of 2 to 15 volts with currents approaching 100 000 amps. Three phase applications can generate significantly higher amperages.

Secondary Conductor includes everything that is attached to the secondary winding of the transformer. The weld arms, holders, and tips are all part of the secondary circuit. The pressure is applied by mechanical, hydraulic, or pneumatic systems. Motion, when it is involved, is applied mechanically. *Electrodes* typically made of copper alloys, electrodes actually have three separate functions: to conduct current to the workpieces being welded, to transmit the proper pressure or force to those workpieces to produce and forge a good weld, and to help dissipate heat from the area being welded. To ensure that all three of these functions are executed properly, it is important to regularly maintain the electrodes, keeping them clean and in good condition.

Cost of the total system typically ranges from $20,000 to more than $50,000. The machinery is generally not portable, and the process is more suitable for use in manufacturing plants and machine shops. Operator skill required is minimal, particularly with modern machinery.

Resistance spot welding

Definition: ***Resistance spot welding is a resistance welding process which produces coalescence at the faying surfaces in one spot by the heat obtained from resistance to electric current through the work parts held together under pressure by electrodes.***

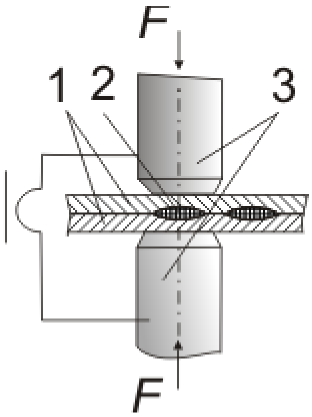


Fig. 23 – Resistance spot welding

Principles of operation

The pressure of the electrode tips *3* on the workpiece holds the parts *1* in close and intimate contact during the making of the weld. Resistance welding is accomplished when current is caused to flow through electrode tips and the separate pieces of metal to be joined. The resistance of the base metal to electrical current flow causes localized heating in the joint, and the weld *2* is made. The resistance spot weld is unique because the actual weld nugget is formed internally in relation to the surface of the base metal.

The electrodes need to be of a material with a high hardness, low electrical resistance and high thermal conductivity. Cooling is decisive for their life. Wear and tear, together with deformation, increase the effective contact size of the electrodes, which reduces the current density and the strength of the welds.

Previously made welds may affect the subsequent welding if the welds are spaced close to each other due to *electric current shunting*. The welding current may be diverted from the intended path by the previously made welds. As a result, the current or current density may not be sufficient to produce a quality weld. The shunting effect is a strong function of the bulk resistivity of the sheet material. A high conductive metal, such as aluminum, requires a large space between the welds.

During spot welding, the large electric current induces a large magnetic field, and the electric current and magnetic field interact with each other to produce a large magnetic force field too, which drives the melted metal to move very fast.

Process variables

The spot welding process includes a number of variables that can be adjusted in order to achieve optimum welding performance. Tables of optimum values have been produced, but it is also necessary to optimise the process by trial and error.

The **welding current** is the current that flows through the workpiece. Of all the parameters, it is this that has the greatest effect on strength and quality of the weld, as the amount of heat produced is proportional to the square of the welding current. The welding current must therefore be carefully adjusted: too high a current results in a weld with poor strength, with too great a crater depression, spatter and some distortion. It also means that the electrodes are worn unnecessarily. Too low a current, on the other hand, also produces a weld of limited strength, but this time with too small a weld area.

The **clamping force** is the force with which the electrodes press the sheets together. It is important that this should be carefully controlled, as too low a clamping force results in a high contact resistance, accompanied by spatter and resulting in a poor weld strength, while too high a force results in too small a weld, again with poor strength, but accompanied by unnecessary wear on the electrodes and too great a crater depression.

The **electrode area** determines the size of the area through which the welding current passes, i.e. the current density. The electrode diameter *d* is determined in relation to the thickness *t* of the low carbon steel from the following formula: $d = 5\sqrt{t}$. When welding high-strength steels, a factor of 5 in the formula can suitably be increased to about 6-8.

Squeeze time is the time needed to build up the clamping force. It varies with the thickness of the metal and with the closeness of the fit, and is also affected by the design of the electrode jaws.

Welding time is the time for which current flows through the workpiece, and is measured in cycles, i.e. during which alternating current passes through one cycle.

Hold time is the time from when the current is interrupted until the clamping force can be released. The plates must be held together until the weld pool has solidified, so that the joint can be moved or the electrodes moved to the next welding position.

Aluminum is readily welded using the resistance spot welding process. However, because of the relatively low electrical resistance of aluminum, the current requirements for welding are two to three times the values required for welding a similar thickness of carbon steel. The high welding currents required for aluminum result in heating of the copper welding electrodes and “mushrooming” of the contact tips. There is also the problem of “pickup” of aluminum on the copper electrodes during the welding cycle. Both of these phenomena result in changes in current density, and therefore weld quality. Another problem is the oxide scale which forms on aluminum. In spite of careful cleaning methods prior to welding, the oxide layer forms on aluminum very quickly and can cause wide variations in the welding heat because of variations in the welding contact resistance.

One of the methods used to minimize these problems is to circulate a refrigerated coolant through the electrodes. A coolant temperature of -12°C (10°F) was found to reduce the softening and pickup problems to the point that the electrodes could be used to make as many as 2000 spot welds between electrode dressings (with a file or emery cloth). While this extended electrode service life by a factor of ten, the refrigerated coolant method has been partially replaced by the development of copper alloy electrodes that do not deform plastically at the temperatures encountered.

Equipment

RSW machines can be divided into portable and stationary machines.

Portable welding guns are used in RSW when it is impractical or inconvenient to transport the work to the machine. Because of the high secondary losses of portable machines, transformers used in these machines have a secondary voltage two to four times as great as the voltage of transformers used in stationary machines of equal rating.

Gun welders typical of portable manually operated and robotic welding cells can be classified into two basic types: S-type welding guns, J-type welding guns. An ***S-type gun*** utilizes a lever action to transmit the force applied by the cylinder head to the welding electrodes. However, due to an unbalanced pivot point, the force measured at the electrodes is less than that applied at the cylinder. With ***J-type welding guns***, the force applied by the pneumatic cylinder is transmitted directly to the welding electrode. The rigidity of the framework of the welding gun is characterized by the extent to which the electrode arms deflect on application of the electrode force. This is an important factor in determining weld quality.

Stationary welding may be performed by means of single or multiple electrodes. The size and shape of the individually formed welds are limited primarily by the size and contour of the electrodes. The equipment for resistance spot welding can be relatively simple and inexpensive up through extremely large multiple spot welding machines.

The stationary **single spot welding machines** are of two general types: the horn or rocker arm type and the press type.

The ***horn type machines*** have a pivoted or rocking upper electrode arm, which is actuated by pneumatic power or by the operator`s physical power. They can be used for a wide range of work but are restricted to 50 kVA and are used for thinner gauges. For larger machines normally over 50 kVA, the ***press type machine*** is used. In these machines, the upper electrode moves in a slide. The pressure and motion are provided on the upper electrode by hydraulic or pneumatic pressure, or are motor operated.

For high-volume production work, such as in the automotive industry, **multiple spot welding machines** are used. These are in the form of a press on which individual guns carrying electrode tips are mounted. Welds are made in a sequential order so that all electrodes are not carrying current at the same time. Modern equipment used for spot welding is computer controlled for optimum timing of current and pressure, and the spot welding guns are manipulated by programmable robots.

Advantages of the process

1. Low energy consumption.

The high current, in combination with a rapid heating time, means that the thermal energy input is efficiently used: very little is conducted away to the surrounding metal. Little deformation of the workpiece, as the thermal energy is more or less restricted to the immediate vicinity of the weld.

2. Very high rate of production.

Major advantage of spot welding includes high operating speeds and suitability for automation or robotization and inclusion in high-production assembly lines together with other fabricating operations. With automatic control of current, timing, and electrode force, sound spot welds can be produced consistently at high production rates and low unit labor costsusing semiskilled operators. Resistance welding of 1 + 1 mm sheet, for example, takes 0.20 s. No filler materials required.

3. Clean and environmentally friendly.

Very little pollution and less environmental impact than when welding with an arc. Operator safety because of low voltage.

Limitations of the process

1. Limited range of thicknesses and joint types.

Used for joining thin sheet materials (from 0.3+0.3 up to 3 + 3 mm) by overlap joints.

2. Require special quality controls.

If the current is not strong enough, hot enough or the metal is not held together with enough force, the spot weld may be small or weak. Due to the fact that weld nugget inside the metal, it is very hard to test its quality.

3. Require double side approach

The electrodes have to be able to reach both sides of the pieces of metal that are being joined together. A spot welding machine will be able to hold only a certain thickness of metal and although the position of the electrodes can be adjusted, there will be only a limited amount of movement in most electrode holders.

4. Fatigue strength loss.

Warping and a loss of fatigue strength can occur around the point where metal has been spot welded. The appearance of the join is often rather ugly, and there can be cracks. The metal may also become less resistant to corrosion.

Process variations

Projection welding (RPW) is a modification of spot welding. In this process, the weld is localized by means of raised sections, or projections, on one or both of the workpieces to be joined. Heat is concentrated at the projections, which permits the welding of heavier sections or the closer spacing of welds. The projections can also serve as a means of positioning the workpieces and allows the use of flat electrodes, which are most easily dressed to an original condition, but embossing workpieces are an added expense.

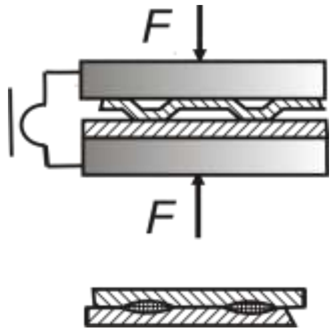


Fig. 24 – Projection welding

The resulting welds are localized at predetermined points by projections, embossments, or intersections. Localization of heating is obtained by a projection or embossment on one or both of the parts being welded. There are several types of projections: 1) the button or dome type, usually round, 2) elongated projections, 3) ring projections, 4) shoulder projections, 6) radius projection.

The major advantage of projection welding is that electrode life is increased because larger contact surfaces are used. Welding metals of different thicknesses is capable. A very common use of projection welding is the use of special nuts that have projections on the portion of the part to be welded to the assembly.

Hybrid weld-adhesive joining is a specific process combination of spot resistance welding and adhesive bonding, which were applied for joining high strength aluminum alloys in aircraft constructions. The adhesive is applied to the faying surfaces of sheets to be welded, and subsequently resistance spot weld is made through the sheets before curing of the adhesive. The weld-adhesive procedure affords many advantages over the resistance spot welding, e.g. higher mechanical strength, improved crash performance and higher fatigue resistance of the joined components.

Cross Wire Welding is a resistance welding process for joining bars or wires in cross joints by directly applying opposing forces with usually flat electrodes. The current and the heat generation are localized at the contact points of the crossed bars or wires. Cross wire welding is widely used in construction and electrical industry as well as for manufacturing of metal wire nets and shopping trolleys etc.

Applications

Spot welding is the best-known resistance welding method. It is widely used, e.g. in the automotive industry. An ordinary private car can have up to 5 000 spot-welded joints. It used also in domestic appliances, furniture, building products, enclosures and, to a limited extent, aircraft components.

Resistance seam welding (RSEW)

Principles of operation

Resistance seam welding is similar to spot welding, but the material *1* moves between two rotating weld wheels *3* (electrodes) with continuous current being applied.

The resulting weld is a series of overlapping resistance spot welds *2* made progressively along a joint rotating the electrodes. Both the upper and lower electrode wheels are powered. Pressure is applied in the same manner as a press type welder. The wheels can be either in line with the throat of the machine or transverse.

Welding current is transferred through the bearing of the roller electrode wheels. Water cooling is not provided internally and therefore the weld area is flooded with cooling water to keep the electrode wheels cool.

In seam welding a rather complex control system is required. This involves the travel speed as well as the sequence of current flow to provide for overlapping welds. The welding speed, the spots per inch, and the timing schedule are dependent on each other. Welding schedules provide the pressure, the current, the speed, and the size of the electrode wheels.

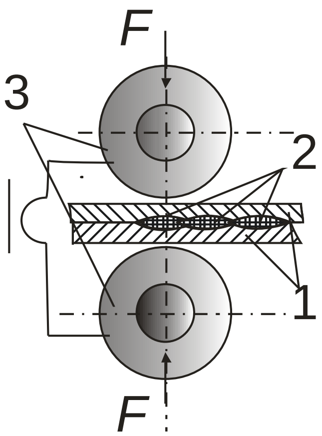


Fig. 25 – Seam welding

This process is quite common for making flange welds, for making watertight joints for tanks, etc.

Equipment

Most seam welding machines are press-type resistance welding machine. The upper electrode wheel is mounted to, and insulated from, the operating head. The head, which is actuated by a direct-acting air or hydraulic cylinder, applies the electrode force. The lower electrode wheel is mounted on a supporting arm or knee.

The wheels can be either in line with the throat of the machine or transverse. If they are in line it is normally called a *longitudinal seam welding machine*. If wheels are transverse with the throat of the machine it is called *circumferential seam welding machine*.

Advantages of the process

1. Gas-tight or liquid-tight joints can be produced (not possible with spot or projection welding)
2. High-speed welding (especially on thin stock) is possible.

Disadvantages and limitations of the process

1. Welds must ordinarily proceed in a single plane or on a uniformly curved surface.
2. Current shunting decreases energy efficiency of the process.

Process variations

When the spots are not overlapped enough to produce gaslight welds it is a variation known as **roll resistance spot welding**. This process differs from spot welding since the electrodes are wheels.

Another variation is the so-called **mash seam welding** where the lap is fairly narrow and the electrode wheel is at least twice as wide as used for standard seam welding. The pressure is increased to approximately 300 times normal pressure. The final weld mash seam thickness is only 25% greater than the original single sheet.

Butt resistance welding

There are two main butt resistance processes. These are flash welding and upset welding. Flash welding and upset welding are resistance welding processes in which coalescence is produced simultaneously over the entire area of two abutting surfaces. In both processes, heat for welding obtained by the resistance to electric current between the two facing surfaces.

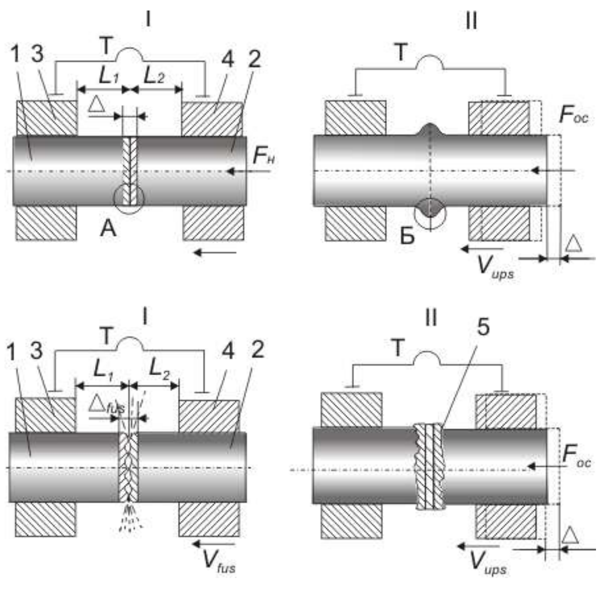


Fig. 26 – Resistance butt welding

Upset welding. One of the earliest forms of resistance welding to be used in the metal-working industry is the upset welding process. Although flash welding and upset welding are accomplished on welding machines that are similar, the most notable exceptions are the applications of pressure and current. In a basic upset weld, the two work pieces to be welded are first brought together under pressure. Current is then applied, heating the contact area enough to allow the applied pressure to forge the parts together. In other words, a upset weld is a single-stage operation of both current and pressure.

The pressure and current are applied throughout the weld cycle until the joint becomes plastic. The constant pressure overcomes the softened area, producing the forging effect and subsequent welded joint. This is done without a change in current or pressure throughout the cycle.

The true upset weld has no flash splatter. The final upset at the weld joint is usually smooth and symmetrical. Very little fagged expulsion of metal is evident.

Examples of modern-day applications of the AC butt welding process are joining small diameter wires and rods, such as coils for continuous line operations, and wire frame applications.

Although butt welding was widely used during the early industrial years, it was limited because of the high current required to bring the ends of a large workpiece to the forging temperature. It can be used only if the parts to be welded are equal in cross-sectional area. Careful end preparation was also needed. The welding surfaces of the workpiece had to be very clean, smooth, and parallel. If the proper preparation was not performed, hot spots in the weld face would be created form an uneven current flow. Butt welding was thought to produce weaker welds than flash welding. The advance of modern microprocessor controls and the use of DC and finite control over the abutting surfaces has helped dispel this belief.

Early on, butt welding was limited to smaller machines of 5 to 100 KVA and single phase AC. Larger applications required high currents. This machine secondary current demand put a strain on the user's primary power supply and required large distribution equipment.

In later years, a three phase DC power supply was applied to butt welding. A welding machine equipped with a three-phase DC power supply provides balanced line demand, reduced primary current, and a more even heating of the weld area. Inductive losses are minimized, allowing a greater freedom in machine design. Larger cross sections of both ferrous and nonferrous material have been successfully welded with the three-phase DC butt weld.

However, the three phase DC power supply, with its rectification, physical size, and associated items required to support the butt weld system, involves increased costs. A three-phase control is required, as is increased water supply on the rectified secondary of the transformer.

Research studies have found that a narrower heat-affected zone (HAZ) can be produced on a three-phase DC butt welder. Additional tests have pointed out that there is no significant difference in weld quality of three-phase DC butt weld over AC flash welding.

Upset welding is used to fabricate a wide variety of products from bar, strip, and tubing stock. Wire and rod from 12.7 to 31.8 mm diameter can be upset welded.

Flash Welding. The term "flash welding" is fairly self-descriptive - a "flashing action" is produced during the process. The heat is produced in the flash welding process by the flashing action resistance at the interface surfaces rather than contact resistance, as in the butt weld process. Whereas butt welding is a single stage operation, flash welding is a two stage process.

The first stage is the flashing action. The current applied to the workpieces produces a flashing across the interface of the two butting ends of the material. The flashing action increases to the point of bringing the material to a plastic state. This flashing action forms a HAZ very similar to a butt weld.

Once the area has become plastic and reached the proper temperature, the second stage of the operation begins - the upset or forging action. The two ends of the workpieces are then brought together with a very high force sufficient enough to cause the material to upset. This forces the plastic metal along with most of the impurities out of the joint.

Smooth, clean workpiece surfaces are not as critical with this process as they are for butt welding, because the flashing action burns away irregularities at the weld surfaces. This allows joining of a wide variety of materials. Such items as wide, thin sheets of material; tubing; forgings; and ferrous and nonferrous materials can successfully be welded.

With the single phase AC power supplies (transformers), applications with large cross-sectional areas can be welded with lower current demands because of the flashing action. Flash welding can also be applied as shown. This door mitre example has rough edges, and the two ends do not perfectly match. Subsequent sanding and removal of excess flash and upset material with a final polish eliminates any preparation of the sheared edge of the extruded sheet metal workpiece. In other applications, the flash or slag can be knocked loose for removal. The upset underneath the slag is solid metal similar to a butt weld and requires a cutting operation, trimming, or deburring for removal.

The disadvantage of this process is the flash itself. The operator and the surrounding area need to be protected, and smoke and fumes must be removed. The resultant slag particles build up around the machine surfaces, and frequent cleaning is needed.

Advantages of the flash welding

1) Various cross section shapes can be welded.

Cross sectioned shapes other than circular can be flash welded: for example, angles, H sections, and rectangles. Rotation of parts is not required. Parts of similar cross section can be welded with their axes aligned or at an angle to each other, within limits. Rings of various cross sections can be welded

2) Preparation of the faying surfaces is not critical.

The molten metal film on the faying surfaces and its ejection during upset acts to remove impurities from the interface. Preparation of the faying surfaces is not critical except for large parts that may require a bevel to initiate flashing.

3) Narrow HAZ.

The heat-affected zones of flash welds are much narrower than those of upset welds.

Limitations of the process

1) Flashing presents a fire hazards.

The molten metal particles ejected during flashing present a fire hazard, may injure the operator, and may damage shafts and bearings. The operator should wear face and eye protection, and a barrier or shield should be used to block flying sparks.

2) Removal of flash and upset metal is generally necessary and may require special equipment.

3) Limited to identical cross sections.

Alignment of workpieces with small cross sections is sometimes difficult. The parts to be joined must have almost identical cross sections.

Process variations

High frequency butt resistance welding is a resistance welding process which produces coalescence of metals with the heat generated from the resistance of the work pieces to a high-frequency alternating current in the 10,000 to 500,000 hertz range and the rapid application of an upsetting force after heating is substantially completed. The path of the current in the work piece is controlled by the proximity effect.

This process is ideally suited for making pipe, tubing, and structural shapes. It is used for other manufactured items made from continuous strips of material. In this process the high frequency welding current is introduced into the metal at the surfaces to be welded but prior to their contact with each other.

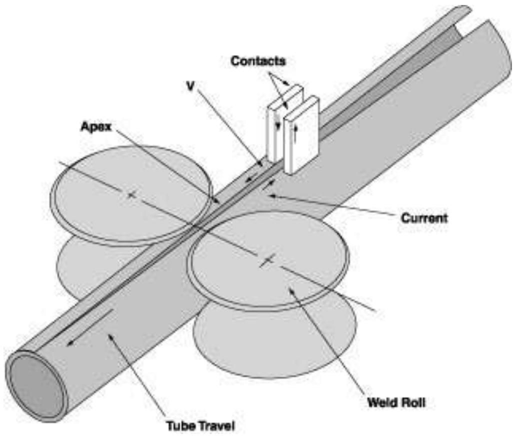


Fig. 27 – High frequency resistance welding

In one method, the current is conducted through two sliding contacts to the edges of roll-formed tubes. The high-frequency welding current flows along one edge of the seam to the welding point between the pressure rolls and back along the opposite edge to the other sliding contact. The heated edges are then pressed together by passing the tube through the pressure rolls.

In another method, the roll-formed tube is subjected to high-frequency induction heating. The current is of such high frequency that it flows along the metal surface to a depth of several thousandths of an inch. Each edge of the joint is the conductor of the current and the heating is concentrated on the surface of these edges. At the area between the closing rolls the material is at the plastic temperature, and with the pressure applied, coalescence occurs.

Questions

What is resistance welding?

Who discovered principles of resistance welding?
Who develops the process for practical applications?
What are factors involved in making a resistance weld?
How is the heat generated in workpiece?
How to calculate total resistance of the joint?
How to calculate resistance of workpiece?
What does actual temperature rise depend on?
How to modify contact resistance?
How does contact resistance change during the welding?
How does Al_2O_3 layer affect the contact resistance?
How high the welding currents in resistance welding?
Why the maximum temperature take place in the halfway between the electrodes?
What are the main components of welding machine?
What is a weld time?
What is a squeeze time?
What is a hold time?
What is an off time?
What does transformer consist of?
What does the secondary conductor include?
What is resistance spot welding?
Describe electric current shunting.
What metal requires a large space between the welds?
How does welding current effect on strength of the weld?
How to select clamping force?
How to calculate electrode area required?
What problems can occur in welding aluminum?
What types of equipment for spot welding do you know?
Recount the process advantages.
Recount the limitations of the process.
Describe projection welding.
What are there types of resistance seam machines?
Recount advantages and disadvantages of seam welding.
What are process variations?

Diffusion welding

Diffusion welding is a solid-state welding process that produces a weld by the application of pressure at elevated temperature with no macroscopic deformation or relative motion of the workpieces. A solid filler metal may be inserted between the faying surfaces to take up gaps or facilitate the diffusion process. The method was invented by the Soviet scientist N.F. Kazakov in 1953.

This is a process in which two absolutely clean, perfectly matched, metal (or ceramic or intermetallic) surfaces are placed in contact and heated, but not to the melting point. As a result of the heating, the diffusion of atoms in each direction across the interface will interlock the two atomic structures so that they become one, eliminating the interface. Temperature is a very important factor in diffusion welding. Pressure may be of secondary importance, as long as intimate contact is maintained throughout the solid state diffusion process.

One of the difficulties in diffusion welding is that the surfaces to be joined are seldom, if ever, perfectly clean or perfectly matched. All metal and many intermetallic surfaces, no matter how carefully finished, have surface irregularities and become covered with an oxide film or other tarnish layers when exposed to air. Ceramic surfaces are normally free of hindering tarnish layers.

Other surface materials may also be present, such as oil, grinding compounds or cleaning chemicals. A weakened or defective bond is sometimes the result.

Diffusion Welding Principles

Metal surfaces have several general characteristics: roughness, an oxidized or chemically reacted and adherent layer, other randomly distributed solid or liquid (oil, grease, and dirt), and adsorbed gas or moisture, or both.

Two necessary conditions must be met for a satisfactory diffusion weld:

1) Mechanical intimacy of faying surfaces

2) The disruption and dispersion of interfering surface contaminants to permit metallic bonding.

A diffusion weld is formed in three stages. In the first stage, deformation of the contacting surface roughness occurs primarily by yielding and by creep deformation mechanisms which produce intimate contact over a large fraction of the interfacial area. At the end of this stage, the joint is essentially a grain boundary at the areas of contact with voids between these areas. During the second stage, diffusion becomes more important than deformation, and many of the voids disappear as grain boundary diffusion of atoms continues. Simultaneously, the interfacial grain boundary migrates to an equilibrium configuration away from the original weld interface, leaving many of the remaining voids within the grains. In the third stage, the remaining voids are eliminated by volume diffusion of atoms to the void surface (equivalent to diffusion of vacancies away from the void). The stages overlap, and mechanisms that may dominate one stage also operate to some extent during the other stages.

This description is consistent with several experimentally observed trends:

1) Temperature is the most influential variable, since it, together with pressure, determines the extent of contact area during stage one, and it alone determines the rate of diffusion that governs void elimination during the second and third stages of welding.

2) Pressure is necessary only during the first stage of welding to produce a large area of contact at the welding temperature. Removal of pressure after this stage does not significantly affect joint formation. However, removal of pressure before completion of the first stage is detrimental to the process.

3) Rough initial surface finishes generally adversely affect welding by impeding the first stage and leaving large voids that must be eliminated during the later stages of welding.

4) The time required to form a joint depends on the temperature and pressure used; time is not an independent variable. This description of diffusion welding is not applicable to diffusion brazing or hot pressure welding processes where intimate contact is achieved through the use of molten filler metal and bulk deformation, respectively.

Advantages and Limitations

Diffusion welding and brazing have a number of advantages over the more commonly used welding and brazing processes, as well as a number of distinct limitations on their applications. Following are advantages of diffusion welding and brazing:

1) High quality of weld.

Joints can be produced with properties and microstructure very similar to those of the base metal. This is particularly important for lightweight fabrications. Components can be joined with minimum distortion.

2) Materials can be welded which can not be welded by fusion welding.

Dissimilar alloys can be joined that are not weldable by fusion processes or by processes requiring axial symmetry, such as friction welding. Large joint members of base metals that would require extensive preheat for fusion welding can be more readily joined. An example is thick copper. Members with limited access can be joined. Defects normally associated with fusion welding are not encountered. Components can be joined without subsequent machining or forming. A number of joints in an assembly can be made simultaneously.

Among the disadvantages of diffusion welding and brazing are the following:

1) Low production rate.

The processes are not adaptable to a high production rate, although a number of assemblies may be joined simultaneously. The thermal cycle is normally longer than that of conventional welding and brazing processes.

2) High capital costs.

The need to apply heat and a high compressive force simultaneously in the restrictive environment of a vacuum or protective atmosphere requires specialized equipment. Equipment costs are usually high, and this can limit the maximum size of components that can be produced. Adequate nondestructive inspection techniques for quality assurance are not available, particularly those that assure design properties in the joint. Suitable filler metals and procedures have not yet been developed for all structural alloys.

3) Require fit-up preparation.

The faying surfaces and the fit of joint members generally require greater care in preparation than for conventional hot pressure welding or brazing processes. Surface smoothness may be an important factor in quality control in the case of diffusion brazing.

Applications

A wide variety of similar and dissimilar metal combinations may be successfully joined by diffusion welding and brazing. Most applications involve titanium, nickel, and aluminum alloys, as well as several dissimilar metal combinations. The mechanical properties of the joint depend on the characteristics of the base metals. For example, the relatively low creep strength and the solubility of oxygen at elevated temperatures contribute to the excellent properties of titanium alloy diffusion weldments.

Several industries use the diffusion welding process to advantage, particularly the aerospace industry. The engine mount of the space shuttle vehicle was designed to have 28 diffusion welded titanium parts, ranging from large frames to interconnecting box tubes. This structure is capable of withstanding three million pounds of thrust. Tubes 203 mm square were fabricated with diffusion welding in lengths up to 457 cm. The gas turbine industry has used diffusion welding to produce a Ti-6%A1-4%V component for an advanced high-thrust engine. This application marked the first production use of diffusion welding in a rotating engine component.

Cold welding

Cold welding is a solid-state welding process in which pressure is used to produce a weld at room temperature with substantial deformation at the weld.

A characteristic of the cold welding process is the absence of heat, either applied externally or generated by the welding process itself. A fundamental requisite for satisfactory cold welds is that at least one of the metals to be joined is highly ductile and does not exhibit extreme work-hardening. Both butt and lap joints can be cold welded.

Cold welding involves two concurrent steps: 1) distorting the contact surfaces of two ductile metals to rupture their surface oxide layers, thus exposing clean metal, and 2) applying enough pressure across those surfaces to allow interatomic bonding. The oxides and other surface contaminants become scattered as minute particles within the joint. Although most commonly used to join sheets of nonferrous metals such as aluminum and copper, cold welding also allows dissimilar metals and other shapes to be joined.

In all cases, however, the contacting surfaces must be clean of surface contaminants and then deformed sufficiently to force the surface oxides to rupture and intimate contact of the surfaces to be made. Since work hardening is inevitable, the joints are somewhat stronger than might be expected. When joining sheet metals these objectives can be accomplished with dies. The ends of bars also can be joined by using strong clamping shoes, powerful hydraulic forces and containment dies to deform the ends. Even tubes can be cold welded by positioning one tube inside the other and pulling them between a drawing die and a mandrel to cause the needed surface deformation.

Materials for Cold Welding

Materials with face-centered cubic (FCC) lattice structure are best suited for cold welding, provided they do not work-harden rapidly. Soft tempers of metals such as aluminum and copper are most easily cold welded. It is more difficult to weld cold worked or heat treated alloys of these metals. Other FCC metals that may be cold welded readily are gold, silver, palladium and platinum.

Joining copper to aluminum by cold welding is a good application of the process, especially where aluminum tubing or electrical conductor grade aluminum is joined to short sections of copper to provide transition joints between the two metals. Such cold welds are characterized by substantially greater deformation of the aluminum than the copper because of the difference in the yield strengths and work-hardening behaviors of the two metals.

Numerous dissimilar metals may be joined by cold welding, whether or not they are soluble in one another. In some cases, the two metals may combine to form intermetallic compounds. Since cold welding is carried out at room temperature, there is no significant diffusion between dissimilar metals during welding.

The alloying characteristics of the metals being joined do not affect the manner in which the cold welding operation is carried out. However, the interdiffusion at elevated temperatures can affect the choice of postweld thermal treatments and the performance of the weld in service.

Welds made between metals that are essentially insoluble in each other are usually stable. Diffusion can form an intermetallic compound at elevated service temperatures. In some cases, this intermetallic layer can be brittle and cause a marked reduction in the ductility of the weld. Such welds are particularly sensitive to bending or impact loading after an intermetallic layer has formed.

Surface Preparation

The contacting surfaces must be clean of surface contaminants. Dirt, absorbed gas, oils, (even fingerprints) or oxide films on the surfaces interfere with metal-to-metal contact and must be removed to obtain strong welds. Rotary brushes of 0.1 mm diameter stainless steel wire, brushing at a surface speed of about 15 m/s is recommended.

Chemical and abrasive cleaning methods are not satisfactory because the chemical residue or abrasive particles in or on the surface may prevent the formation of a sound weld.

Equipment

Pressure for welding may be applied to overlapped or butted surfaces with hydraulic or mechanical presses, rolls, or special manually or pneumatically operated tools. A hand tool of the toggle cutter type is suitable for very light work; common manually operated presses can be used for medium size work. Heavy work requires power operated machines. The rate of pressure application does not usually affect the strength or quality of the weld.

Pressure required to effect a weld depends on the working area of the dies. Pressures are generally slightly above the flow point of the material, and range from 186 to 276 MPa for aluminum, and from two to four times as much for copper. Time during which the pressure is applied is not critical; good welds can be made with either slow squeeze or impact. Hand welding by impact on an anvil is quite feasible, provided correct penetration of the die can be achieved.

Given a suitable arrangement of workpieces and dies, the application of pressure forces the work surfaces into close contact while the flow takes place, welding them solidly together. The work hardening that necessarily takes place is an advantage, because it tends to balance the loss in strength resulting from the decrease in the cross section.

The term cold welding is also applied to the selfdiffusion property of a material. For example, two sheets or strips of silver in contact with one another will adhere at temperatures ranging from 200 to 400°C at pressures up to 310 MPa. Lead and other materials have this same quality.

Applications

Cold welding is commonly used to produce butt joints in wire, tubing, and simple extruded shapes of like and unlike metals. A major application is in the manufacture of aluminum, copper, gold, silver, and platinum wire. The most common use is to join successive reels of wire for continuous drawing to smaller diameters. Diameters ranging from 0.06 to 12.7 mm have been successfully welded.

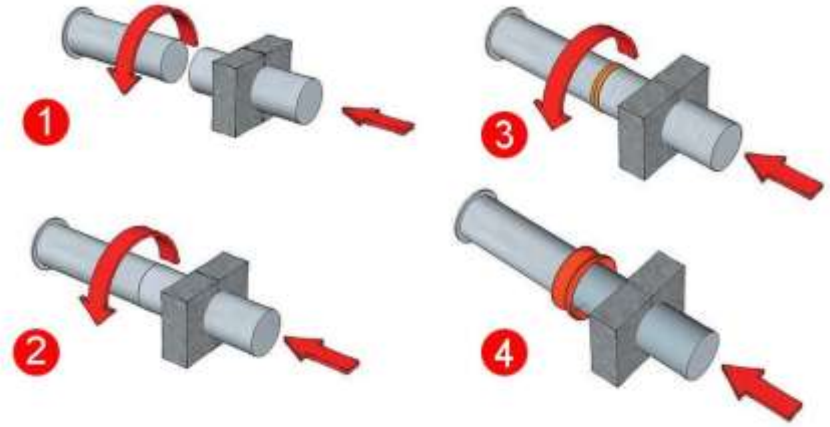
Lap welds can be used for joining aluminum sheet or foil to itself and also to copper sheet or foil. Commercial uses of lap welding include packaging applications, as well as electrical applications, which is probably the major use for cold welding. It is especially useful in the fabrication of electrical devices in which a transition from aluminum windings to copper terminations is required. The range of electrical applications covers large distribution transformers to small electronic devices. A variation of cold lap welding is applied to the sealing of commercially pure aluminum, copper, or nickel tubing.

Friction welding

A solid-state welding process that produces a weld under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces.

While considered a solid-state welding process, under some circumstances a molten film may be produced at the interface. However, even then the final weld should not exhibit evidence of a molten state because of the extensive hot working during the final stage of the process. Filler metal, flux, and shielding gas are not required with this process.

First, one workpiece is rotated and the other is held stationary (1). When the appropriate rotational speed is reached, the two workpieces are brought together and an axial force is applied (2). Rubbing at the interface heats the workpiece locally and upsetting begins (3). Finally, rotation of one of the workpieces stops and upsetting is completed (4).



The weld produced is characterized by a narrow heat-affected zone, the presence of plastically deformed material around the weld (flash), and the absence of a fusion zone.

Energy Input Methods

There are two methods of supplying energy in friction welding. Direct drive friction welding, sometimes called conventional friction welding, uses a continuous input. Inertia friction welding, sometimes called flywheel friction welding, uses energy stored in a flywheel.

Advantages

Friction welding, like any welding process, has its specific advantages and disadvantages. The following are some advantages of friction welding:

1) High skilled labor is not requiring.

Operators are not required to have manual welding skills. Surface cleanliness is not as significant, compared with other welding processes, since friction welding tends to disrupt and displace surface films. Plant requirements (space, power, special foundations, etc.) are minimal.

2) Dissimilar metal welding is available.

Friction welding is suitable for welding most engineering materials and is well suited for joining many dissimilar metal combinations.

3) High strength of the weld.

In most cases, the weld strength is as strong or stronger than the weaker of the two materials being joined. There are narrow heat-affected zones.

4) High production rate

The process is easily automated for mass production welding processes. Welds are made rapidly compared to other

5) Process is environmentally clean.

No filler metal is needed. Flux and shielding gas are not required. The process is environmentally clean; no arcs, sparks, smoke or fumes are generated by clean parts.

Limitations

1) In general, one workpiece must have an axis of symmetry and be capable of being rotated about that axis.

2) Preparation and alignment of the workpieces may be critical for developing uniform rubbing and heating, particularly with diameters greater than 50 mm.

3) Capital equipment and tooling costs are high.

4) Dry bearing and nonforgeable materials cannot

5) If both parts are longer than 1 m, special equipment required.

6) Free-machining alloys are difficult to weld.

Materials Welded

Friction welding can be used to join a wide range of similar and dissimilar materials, including: metals, some metal matrix composites, ceramics, and plastics. Specific weldability may depend upon a number of factors including specific alloy compositions, applicable process variation, component design, and service requirements.

Applications

Friction welded parts in production applications span the aerospace, agricultural, automotive, defense, marine, and oil industries. Everything from tong holds on forging billets to critical aircraft engine components are friction welded in production.

Automotive parts which are manufactured by friction welding include gears, engine valves, axle tubes, drive line components, strut rods and shock absorbers.

Hydraulic piston rods, track rollers, gears, bushings, axles and similar parts are commonly friction welded by the manufacturers of agricultural equipment. Friction welded aluminudcopper joints are in wide usage in the electrical industry. Stainless steels are friction welded to carbon steel in various sizes for use in marine drive systems and water pumps for home and industrial use. Friction welded assemblies are often used to replace expensive castings and forgings.

Friction stir welding

Friction stir welding is a variation of friction welding that produces a weld between two butted workpieces by the friction heating and plastic material displacement caused by a high speed rotating tool that traverses along the weld joint.

A solid phase, autogenous welding method introduced in 1991 that has been used successfully in welding the 2000, 5000, and 6000 series of aluminum sheet alloys.

Welding is accomplished by rotating a nonconsumable probe and entering it into the abutting edges of the sheets to be welded. The frictional heat generated between the tool and the workpieces produces plastic deformation, then the tool is moved along the joint. The base material fills in behind the probe to complete the weld. No melting occurs during the operation, so the process is solid phase in nature. For certain aluminum alloys, no shielding gas is required.

The joining of aluminum alloys, especially those that are often difficult to weld, has been the initial target for developing and judging the performance of friction stir welding. As the technology for this process is developed, its use will be applied to other materials.

Applications

Friction stir welding has potential applications in major industries such as aerospace, aluminum production, automotive, construction, rail car manufacturing, refrigeration, shipbuilding, and storage tanks and pressure vessels.

Boeing made a $15 million investment in the use of FSW to weld the booster core tanks for the Delta range of space launch vehicles, which was the first production FSW in the USA. The first launch of a FSW tank in Delta II rocket happened in August 1999. This process is currently being considered for the joining of aluminum–berilium alloys such as 2195 for the central tank of the Space shuttle, and also titanium alloys for other aeronautical uses.

Friction stir welding eliminated 60 percent of the rivets that small turbojet Eclipse 500 aircraft would have otherwise required (263 welds replaced more than 7 000 fasteners). Eclipse Aviation Corp. estimates that FSW reduces process time for assemblies by two-thirds; that is, stir welded assemblies will take 1.2 shifts to complete, versus 3.6 shifts for automatically riveted assemblies. Stir welding also eliminates rivet costs, as well as any handling and overhead costs associated with fasteners.

Advantages

1) The electromechanical machine tool equipment is energy efficient (a single pass 12.5 mm deep weld can be made in 6xxx alloy with a gross power of 3 kW), requires very little maintenance, and apart from welding tools and electric power, relies on no other consumable.

2) A high level of operator skill and training is not required.

3) The welding process requires neither filler metals nor weld pool shielding gas.

4) Special joint edge profiling is unnecessary.

5) Oxide removal immediately prior to welding is unnecessary.

6) The technique is ideally suited to automation.

7) If necessary, the welding operation can take place in all positions from flat to overhead.

Limitations

1) Single-pass welding speeds in some sheet alloys are slower than for some mechanized arc welding techniques.

2) The parts must be rigidly clamped against a backing bar to prevent weld metal breakout, if full penetrations are required.

3) At the end of each weld run a hole is left where the tool pin is withdrawn. In many cases it may be necessary to fill the hole by an alternative process, such as friction taper plug welding.

4) Run-on/run-off plates are necessary where continuous welds are required from one edge of a plate to the other.

5) Due to workpiece clamping and access requirements, applications where portable equipment could be used may be limited.

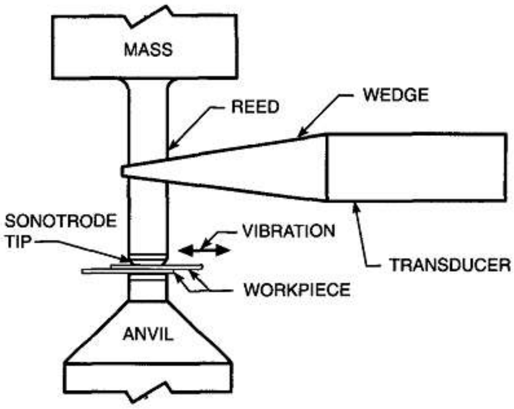
Ultrasonic welding

Ultrasonic welding is a solid-state welding process that produces a weld by the local application of high-frequency vibratory energy as the workpieces are held together under pressure.

Ultrasonic welding produces a sound metallurgical bond without melting the base metal. The basic force in ultrasonic welding is high-intensity vibrational energy. High- frequency electrical energy is converted to mechanical vibration, and a coupler (sonotrode) transmits the vibration to the work. An anvil counters the clamping force.

This process involves complex relationships between the static clamping force, the oscillating shear forces, and a moderate temperature rise in the weld zone. The magnitudes of these factors required to produce a weld are functions of the thickness, surface condition, and the mechanical properties of the workpieces.

Typical components of an ultrasonic welding system are illustrated below. The ultrasonic vibration is generated in the transducer. This vibration is transmitted through a coupling system or sonotrode. The sonotrode tip is the component that directly contacts one of the workpieces and transmits the vibratory energy into it. (The sonotrode is the acoustical equivalent of the electrode and its holder used in resistance spot or seam welding). The clamping force is applied through at least part of the sonotrode, which in this case is the reed member. The anvil supports the weldment and opposes the clamping force.



Applications

Ultrasonic welding is used to join both monometallic and bimetallic joints. The process is used to produce lap joints between metal sheets or foils, between wires or ribbons and flat surfaces, between crossed or parallel wires, and for joining other types of assemblies that can be supported on the anvil.

This process is being used as a production tool in the semiconductor, microcircuit, and electrical contact industries, for fabricating small motor armatures, in the manufacture of aluminum foil, and in the assembly of aluminum components. It is receiving acceptance as a structural joining method by the automotive and aerospace industries. The process is uniquely useful for encapsulating materials such as explosives, pyrotechnics, and reactive chemicals that require hermetic sealing but cannot be processed by high-temperature joining methods.

The most important application of the USW process is the assembly of miniaturized electronics components. Fine aluminum and gold lead wires are attached to transistors, diodes, and other semiconductor devices. Wires and ribbons are bonded to thin films and microminiaturized circuits. Diode and transistor chips are mounted directly on substrates. Reliable joints with low electrical resistance are produced without contamination or thermal distortion of the components.

Electrical connections, both single and stranded wires, can be joined to other wires and to terminals. The joints are frequently made through anodized coatings on aluminum, or through certain types of electrical insulation. Other current carrying devices, such as electric motors, field coils, harnesses, transformers and capacitors may be assembled with ultrasonically welded connections.

Broken and random lengths of aluminum foil are welded in continuous seams by foil rolling mills, with almost undetectable splices after subsequent working operations. Aluminum and copper sheet up to about 0.5 mm can be spliced together using special processing and equipment.

In structural applications, USW produces joints of high integrity within the limitations of weldable sheet thickness. An example is the assembly of a helicopter access door, in which inner and outer skins of aluminum alloy are joined by multiple ultrasonic spot welds.

Ultrasonic welding has reduced fabrication costs for some solar energy conversion and collection systems. An ultrasonic seam welding machine, operating at speeds up to 9 m/min, joins all connectors in a single row in a fraction of the time require for hand soldering or individual spot welding. Solar collectors for hot water heating systems consisting of copper or aluminum tubing can be welded at significantly lower energy cost than soldering, resistance spot welding, or roll welding.

Other applications include continuous seam welding to assemble components of corrugated heat exchangers, and welding strainer screens without clogging the holes. Beryllium foil windows for space radiation counters have been ring welded to stainless steel frames to provide a helium leak-tight bond. Pinch-off weld closures in copper and aluminum tubing used in refrigeration and air conditioning are produced with special serrated bar tips and anvils.

Process Variations

There are four variations of the process, based on the type of weld produced. These are spot, ring, line and continuous seam welding. In addition, two variants of ultrasonic spot welding are used in microelectronics.

In spot welding, individual weld spots are produced by the momentary introduction of vibratory energy into the workpieces as they are held together under pressure between the sonotrode tip and the anvil face. The tip vibrates in a plane essentially parallel to the plane of the weld interface, perpendicular to the axis of static force application. Spot welds between sheets are roughly elliptical in shape at the interface. They can be overlapped to produce an essentially continuous weld joint. This type of seam may contain as few as 2 to 4 welds/cm. Closer weld spacing may be necessary if a leaktight joint is required.

Ring welding produces a closed loop weld which is usually circular in form but may also be square, rectangular or oval. In this variation, the sonotrode tip is hollow, and the tip face is contoured to the shape of the desired weld. The tip is vibrated torsionally in a plane parallel to the weld interface. The weld is completed in a single, brief weld cycle.

Line welding is a variation of spot welding in which the workpieces are clamped between an anvil and a linear sonotrode tip. The tip is oscillated parallel to the plane of the weld interface and perpendicular to both the weld line and the direction of applied static force. The result is a narrow linear weld, which can be up to 150 mm long, produced in a single weld cycle.

In continuous seam welding, joints are produced between workpieces that are passed between a rotating, disk-shaped sonotrode tip and a roller type or flat anvil. The tip may traverse the work while it is supported on a fixed anvil, or the work may be moved between the tip and a counter-rotating or traversing anvil. Area bonds may be produced by overlapping seam welds.

The flow of energy through an ultrasonic welding system begins with the introduction of 60 Hz electrical power into a frequency converter. This device converts the applied frequency to that required for the welding system, which is usually in the range of 10 to 75 kHz.

The high-frequency electrical energy is conducted to one or more transducers in the welding system, where it is converted to mechanical vibratory energy of the same frequency. The vibratory energy is transmitted through the sonotrode and sonotrode tip into the workpiece. Some of the energy passes through the weld zone and dissipates in the anvil support structure.

For practical usage, the power required for welding is usually measured in terms of the high-frequency electrical power delivered to the transducer. This power can be monitored continuously and provides a reliable average value to associate with equipment performance as well as with weld quality. The product of the power in watts and welding time in deconds is the energy, in watt-seconds or joules, used in welding.

The energy required to make an ultrasonic weld can be related to the hardness of the workpieces and the thickness of the part in contact with the sonotrode tip.

Advantages and Limitations.

Ultrasonic welding has advantages over resistance spot welding in that little heat is applied during joining and no melting of the metal occurs. This process permits welding thin to thick sections, as well as joining a wide variety of dissimilar metals. Welds can be made through certain types of surface coatings and platings.

Ultrasonic welding of aluminum, copper and other high-conductivity metals requires substantially less energy than resistance welding. As compared to cold welding, the pressures used in USW are much lower, welding times are shorter, and thickness deformation is significantly lower.

A major disadvantage is that the thickness of the component adjacent to the sonotrode tip must not exceed relatively thin gauges because of the power limitations of present ultrasonic welding equipment. The range of thicknesses of a particular metal that can be welded depends on the properties of that metal.

Ultrasonic welding is limited to lap joints. Butt welds cannot be made in metals because there is no effective means of supporting the workpieces and applying clamping force. However, ultrasonic butt welds are made in some polymer systems.