NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE

(NAAC Accredited)

(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF MECHANICAL ENGINEERING

COURSE MATERIALS

ME366 ADVANCED METAL JOINING TECHNOLOGY

VISION OF THE INSTITUTION

To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2002

- ♦ Course offered : B.Tech in Mechanical Engineering
- ♦ Approved by AICTE New Delhi and Accredited by NAAC
- ♦ Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

Producing internationally competitive Mechanical Engineers with social responsibility & sustainable employability through viable strategies as well as competent exposure oriented quality education.

DEPARTMENT MISSION

1. Imparting high impact education by providing conductive teaching learning environment.
2. Fostering effective modes of continuous learning process with moral & ethical values.
3. Enhancing leadership qualities with social commitment, professional attitude, unity, team spirit & communication skill.
4. Introducing the present scenario in research & development through collaborative efforts blended with industry & institution.

PROGRAMME EDUCATIONAL OBJECTIVES

PEO1: Graduates shall have strong practical & technical exposures in the field of Mechanical Engineering & will contribute to the society through innovation & enterprise.

PEO2: Graduates will have the demonstrated ability to analyze, formulate & solve design engineering / thermal engineering / materials & manufacturing / design issues & real life problems.

PEO3: Graduates will be capable of pursuing Mechanical Engineering profession with good communication skills, leadership qualities, team spirit & communication skills.

PEO4: Graduates will sustain an appetite for continuous learning by pursuing higher education & research in the allied areas of technology.

PROGRAM OUTCOMES (POS)

Engineering Graduates will be able to:

1. **Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

2. **Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
3. **Design/development of solutions**: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
4. **Conduct investigations of complex problems**: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
5. **Modern tool usage**: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
6. **The engineer and society**: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
7. **Environment and sustainability**: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
8. **Ethics**: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
9. **Individual and teamwork**: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
10. **Communication**: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

11. **Project management and finance**: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
12. **Life-long learning**: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES (PSO)

PSO1: graduates able to apply principles of engineering, basic sciences & analytics including multi variant calculus & higher order partial differential equations..

PSO2: Graduates able to perform modeling, analyzing, designing & simulating physical systems, components & processes.

PSO3: Graduates able to work professionally on mechanical systems, thermal systems & production systems.

COURSE OUTCOMES

CO	Course Outcome
CO1	Gain knowledge on the principles of radiant energy metal joining process and design of joints
CO2	Enumerate principles of diffusion welding process and design of joints
CO3	Understand the basic principles of explosive welding and analyse the design, economics of the process and applications
CO4	Identify the principles of ultrasonic welding and apply the knowledge in economic considerations
CO5	Develop the concept of Plasma arc welding and design principles in welding joints
CO6	Explore the principle of friction stir welding and emphasize on the process and application of the same

COURSE MAPPING

	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3
CO1	**3**	**2**	**-**	**-**	**-**	**3**	**3**	**-**	**-**	**-**	**-**	**3**	3	3	3
CO2	**3**	**2**	**-**	**-**	**-**	**3**	**3**	**-**	**-**	**-**	**-**	**3**	3	3	3
CO3	**3**	**-**	**-**	**-**	**-**	**3**	**3**	**-**	**-**	**-**	**-**	**3**	3	3	3
CO4	**3**	**-**	**-**	**-**	**-**	**3**	**3**	**-**	**-**	**-**	**-**	**3**	3	3	3
CO5	**3**	**3**	**-**	**-**	**-**	**3**	**3**	**-**	**-**	**-**	**-**	**3**	3	3	3
CO6	**3**	**3**	**-**	**-**	**-**	**3**	**3**	**-**	**-**	**-**	**-**	**3**	3	3	3

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Course code	Course Name	L-T-P-Credits	Year of Introduction
ME366	ADVANCED METAL JOINING TECHNOLOGY	3-0-0-3	2016

Prerequisite : Nil

Course Objectives

- To expose the students to the fundamental concepts of advanced welding technologies and their relevance

Syllabus

Radiant energy welding, Electron beam and Laser beam welding, Plasma arc welding, Micro plasma welding, Magnetically impelled arc butt welding, Underwater welding, Explosive welding, Adhesive bonding, Friction welding, Friction stir welding, Friction stir processing, Diffusion welding, Cold Pressure welding, Ultrasonic welding, Vacuum brazing.

Expected outcome

- The students will be able to understand the advancements in welding technologies and processes, their significance, application areas etc. leading to the development of products and processes.

References Books:

1. ASM Metals Hand Book "Welding and Brazing", Vol. 6, ASM, Ohio, 1988.
2. Parmar R.S., "Welding Processes and Technology", Khanna Publishers, Delhi, 1998.
3. Parmer R. S., Welding Engineering and Technology", Khanna Publishers, 1997
4. Rossi, Welding Engineering, McGraw Hill, 1954.
5. Schwartz M.M., "Metals Joining Manual", McGraw-Hill Inc., 1979.
6. Udin et al., Welding for Engineers, John Wiley & Sons, New York, 1967.
7. Welding Engineers Hand Book- ASHE Vol . I, II, III and IV.

Course Plan

Module	Contents	Hours	End Sem. Exam Marks
I	Radiant energy welding: Electron Beam Welding- Background of the Process, Guns, Weld Environment, Welding in Different Degrees of Vacuum, Equipment and Safety, Joint Design, Applications, Laser Beam Welding, Physics of Lasers, Types of Lasers, Process Parameters, Applications and Limitations.	7	15%

II	Diffusion Welding- theory and Principle of Process, Key Variables, Intermediate Materials, Deformation Welding, Equipment and Tooling, Joint Design, Economics, Advantages and Limitations, Materials and Applications, Cold Pressure Welding- Process, Equipment and Setup, Applications	6	15%
FIRST INTERNAL EXAM			
III	Explosive Welding- theory and Key Variables, Parameters, Weld Quality, Equipment and Tooling, Advantages and Limitations, Joint Design, Materials and Applications, Adhesive Bonding- theory and Key Parameters, Physical Characteristics, Metal Adhesive, Equipment, Design, Economics of Process, Materials and Applications.	7	15%
IV	Ultrasonic welding-Principles of operation, Process Characteristics and Applications, Vacuum brazing- Theory, Mechanisms and Key Variables, Equipment and Tooling, Stop-Off and Parting Agents, Advantages, Limitations, Economics Materials and Applications.	6	15%
SECOND INTERNAL EXAM			
V	Plasma arc welding: Plasma Arc Welding- theory and Principles, Transfered arc and Non-Transferred arc Techniques, Equipment and Tooling, Joint Design Advantages, Disadvantages, Economics, Materials and Applications, Needle Arc Micro Plasma Welding - Characteristics of Process, Operating Characteristics, Fixturing and Joint Design, Shielding, Weld Penetration and Shape, Applications, Magnetically impelled arc butt (MIAB) welding, Under Water Welding- Wet and Dry Under Water Welding	8	20%
VI	Friction Welding- Basic Principles, Process Variants, Different Stages of Friction Welding, Mechanism of Bonding, Influence of Process Parameters, Weld Quality and Process Control, Joining of Dissimilar Materials, Advantages, Limitations and Applications, Friction Stir Welding-Metal flow phenomena, tools, process variables and applications, Friction Stir Processing- Process, Application	8	20%
END SEMESTER EXAM			

Question Paper Pattern

Maximum marks: 100 **Time: 3 hrs**

The question paper should consist of three parts

Part A

There should be 2 questions each from module I and II

Each question carries 10 marks

Students will have to answer any three questions out of 4 (3x10 marks =30 marks)

Part B

There should be 2 questions each from module III and IV

Each question carries 10 marks

Students will have to answer any three questions out of 4 (3x10 marks =30 marks)

Part C

There should be 3 questions each from module V and VI

Each question carries 10 marks

Students will have to answer any four questions out of 6 (4x10 marks =40 marks)

Note: Each question can have a maximum of four sub questions, if needed.

SAMPLE UNIVERSITY QUESTION PAPER

Reg No.:_______________ Name:__________________________

APJ ABDUL KALAM TECHNOLOGICAL UNIVERSITY

SIXTH SEMESTER B.TECH DEGREE EXAMINATION(R&S), MAY 2019

Course Code: ME366

Course Name: Advanced metal joining technology

Max. Marks: 100 Duration: 3 Hours

PART A

Answer any three full questions, each carries 10 marks. Marks

1	a)	List major components of an Electron Beam Welding Equipment	(2)
	b)	What are the different degrees of vacuum used in EBW ?	(3)
	c)	What are the classification of electron beam gun? Explain	(5)
2	a)	Draw schematic of a solid state laser beam and identify the parts	(5)
	b)	Explain laser beam hazards and safety measures taken in laser beam welding	(5)
3	a)	What is meant by deformation welding?	(2)
	b)	What are the factors affecting cold pressure welding?	(3)
	c)	List the advantages of diffusion welding	(5)
4	a)	Explain theory of diffusion welding	(5)
	b)	Describe the different techniques employed for cold pressure welding	(5)

PART B

Answer any three full questions, each carries 10 marks.

5	a)	With the help of a diagram, explain explosive welding procedure	(7)
	b)	List different types of explosives used in explosive welding	(3)
6	a)	With the help of a neat sketch, explain the working of Ultrasonic welding	(7)
	b)	List major process parameters of Ultrasonic welding	(3)
7	a)	Explain major adhesive bonding theories	(7)
	b)	List the conditions for satisfactory bonding in adhesive joining	(3)
8	a)	With the help of a neat sketch, explain vacuum brazing	(5)
	b)	Explain the advantageous and disadvantages of vacuum brazing	(5)

PART C

Answer any four full questions, each carries 10 marks.

9	a)	Differentiate between wet and dry underwater welding	(5)

	b)	Explain Needle Arc Micro Plasma welding	(5)
10	a)	Explain magnetically impelled arc butt welding process with a neat diagram	(6)
	b)	List advantages and disadvantages of MIAB welding	(4)
11	a)	Differentiate between plasma arc welding and TIG welding	(6)
	b)	Explain transferred and non-transferred arc techniques in plasma arc welding	(4)
12	a)	Explain different modes of friction welding	(5)
	b)	What are the major process parameters in friction welding?	(5)
13	a)	What are the major concerns in designing Friction weld joint?	(6)
	b)	List major application of friction welding	(4)
14	a)	Explain friction stir welding with the help of a neat sketch	(5)
	b)	Explain mechanism of bonding in friction stir welding	(5)

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Scheme of Valuation/Answer Key

(Scheme of evaluation (marks in brackets) and answers of problems/key)

APJ ABDUL KALAM TECHNOLOGICAL UNIVERSITY

SIXTH SEMESTER B.TECH DEGREE EXAMINATION, MAY 2019

Course Code: ME366

Course Name: Advanced metal joining technology

Max. Marks: 100 Duration: 3 Hours

PART A

		Answer any three full questions, each carries 10 marks.	Marks
1	a)	Electron gun, power supply unit, vacuum pumping system, workpiece handling device	(2)
	b)	Hard, medium and atmospheric vacuum	(3)
	c)	Classification of electron beam gun	(5)
2	a)	Diagram (4 marks) parts mention (1mark)	(5)
	b)	Any 5 hazards and its safety measures	(5)
	c)		( )
3	a)	Definition of Diffusion welding	(2)
	b)	Factors affecting cold pressure welding	(3)
	c)	Any 5 applications	(5)
4	a)	Figure (2) Explanation (3)	(5)
	b)	Different techniques employed in cold pressure welding	(5)
	c)		( )

PART B

Answer any three full questions, each carries 10 marks.			
5	a)	Diagram (3) Explanation (4)	(7)
	b)	Types of explosives	(3)
	c)		( )
6	a)	Diagram (3) Explanation (4)	(7)
	b)	3 Parameters (1 mark each)	(3)
	c)		( )
7	a)	Any 5 adhesive bonding theories	(7)
	b)	3 conditions (1 mark each)	(3)
	c)		( )
8	a)	Diagram (2) Explanation(3)	(5)
	b)	5 advantages, 5 disadvantages (0.5 marks each)	(5)
	c)		( )
PART C			
Answer any four full questions, each carries 10 marks.			
9	a)	Any 5 differentiation	(5)
	b)	Diagram(2) Explanation (3)	(5)
	c)		( )
10	a)	Diagram(2) Explanation(4)	(6)
	b)	4 advantages & 4 disadvantages (0.5 marks each)	(4)
	c)		( )
11	a)	Any 6 differentiation	(6)
	b)	Explanation	(4)
	c)		( )
12	a)	Any 5 modes and explanation	(5)
	b)	Process parameters of friction welding	(5)
	c)		( )
13	a)	Any 6 points and explanation	(6)
	b)	Any 8 applications (0.5 each)	(4)
	c)		( )
14	a)	Diagram(2) Explanation (3)	(5)
	b)	Explanation	(5)
	c)		( )

MODULE 1

RADIANT ENERGY METHODS

In radiant energy method, a stream of electrons or a beam of electromagnetic radiations is used to provide heat at the point of welding. Unlike the arc or gas welding processes, this process can be carried out in vacuum or at low pressure and hence the welds of highest quality can be produced.

ELECTRON BEAM WELDING

Principle:

This welding works on same principle of electron beam machining. This process uses kinetic energy of electrons to produce heat. This heat is further used to weld two welding plates. When a high jet of electrons strike at welding plates, its kinetic energy gets converted into heat energy. This heat energy is sufficient to fuse two metal plates together to form a weld joint.

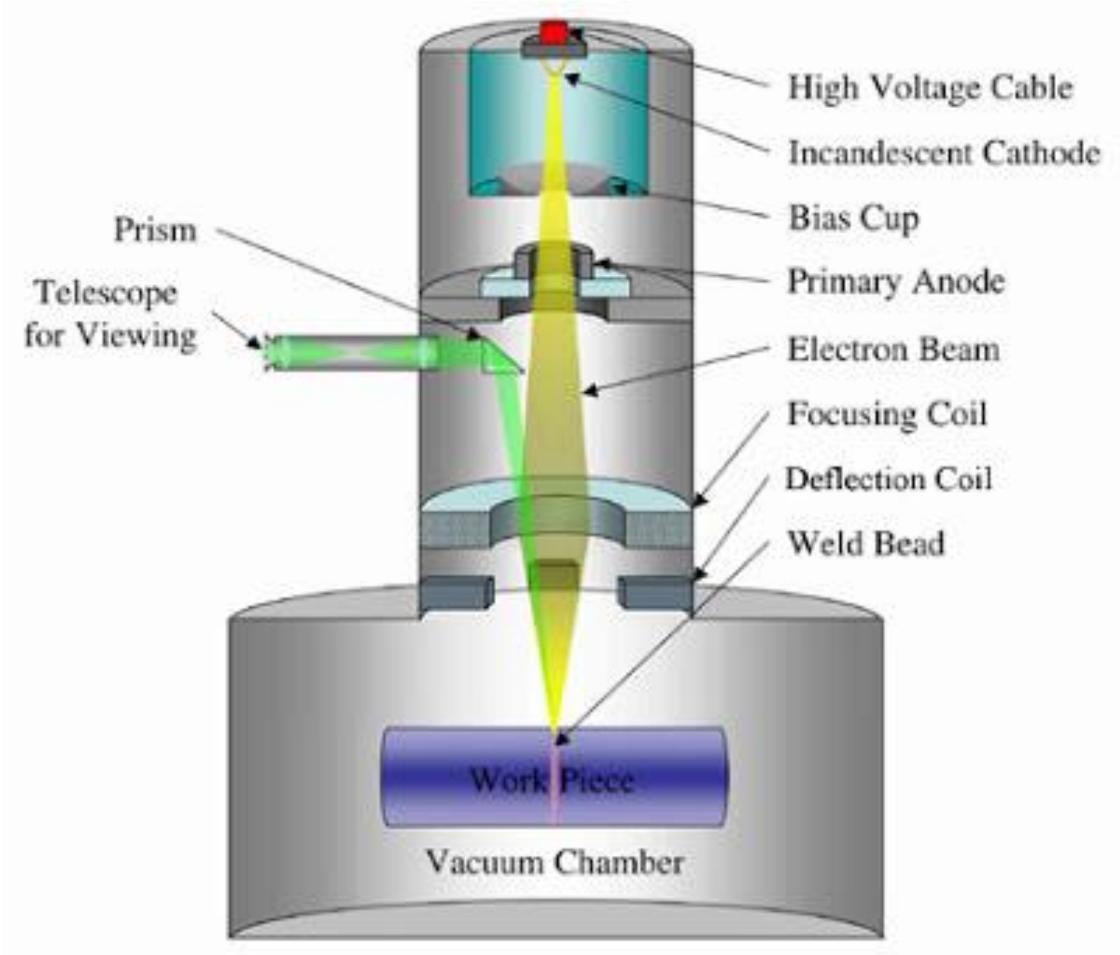
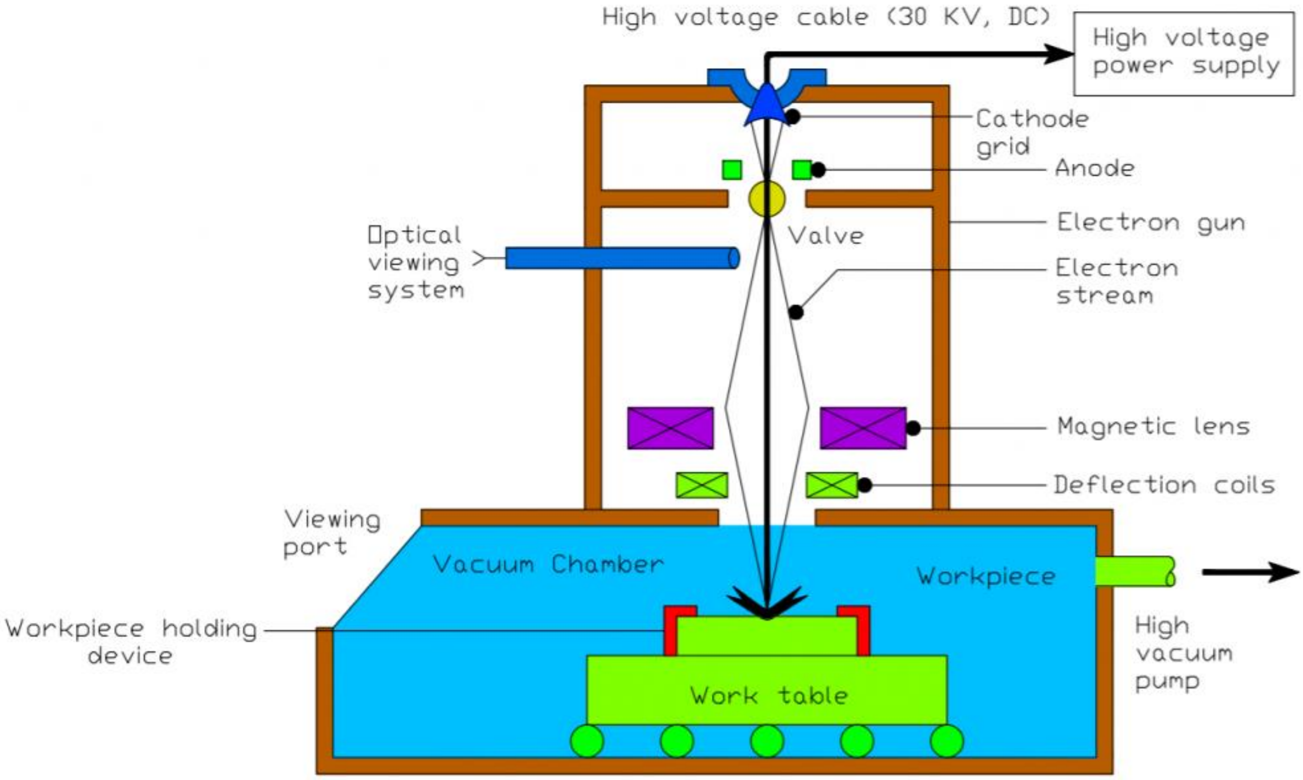


Fig. 1 EBW Machine



CONSTRUCTION OF ELECTRON BEAM WELDING MACHINE:

Electron Beam Welding Machine consists of following parts:

- *High Voltage Power Supply*
- *Electron Gun*
- *Cathode Grid*
- *Anode*
- *Optical Viewing System*
- *Magnetic Lens*
- *Deflecting Coil*
- *Vacuum chamber*
- *Workpiece*
- *Workpiece Holding Device*

Power Supply: This process uses a power source to supply continuous beam of electrons for welding process. The voltage range of welding is about 5 – 30 kV for low voltage equipment's or for thin welding and 70 – 150 kV for high voltage equipment's or for thick welding.

Electron Gun: It is heart of electron beam welding. It is a cathode tube (negative pole) which generates electrons, accelerate them and focus it on a spot. This gun is mostly made by tungsten or tantalum alloys. The cathode filament heated up to 2500 degree centigrade for continuous emission of electrons.

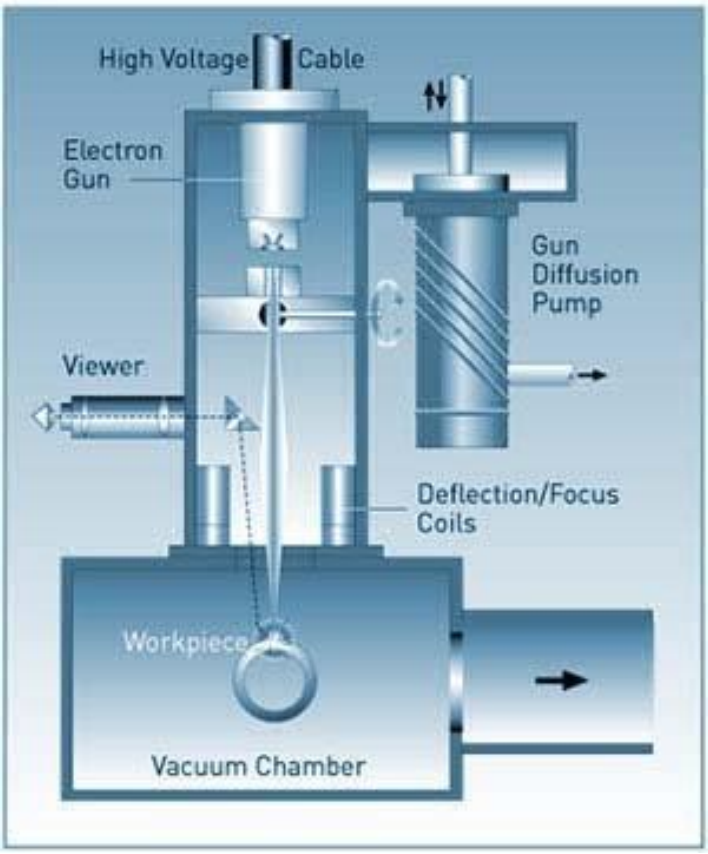
Anode: Anode is a positive pole which is just after the electron gun. Its main function is to attract negative charge, (in this case electron) provide them a path and don't allow them to diverge from its path.

Magnetic Lenses: There are a series of magnetic lenses which allows only convergent electrons to pass. They absorb all low energy and divergent electrons, and provide a high intense electron beam.

Electromagnetic lens and deflection coil: Electromagnetic lens used to focus the electron beam on work piece and deflection coil deflect the beam at required weld area. These are last unit of EBW process.

Work holding device: EBW uses CNC table for hold work piece which can move in all three direction. The welding plates are clamped on CNC table with the use of suitable fixtures.

Vacuum Chamber: Whole of this process takes place in a vacuum chamber. Vacuum Chamber helps to maintain high velocity of electron and also prevents chemical reactions at the time of welding. Vacuum is created by mechanical or electric driven pump. The pressure ranges in vacuum chamber is about 0.1 to 10 Pa.



DESCRIPTION OF MAIN COMPONENTS IN EBW MACHINE:

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The main components of the EBW gun include the cathode or the filament for emitting electrons, the electron accelerating system, beaming and focussing devices, the viewing or optics system, and the vacuum or work chamber incorporating work traversing system and sometimes seam-tracking devices are also included to ensure high quality defect-free welds. Fig. 14·2 gives a schematic representation of most of the components of a typical EBW gun.

14.2.1. The Cathode

The kinetic energy of electrons travelling at high speeds in vacuum being the source of energy in EBW, thus this process needs free electrons suitably concentrated and accelerated to provide sufficient energy to produce welding heat as they are suddenly stopped on hitting the work surface. This is done with the help of a filament which is also referred to as the cathode or the emitter.

The cathodes for EBW gun are mostly made from metals which are reasonably workable and have fairly low thermionic or *work function**. The metal must also be able to operate consistently in a vacuum and be durable. Unfortunately the highly efficient doped (thoriated or zirconated) cathodes cannot generally be used for EBW guns due to the imperfect vacuum conditions inherent to welding. Because of the high temperatures prevalent, metals with high thermionic functions must be used to avoid an emission of excess number of electrons. Tungsten filaments are usually employed because of their high melting point and high work function and also tungsten is less sensitive to contamination. The work functions of some of the relevant metals are given in Table 14·1.

Table 14·1 Work Functions of Metals

Metal	*Work function (electron volts)*
Aluminium	4·0
Barium	2·1
Copper	4·3
Iron	4·5
Nickel	5·0
Tungsten	4·5

The cathode may be either a directly heated or ribbon type filament or a rod or disc type filament indirectly heated by electron bombardment or induction heating. The cathode design affects the characteristics of the final beam spot produced on the work surface.

Directly heated wire or ribbon cathodes are typically formed in a hair-pin like shape which is heated by the passage of electric current through it. The heating current may be a.c. or d.c. though d.c. is preferred because the magnetic field created by the heating current can influence the direction of the beam. Current and voltage ratings of a filament power supply depend upon the type and size of the directly heated filament. For 0·5 mm diameter tungsten wire filaments the supply would be rated for 30 A at 20 V. Compared with wire filaments, ribbon type filaments provide much larger emitting area and the power supply rating may be 30 to 70 A at 5 to 10 volt. The coiled tungsten filament is heated to about 2300°C by the passage of the heating current. At this temperature the filament emits about 6×10^{18} electrons per second for each square centimeter of filament area.

The power supply for an auxiliary source for a typical indirectly heated emitter by bombardment would be 100 to 200 mA at several kilovolts. Lantanum hexaboride (LaB_6) is used in some of the indirectly heated cathodes as it is considered superior to all known high temperature cathodes in emission properties. These cathodes have sufficiently long service life of 250 to 300 hours under normal operating conditions. Lantanum hexaboride cathodes are raised to their working temperature of 1400 to 1650°C by tungsten heaters. Replaceable cathode mode of LaB_6 are available in different sizes viz., 3.0, 4.2 and 4·75 mm emitting surface diameters. These cathode sizes span a range of beam powers varying from a few watts to a maximum of about 12 KW.

14.2.2. Electron Accelerating System

The electrons leave the cathode surface in all directions with a range of initial velocities. Ideally, therefore, the cathode should be kept as small as possible consistent with its ability to pass the required current for heating. Precise controls of cathode geometry is important as change in its shape during use can change the path of the electrons which leave its surface. The randomly emitted electrons from the filament are given direction and speed by a cup-shaped electrode surrounding the emitter filament and accurately placed anode at a designed distance. This cup-shaped electrode surrounding the emitter, electrostatically shape the ejected electrons into a beam. In a diode type gun this beam-shaping electrode is often biased to a slightly more negative potential to control beam current flow. In the latter case the emitter alone is referred to as the cathode, and the beam-shaping electrode is called the bias electrode or the grid cup. A deep cup-shaped electrode is particularly effective in giving the stream of electrons an inward component of velocity so that the beam comes to a focus. The negative bias on the control electrode can be upto 3000 V though the usual range is 0 – 1000 volt and as this is infinitely variable, adjustment of bias voltage is a simple and convenient method of controlling the beam current.

The electrons emitted from the cathode do not possess adequate energy to generate required heat for welding the metal. The mass of the electron being fixed its kinetic energy ($^1/_2\, mv^2$) can be increased only by increasing its velocity and this is done by applying a very high potential difference between the cathode and the anode. The speeds of the accelerated electrons in the electron beam range between 50,000 and 2,00,000 km/sec, depending upon the applied voltage. These accelerated electrons in the form of a beam pass through a small hole in the centre of the anode and travel towards the workpiece.

Two ranges of voltage, low and high are used. In the low voltage system the difference between the anode and the cathode is usually 15 to 30 KV, while a range of 70 to 150 KV is common for high voltage units. The

14.2.3. Beam Focussing System

After passing through the accelerating anode, the electrons travel at a constant velocity. Since all the electrons are negatively charged they repel each other causing the beam to spread and thus the energy density of the beam decreases. In order to produce a beam of high energy density it must be focussed to a fine point of concentration. Focussing of EB can be achieved by a magnetic lens through electromagnetic shifting of beam. The electromagnetic lens includes a coil encased in iron casing with windows cut appropriately. The electromagnetic deflection system used in EBW guns are capable of deflecting the beam through a precisely selected distance and can position it exactly at the desired spot on the weld line. A typical electromagnetic deflection system is made up of four coils arranged in two pairs in which the coils are connected in series and make an angle of 180° with each other. By varying the current flowing through the coils, it is possible to position the beam at any point.

As a method of obtaining a high energy density beam and improving the energy distribution over the beam cross-section some systems include an aperture diaphragm between the accelerating or field anode and the electromagnetic focussing lens to cut out the peripheral part of the beam which has a minimal energy density. The gun, therefore, contains magnetic coils which deflect the electrons towards the central longitudinal axis of the beam. By controlling the current flowing in the focussing coils the strength of the magnetic field can be controlled and by doing so the beam can be focussed to a diameter of about 0·5 mm. With such a small diameter beam it is of utmost importance that the beam should be accurately aligned with the joint to be welded. This can be done by providing a viewing system fitted into the walls of the EBW gun column or the chamber containing it.

14.2.4. Weld Viewing System

The majority of chambers are fitted with devices for optical viewing of the weld at a suitable magnification. It is important that the line of sight should be as near as possible co-axial with the electron beam. This will enable the operator to set the small beam spot accurately on the weld line for welding and afford the possibility of seeing into the inaccessible positions.

The welding operation inside the chamber may also be observed by direct viewing through lead glass windows. The effectiveness of this technique however depends upon the distance between the operator and the point of welding as well as the shape of the workpiece. When direct viewing is not possible then optical viewing system may be incorporated to give the operator a magnified view of the weld seam. This latter system may be used for setup operation, sharp focussing of the beam at the desired point, alignment of the electron beam with respect to the weld line and for visual inspection of the final weldment.

The latest viewing system is based on the use of closed-circuit television. The light source and the television camera may be mounted outside the work chamber to shield the viewing equipment from the ill effects of weld spatter and metal vapour deposition. This system allows continuous monitoring of welds with minimum exposure to the intense light from the welding zone.

14.2.5. Vacuum Chamber

The electron beam is required to reach the workpiece placed in the welding chamber to affect the necessary welding. If the electrons are projected into the normal atmosphere they lose all their kinetic energy in collision with atoms and molecules of oxygen and nitrogen. Thus it is imperative to operate in a vacuum at a pressure of 10^{-4} to 10^{-2} torr (0·013 to 1·3 N/m^2) if the beam is to travel any distance; the normal atmospheric pressure is 760 torr, that is 9·88 $\times 10^4$ N/m^2. The vacuum requirement may often be as low as 10^{-7} that of the standard atmospheric pressure; the systems required to reach that vacuum are obviously costly and complex. To achieve this extreme vacuum two pumps are used; a mechanical roughing pump and a diffusion pump. The roughing pump reduces the chamber pressure to about 0·1 torr (13 N/m^2).

The gas that is still left after attaining the rough vacuum of 0·1 torr is pumped out with the help of a diffusion pump by the oil vaporising process. In this process the oil is heated in the diffusion pump until it evaporates. It is then ejected at a high speed through a venturi system which entraps the gases. The gas is then discharged by a mechanical pump into the external atmosphere. Finally the vaporised oil is condensed and channelled back to the diffusion pump. It is imperative to prevent even the smallest amount of leakage. Rubber or plastic gaskets are inadequate therefore all joints are butt welded.

The material from which the vacuum chamber is fabricated must provide a smooth, non-corroding interior surface that out-gases quickly and contains the X-rays generated during the process. Polished stainless steel provides an ideal surface but due to its high cost it is used only for small chambers while the bigger ones are fabricated from suitably coated mild steel plates. Stainless steel, clad steel, tinned steel or even epoxy coated mild steel are often employed. For high voltage, above 60 KV, EB guns additional protection from X-rays is usually provided in the form of lead coating on the outside. The viewing windows are also provided an extra layer of lead glass for X-ray

14.2.6. Work Traversing System

For short length joints it may be possible to complete the weld by moving the beam through focussing coils, rather than the work; this eliminates the mechanical traverse systems. Current flowing in the focussing coils is programmed to direct the beam along a predetermined path.

The maximum beam deflection is relatively small, thus for majority of work the gun and the component must be moved relative to each other. In general, it is convenient to move the work using a motor mounted outside the chamber. For lubricating the traversing gear, located inside the vacuum chamber, it is imperative to use dry lubricants as normal greases and oils evaporate and contaminate the chamber.

High continuous production rates can be achieved with small parts by dial feeding devices having a number of small chambers which are slid in turn under the electron gun column as shown in Fig. 14.2A. For longer welds which cannot be accomodated in the chamber a small work chamber may be moved over the surface of the work by employing a sliding or stepping seal. Productivity can also be improved by using two EBW guns having separate work chambers operated alternatively from the same power source.

A recent trend has been to use EBW units fitted with work dispensers so that several workpieces can be welded consecuitively during a single pumping cycle. The dispenser is essentially a rotating table having provision for mounting several workpieces. As a rule this type of dispenser is used in units which weld caps, ports and similar components to cylindrical workpieces. Such welding units have high rate of production.

14.2.7. Seam Tracking Methods

Apart from being an automatic process, EBW has some special characteristics which necessitate the use of seam tracking devices to achieve accurate welds. The special characteristics include a very small beam spot producing a narrow bead, high welding speed, high heat density and the inaccessibility of the workpiece due to its placement in a vacuum chamber.

Direct optical viewing of welding and manual correcting for deviation in the joint path is, at best, a difficult task though it is practiced sometimes where possible.

There are two methods of maintaining beam position for a non-linear weld joint. The first method involves programming by analog means or continuous path numerical control and is employed if the parts are machined precisely and placed accurately in position before welding. The second method employs an adaptive electro-mechanical control using tracking device that follows the weld line and provides feedback to the controls to adjust the work or gun position to keep the beam on the desired path. Both these seam tracking devices can be used in conjunction with record-and-playback device that allows the joint configuration to be traced and its location recorded. The weld joint can, then, be made using playback programmed control of the beam or work position.

WORKING:

Its working can be summarized as follow.

- First the electron gun, which is a cathode, produces electrons. These electrons move towards anode which is positive charged and placed right after electron gun.
- The anode accelerates the electrons and forms a electron jet which is further move towards magnetic lenses.
- The magnetic lenses are a series of lenses which are used to absorb low energy electrons and does not allow to divergent electron to passes through it. It provides a high intense electron jet.
- Now this electron beam passes through electromagnetic lens and defecting coil which are used to focus and deflect the electron beam at the required spot. This unit direct high velocity electron beam to the weld cavity where its kinetic energy converts into heat energy due to collision. This heat energy is used to create weld by fusion. This whole welding process carried out in a vacuum chamber otherwise the electrons collides with air particle in the way and loses its energy.

APPLICATION:

- It is used in aerospace industries and marine industries for structure work
- It is used to join titanium and its alloy.
- This type of welding is widely used to join gears, transmission system, turbocharger etc. in automobile industries.
- It is used to weld electronic connectors in electronic industries.
- This process is also used in nuclear reactors and in medical industries

ADVANTAGES AND DISADVANTAGES:

Advantages:

- It can weld both similar and dissimilar metals.
- It provides high metal joining rate.
- Low operating cost because no filler material and flux are used.
- It provide high finish welding surface.
- It can used to weld hard materials.

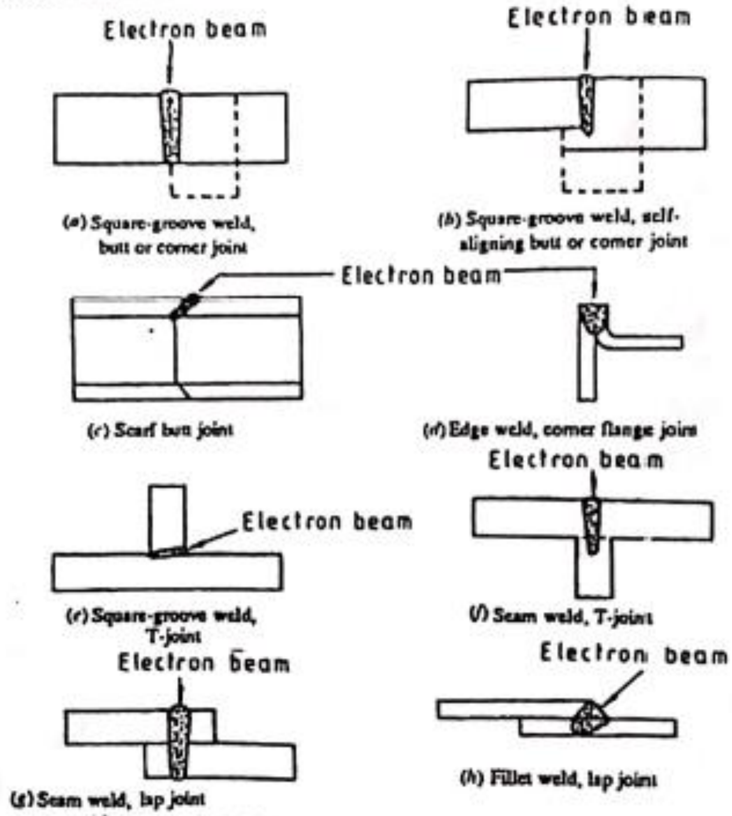
- Less welding defects occur due to whole process carried out in vacuum.

Disadvantages:

- High capital or set up cost.
- High skilled labor required.
- Frequently maintenance required.
- Work pieces size is limited according to vacuum chamber.
- It cannot do at site due to vacuum.

Weld Joint Design and Preparation for EBW:

- The joints commonly made by EBW process, as shown in Fig. 14.11, include butt, corner, lap, edge and Tee types or their modifications to suit particular applications, using square edge preparation.
- Normal fillet welds are difficult to weld and, thus, are usually avoided.



14-11 Typical joint designs for EBW (After AWS Handbook)

- Square butt edge preparation demands the use of fixtures to keep the work components in the required alignment; however when fixtures are to be avoided the joint may be modified to rabbet type as shown in Fig. (b). That also ensures self aligning.
- If the weld metal area is to be increased, as in the case of joining thin pipes, the edges may be scarfed. However, scarf edge preparation and fit-up is more difficult to make. Edge, seam and lap fillets are primarily used for joining sheet metal only.

Note:-

- Contamination of the weld metal is likely to cause porosity or and cracking as well as deterioration of mechanical properties. It is, therefore, imperative to clean the joint thoroughly before fit-up and alignment. Acetone is a preferred solvent for cleaning the components for EBW; however acetone being highly inflammable needs to be handled very carefully.

- Normally in EBW it is aimed to use no filler metal, the weld joint is, therefore, chosen accordingly. However, sometimes filler metal is added to fill the joint during a second or cosmetic pass to provide a full thickness. Filler wire feeding equipment is usually similar to the one employed for gas tungsten arc welding though specific needs may necessitate the use of specially designed units for use in vacuum chambers. Filler wire diameters are generally small with a maximum of about 0-5 mm and the wire is fed into the leading edge of the small weld pool.

- Sometimes filler metal may be added to achieve the desired physical or metallurgical characteristics of the weld metal; the characteristics so controlled may include ductility, tensile strength, hardness and resistance to cracking. The addition of small amount of aluminum wire or shim, for example, can result in the production of killed steel and that reduces porosity.

Variants of EBW Process

High vacuum EBW is a low production and a high cost process. Thus, it is employed for welding very critical components mainly of reactive metals. There are two variants or modes of the main process viz.,

1. Medium vacuum EBW
2. Non-vacuum EBW.

1. Medium Vacuum EBW:

- While high vacuum EBW is carried out at a pressure range of 10^{-3} to 10^{-6} torr, medium vacuum EBW employs a pressure range of 10^{-3} to 25 torr. Within these limits the pressure range between 10^{-3} and 1 torr is referred to as 'soft or partial vacuum' and from 1 to 25 torr it is called 'quick vacuum'.
- The medium vacuum process retains most of the advantages of high vacuum welding and with improved production capability.
- In a medium vacuum EBW gun the beam is generated in high vacuum and then projected into the welding chamber with soft or quick vacuum, as shown in Fig.
- This is accomplished through an orifice which is large enough for the beam to pass but does not allow significant back diffusion of gases from chamber to the gun column.

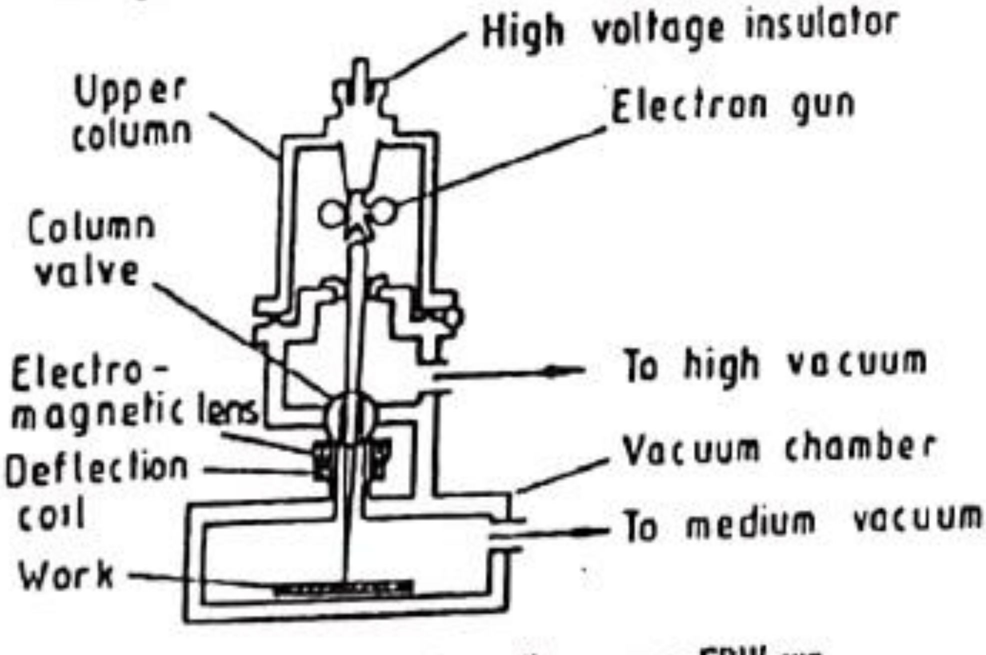


Fig. 14.14 Schematic of a medium vacuum EBW gun

- A major advantage of the medium vacuum EBW is that the requirement for vacuum pumping are considerably reduced resulting in high gains in commercial and economic terms.
- This variant is ideally suited for mass production tasks, for example, gears can be successfully welded to shafts in their final machined condition without involving any subsequent finishing operation while maintaining close tolerances.

2. Non-Vacuum EBW:

- Non-vacuum welding is done at atmospheric pressure though the EB gun must be held at a pressure of 10^{-4} torr or less for stable and efficient welding.
- The EB in non-vacuum welding is brought out of the vacuum system through a series of evacuated chambers with small apertures, as shown in Fig. in such a way as to minimise the flow of atmospheric gases into the gun column.
- The work chamber may be filled with helium as it offers less obstruction to the EB and gives better penetration shape than obtained with argon or air as atmosphere. Also, for a given penetration and gun-to-work distance helium shielding permits welding at a significantly higher welding speed.

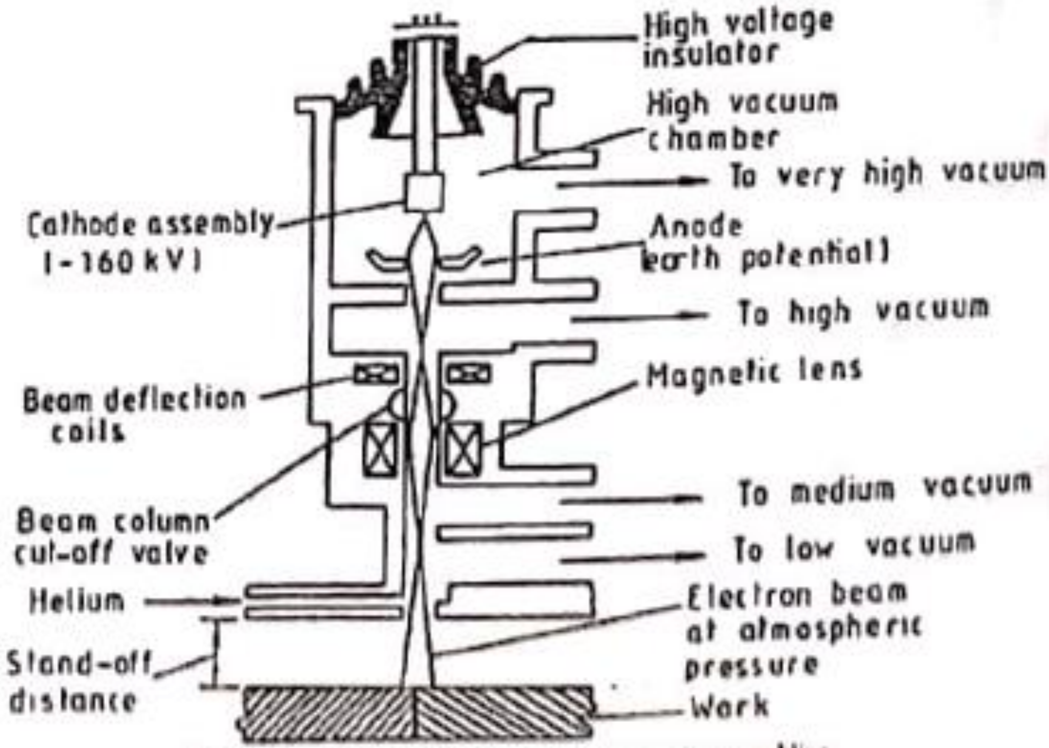


Fig. 14.15 A setup for non-vacuum electron beam welding

- The higher the accelerating voltage the further the beam travels in gas at atmospheric pressure and voltages of 150 to 175 KV are used.
- Apart from the accelerating voltage, beam power, travel speed, gun to work distance, and the shielding gas are important process variables. Fig. shows weld penetration as a function of travel speed for three different power levels of a non- vacuum EBW indicating the significant increase in travel speed by increasing power for a given penetration.

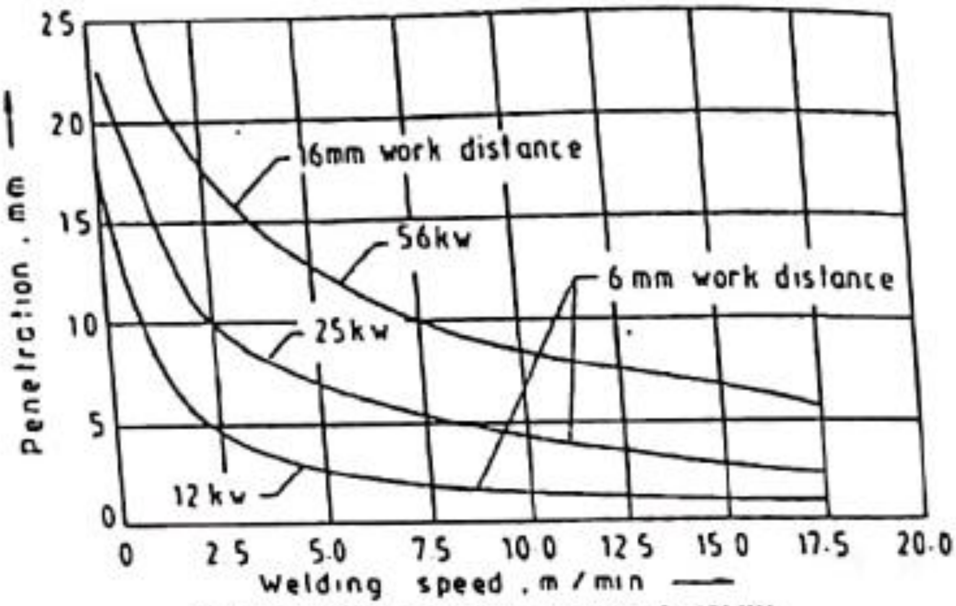


Fig. 14-16 Welding speed versus penetration for 175 KV non-vacuum electron beam welding gun.

- Non- vacuum EBW shows more penetration at power level above 50 KW which has made it possible to weld steel of over 25 mm thickness with keyhole type of penetration which is characteristic of EBW; this also helps in welding at speeds many times more than those feasible with submerged arc welding.

- The main advantage of non-vacuum system is that work is allowed to remain at atmospheric pressure and that leads to higher production rates with reduced costs. Also, the size of the weldment may not be limited by the chamber. However, these advantages are gained at the expense of low weld depth to width ratios, reduced weld penetration and small gun-to-work distances.

- The materials that can be welded by non-vacuum EBW system include carbon, low alloy, and stainless steels, high temperature alloys, refractory alloys as well as copper and aluminum alloys. Some of these metals can be welded in air while others need inert atmosphere usually obtained by the use of argon or helium as the shielding gas.

Weld Characteristics and Quality of EBW

- Due to high penetration-to-width ratios of EB welds two distinct advantages accrue, viz., relatively thick plates can be welded in a single pass and welding speeds much higher than those attainable in arc welding can be used.

- A number of metals can be welded to give a depth-to-width ratio of upto 50. Using square edge preparation, aluminum plates upto 450 mm thick can be welded in a single pass though in steel the corresponding thickness is usually limited to 300 mm.

- The high vacuum EBW process is an excellent tool for welding dissimilar metals of different thicknesses as well as for repair welding of components impossible to salvage by other processes. Generally no preheat is required even for welding, high conductivity materials, with EBW.

- Although EBW is a high power density process yet the energy input per unit length is low as is evident from table. This characteristic of the process leads to two advantages viz., it reduces the size of the heat affected zone and minimizes distortion. The weld metal in EB welds has mechanical properties normally similar to those of base metal.

LASER-BEAM WELDING (LBW)

LASER-BEAM WELDING (LBW) uses a moving high-density (10^5 to 10^7 W/cm^2, or 6 × 10^5 to 6 × 10^7 W/in.^{2}) coherent optical energy source called a laser as the source of heat. "Laser" is an acronym for "Light Amplification by Stimulated Emission Of Radiation." The coherent nature of the laser beam allows it to be focused to a small spot, leading to high energy densities.

Lasers have been promoted as potentially useful welding tools for a variety of applications. Until the 1970s, however, laser welding had been restricted to relatively thin materials and low speeds because of the limited continuous power available. By 1965, a variety of laser systems had been developed for making micro welds in electronic circuit boards, inside vacuum tubes, and in other specialized applications where conventional technology was unable to provide reliable joining. The availability of high-power continuous-wave (CW) Carbon Dioxide (CO2) and Neodymium -Doped Yttrium Aluminum Garnet (Nd:YAG) lasers and the limitations of current welding technology have promoted interest in deep penetration welding in the past 20 years using these devices. The ability of the laser to generate a power density greater than 106 W/cm2 (6 × 106 W/in.2) is a primary factor in establishing its potential for welding (Table 1). Numerous experiments have shown that the laser permits precision (that is, high quality) weld joints rivalled only by those made with an electron beam.

Table 1

WELDING PROCESS	**INTENSITY OF ENERGY SOURCE**		**JOINING EFFICIENCY, MM^2/KJ**	**FUSION ZONE PROFILE**
	w/cm^2	**w/in.^{3}**		
OXYACETYLENE (OAW)	10^2-10^3	6 × 10^2-6 × 10^3	0.2-0.5	SHALLOW FOR SINGLE PASS
ARC WELDING	5 × 10^2-10^4	3 × 10^3-6 × 10^4	0.8-2$^{(A)}$ 2-3$^{(B)}$ 4-10$^{(C)}$	SHALLOW FOR SINGLE PASS
PLASMA ARC (PAW)	10^3-10^6	6 × 10^3-6 × 10^6	5-10	SHALLOW AT LOW-ENERGY END DEEP PENETRATION AT HIGH-ENERGY END
LASER BEAM	10^5-10^7	6 × 10^5-6 × 10^7	15-25	SHALLOW AT LOW-ENERGY DENSITY RANGE DEEP PENETRATION AT HIGH-ENERGY DENSITY RANGE
ELECTRON BEAM	10^5-10^8	6 × 10^5-6 × 10^8	20-30	DEEP PENETRATION

(A) GAS-TUNGSTEN ARC WELDING (GTAW).
(B) GAS-METAL ARC WELDING (GMAW).
(C) SUBMERGED ARC WELDING (SAW)

Types of laser Beam

Types of lasers include gas, liquid and solid.

1. Gas lasers excite the electrons in gases, such as helium, neon, carbon dioxide nitrogen.
2. Liquid lasers include the dye laser, which uses organic dye molecules in liquid form to produce a wavelength of radiation that can be tuned.
3. Solid lasers include the ruby laser, which uses a precious stone to produce a beam of red light.

Penetration Laser Welding

- At high power densities all materials will evaporate if the energy can be absorbed. Thus, when welding in this way a hole is usually formed by evaporation
- This "hole" is then traversed through the material with the molten walls sealing up behind it
- The result is what is known as a "keyhole weld. This is characterized by its parallel sided fusion zone and narrow width .

Fig:- Laser beam Penetration

Working principle

- In general cases heat is required to fuse the metals for any types of welding.
- It works on the principle that when electrons of an atom gets excited by absorbing some energy. And then after some time when it returns back to its ground state, it emits a photon of light. The concentration of this emitted photon increased by stimulated emission of radiation and we get a high energy concentrated laser beam.

- In laser beam welding process the heat is obtained from the application of a concentrated coherent light beam which is striking upon the weld metal and melts the metal, such this weld joint is obtained, this welding process is called laser welding.

- First, the setup of welding machine at the desired location (in between the two metal pieces to be joined) is done.
- After setup, a high voltage power supply is applied to the laser machine. This starts the flash lamps of the machine and it emits light photons. The energy of the light photon is absorbed by the atoms of ruby crystal and electrons get excited to their higher energy level. When they return back to their ground state (lower Energy state) they emit a photon of light. This light photon again stimulates the excited electrons of the atom and produces two photons. This process keeps continue and we get a concentrated laser beam.

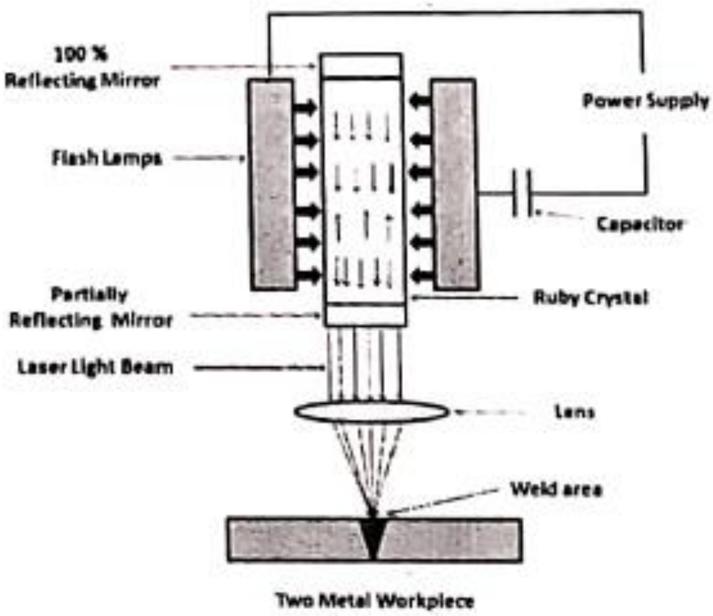


Fig:- Laser beam welding

- This high concentrated laser beam is focused to the desired location for the welding of the multiple pieces together. Lens is used to focus the laser to the area where welding is needed. CAM is used to control the motion of the laser and work piece table during the welding process.

- As the laser beam strikes the cavity between the two metal pieces to be joined, it melts the base metal from both the pieces and fuses them together. After solidification, we get a strong weld.

Main parts of LBW

1. Laser Machine: It is a machine that is used to produce a laser for welding. The main components of the laser machine are shown below.
2. Power Source: A high voltage power source is applied across the laser machine to produce a laser beam.
3. CAM: It is a computer-aided manufacturing in which the laser machine is integrated with the computers to perform the welding process. All the controlling action during the welding process by laser is done by CAM. It speeds up the welding process to a greater extent.
4. CAD: It is called as Computer-aided Design. It is used to design the job for welding. Here computers are used to design the workpiece and how the welding is performed on it.
5. Shielding Gas: A shielding gas may be used during the welding process in order to prevent the w/p from oxidation.

Characteristics of Laser Beam Welding

- The power density of laser beam welding is high. It is of the order 1 MW/cm^2. Because of this high energy density, it has small heat-affected zones. The rate of heating and cooling is high.
- The laser beams produced are coherent (having the same phase) and monochromatic (i.e. having the same wavelength).
- It is used to weld smaller sizes spot, but the spot sizes can vary from .2mm to 13 mm.
- The depth of penetration of the LBW depends upon the amount of power supply and location of the focal point. It is proportional to the amount of power supply. When the focal point is kept slightly below the surface of the work piece, the depth of penetration is maximized.
- Pulsed or continuous laser beams are used for welding. Thin materials are weld by using millisecond-pulses and continuous laser beams are used for deep welds.

Precise part fit-up and alignment are much more critical in laser welding than in ordinary arc welding. The typical focal spot diameter for a laser beam ranges from 100 to 1000 μm (0.004 to 0.040 in.). In addition, capital cost for laser welding devices is almost 10 times more expensive than comparable power arc welding systems. On the other hand, laser welding can provide much higher throughput relative to conventional arc welding. When the capital cost of laser-beam welding is compared to electron-beam welding (EBW), laser-beam welding becomes the more cost-effective of the two processes because no vacuum enclosure is necessary for laser-beam welding. The penetration depth obtained in laser welding is less than that observed in electron-beam welding. The maximum thickness of type 304 stainless steel plate that can be welded using a 77 kW (105 hp) CO2 laser is 50 mm (2 in.) whereas EBW can produce welds in type 304 stainless steel up to everal inches in thickness. However, the penetration depth of EBW extends only a relatively short distance under atmospheric pressure. Welding under a vacuum is required to obtain optimum efficiency in EBW. A laser beam, however, can be transmitted an appreciable distance through the atmosphere without serious attenuation or optical degradation because of its coherent nature. Laser-beam welding thus offers an easily maneuverable, chemically clean, high intensity, atmospheric welding process with narrow HAZ and subsequent low distortion. Peak penetration, p_{max}, for LBW is defined by:

$$P_{MAX} \propto P^{0.7}$$

Where, P is the power (in watts). In terms of weld width (w) and depth (d), both conduction-mode welding and deep-penetration welding can be obtained with lasers.

ADVANTAGES AND LIMITATIONS OF LBW

Laser welding offers the following advantages

- Light is inertialess (hence, high processing speeds with very rapid Stopping and starting become possible).
- Focused laser light provides high energy density.
- Laser welding can be used at room atmosphere.
- Difficult-to-weld materials (for example, titanium, quartz, etc.) Can be joined.
- Workpieces do not need to be rigidly held.
- No electrode or filler materials are required.
- Narrow welds can be made.
- Precise welds (relative to position, diameter, and penetration) can be obtained.
- Welds with little or no contamination can be produced.
- The heat-affected zone (HAZ) adjacent to the weld is very narrow.
- Intricate shapes can be cut or welded at high speed using automatically controlled light deflection techniques.
- The laser beam can also be time shared.

MODULE 2

SOLID STATE WELDING

Solid State Welding (SSW) processes are those that produce coalescence of the faying surfaces at temperatures below the melting point of the base metal being joined without the addition of brazing or solder filler metal. Pressure may or may not be applied. These processes involve either the use of deformation or of diffusion and limited deformation in order to produce high-quality joints between both similar and dissimilar materials. Dissimilar metal joints are necessary in applications that require a variety of material properties within the same component. For example, heat exchangers often require different types of stainless steels at each end, because of temperature-induced corrosion. Under laboratory conditions, dissimilar materials can be chosen based on physical or material properties that influence the phenomenon being studied. In any Solid-State (Non-melting) Welding Process, there are two primary areas of concern: Will the materials bond and how strong is the bond?

DIFFUSION BONDING

Diffusion Bonding or Diffusion Welding is only one of many solid-state joining processes wherein joining is accomplished without the need for a liquid interface (brazing) or the creation of a cast product via melting and re-solidification (welding). In its most narrow definition, which is used to differentiate it from other joining processes such as deformation bonding or transient liquid phase joining, diffusion bonding (DB) is a process that produces solid-state coalescence between two materials under the following conditions:

- Joining occurs at a temperature below the melting point, ***T*M**, of the materials to be joined (usually >1/2***T*M**).
- Coalescence of contacting surfaces is produced with loads below those that would cause macroscopic deformation to the part.
- A bonding aid can be used, such as an interface foil or coating, to either facilitate bonding or prevent the creation of brittle phases between dissimilar materials, but the material should not produce a low temperature.

Thus, diffusion bonding facilitates the joining of materials to produce components with no abrupt discontinuity in the microstructure and with a minimum of deformation. The DB process, that is, the application of pressure and temperature to an interface for a prescribed period of time, is generally considered complete when cavities fully close at the faying surfaces. A second class of material, that is, metals and alloys that exhibit very low solubility for interstitials (such as aluminum-, iron-, nickel-, and cobalt-base alloys) are not readily diffusion bondable. Special consideration must be given to remove surface barriers to atomic diffusion prior to joining and subsequently prevent their reformation during the joining process. This is not an easy processing matter. Accordingly, the potential for high-strength bond interfaces for alloys with low interstitial solubility should be considered on an individual alloy basis.

Factors that affect the relative difficulty of diffusion bonding oxide-bearing surfaces include:

· Surface roughness prior to welding. A rougher surface will result in greater shear deformation.

· Mechanical properties of the oxide. The more brittle the oxide, the greater the dispersion for a given level of deformation.

· Relative hardness of the metal and its oxide film. Because plastic flow controls the amount of bonding area, large differences in their hardness should facilitate bonding.

· Pre-straining or work hardening of the material. Initiation of bonding will occur at lower deformations for pre-strained or work-hardened materials, and the degree of surface extension in the central region of the interface is considerably greater for cold-worked material. Thus, annealed material requires a larger total deformation before bonding will initiate.

MECHANISM OF DIFFUSION BONDING:

In diffusion bonding, the nature of the joining process is essentially the **coalescence of two atomically clean solid surfaces.** Complete coalescence comes about through **a three-stage metallurgical sequence of events**. Each stage, as shown in Fig. 1, is associated with a particular metallurgical mechanism that makes the dominant contribution to the bonding process. Consequently, the stages are not discretely defined, but begin and end gradually, because the **metallurgical mechanisms overlap in time**. During the **first stage, the contact area grows to a large fraction of the joint area by localized deformation of the contacting surface asperities**. Factors such as *surface roughness, yield strength, work hardening, temperature, and pressure are of primary importance* during this stage of bonding. At the completion of this stage, the interface boundary is no longer a planar interface, but consists of voids separated by areas of intimate contact. In these areas of contact, the joint becomes equivalent to a grain boundary between the grains on each surface. The **first stage is usually of short duration** for the common case of relatively high-pressure diffusion bonding. During the second stage of joint formation, **two changes** occur simultaneously. **All of the voids in the joints shrink, and most are eliminated. In addition, the interfacial grain boundary migrates out of the plane of the joint to lower-energy equilibrium**. Creep and diffusion mechanisms are important during the second stage of bonding and for most, if not all, practical applications, **bonding would be considered essentially complete following this**

stage. As the boundary moves, any remaining voids are engulfed within grains where they are no longer in contact with a grain boundary. During this third stage of bonding, **the voids are very small and very likely have no impact on interface strength**. Again, diffusional processes cause the shrinkage and elimination of voids, but the only possible diffusion path is now through the volume of the grains themselves.

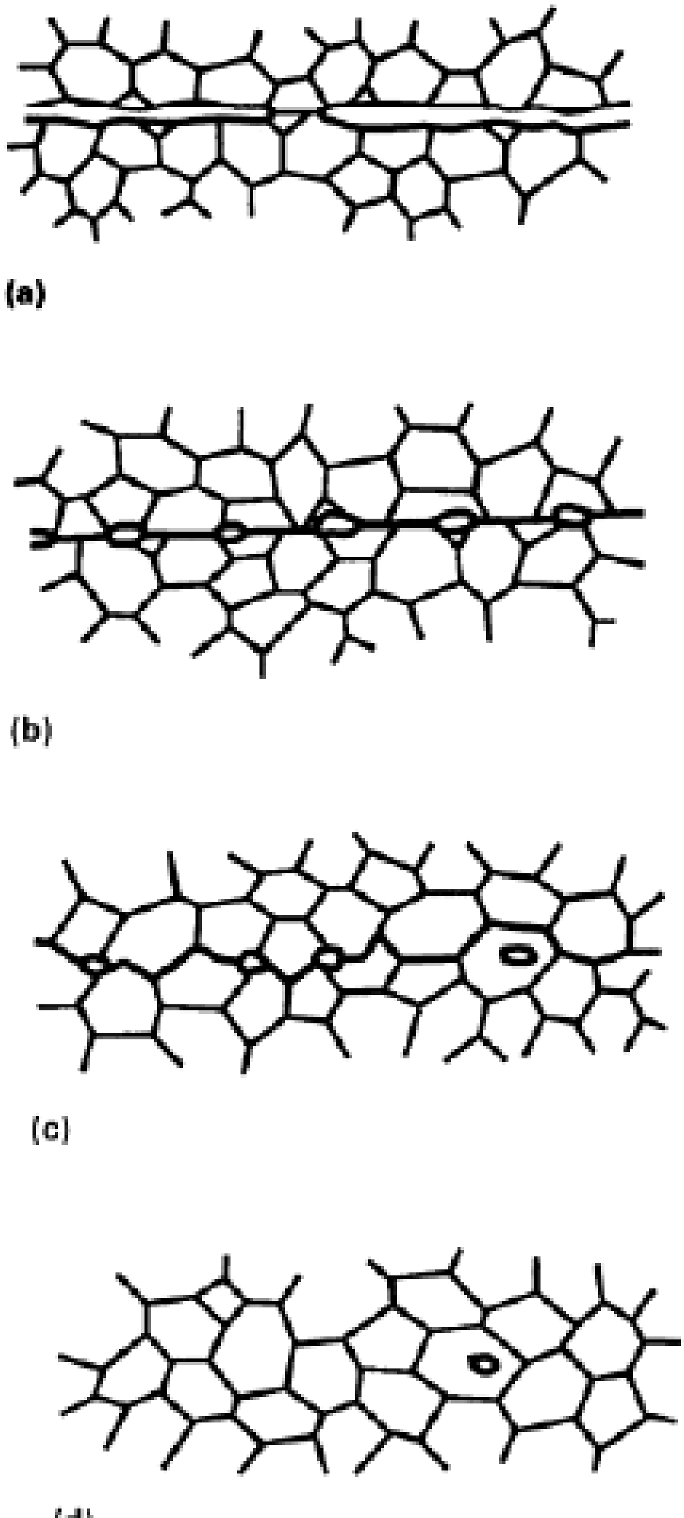


Fig.1 Phases in DB- (a) **initial contact**: limited to a few asperities (room temperature). (b) **first stage:** deformation of surface asperities by plastic flow and creep. (c) **second stage:** grain boundary diffusion of atoms to the voids and grain boundary migration. (d) **third stage:** volume diffusion of atoms to the voids

In general the DB process can be staged into the following three steps:

- **Stage I: Microasperity Deformation**
- **Stage II: Diffusion-Controlled Mass Transport**
- **Stage III: Interface Migration**

INTERMEDIATE MATERIALS

Additional layers of material in the form of coatings or foils are often used as bonding aids for a variety of reasons. For example, an intermediate material can be **used when joining dissimilar materials where a brittle intermetallic would otherwise form**. In this case, the interfacial material would be selected for its compatibility with each of the materials to be joined and for its ability to **prevent the creation of a brittle reaction layer**. To **promote diffusion in materials that contain elements with low diffusivities**, the interfacial material should contain an element with a higher mobility than elements found in the joined materials.

A **common material** for such applications is **electroless nickel, which contains phosphorus** (phosphorus has been shown to have a **high diffusivity** in other metallic systems). However, **caution should be exercised** when considering the addition of high-diffusivity elements, because of their **potential for accumulation at grain boundaries and their resultant influence on mechanical properties.** Another approach is to add an interfacial material that will scavenge impurity elements at the interface and thus produce clean surfaces *in situ.*

Materials with high solubilities for interstitial elements, such as titanium alloys, can be appropriate for this purpose. Because of the importance of localized plastic flow at the interface, a soft material addition can also be of benefit to maximize interfacial contact during the first bonding stage, where deformation mechanisms dominate. With the addition of interfacial materials, geometric as well as metallurgical considerations become important. The mechanical strength of solid-state metallic bonds achieved with a thin interfacial layer of bonding material goes through a maximum, with decreasing joint thickness.

For thick joints, tensile strength is directly related to the bulk properties of the interfacial layer material. As joint thickness decreases, the tensile strength of these joints increases, because of the matrix material restraint on the plastic flow of the interfacial layer. However, for very thin joints, the problems of surface roughness and cleanliness start to diminish the contact area and, thus, effectively reduce the joint tensile strength. Experimental studies should be performed for individual materials. In general, thicknesses of approximately 0.025 mm (0.00098 in.) yield maximum interface strengths.

Time:

- Time is a dependent process parameter.
- An increase in temperature shortens the time required to complete the diffusion welding.
- Time required for diffusion welding varies from a few minutes to several hours.

4. Surface preparation:

- Better prepared and cleaned surfaces lower the minute the minimum diffusion welding temperature or pressure.
- Surface to be diffusion bonded are
  - ✓ Machined, ground or abraded so that they are sufficiently smooth to ensure that the interfaces can be passed to proper contact without excessive deformation.
  - ✓ Cleaned of chemically combined films, oxides etc.
  - ✓ Cleaned of gaseous, aqueous or organic surface films.

5. Metallurgical factors:

a. Allotropic transformation:

Hardenable steels undergo allotropic transformation and involve volume change during diffusion welding. This may affect dimensional stability of the welded component.

b. Recrystallization:

Many cold worked metals tend to recrystallize during diffusion welding. This may be good for certain materials but undesirable for others, e.g., refractory metals.

c. ***Surface oxides:***

Beryllium, aluminium, chromium, etc., form tenacious surface oxides. These and alloys containing them are, therefore, more difficult to weld than those which form less stable oxide films such as copper, nickel etc.

COLD PRESSURE WELDING

Introduction

All metals are surrounded by surface layers (oxide) which must be disrupted if they are to be welded. Cold pressure welding, carried out at ambient (surrounding) temperature, relies upon the use of high compressive pressure 1400- 2800N/mm^2 for Aluminum and at least double that value for copper). This provides interfacial deformations of 60% to 80% that break the oxide layers to expose fresh, uncontaminated metal that makes contact. In this state, take over to interatomic forces produce the weld.

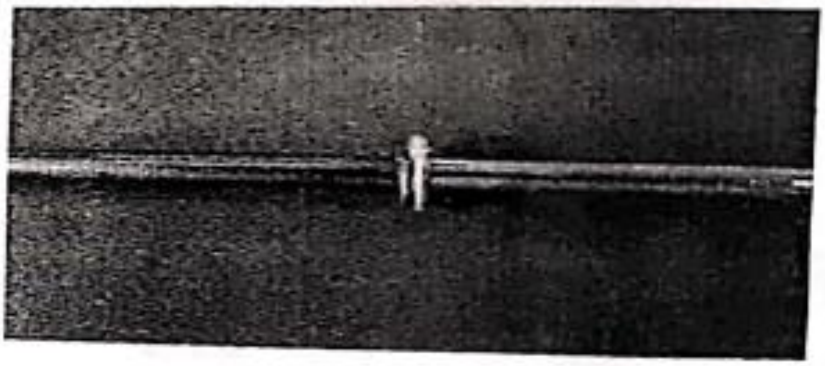


Fig:- Cold pressure welding done at copper nail and steel nail

Cold Pressure Welding

Cold pressure welding is a form of solid phase welding, which is unique because it is carried out at ambient temperatures. Other forms of solid phase welding are conducted at elevated temperatures.

- Joining the metal together using no heat or flux
- Pressure brings the surfaces together , disrupts surface films and allows chemical bonding of clean surfaces
- Applicable to soft ductile metals , e.g. Aluminum

VARIATIONS OF COLD PRESSURE WELDING

Because welding lends itself to numerous techniques of forming, there are many variants of the cold pressure welding process. Cold pressure welding can be accomplished by deforming in a lap or butt configuration, drawing, extrusion, and rolling. The following discussion deals with only the first three variants.

Cold Pressure Lap Welding.

The geometry of the cold pressure lap welding method is similar to the geometry of resistance spot welding. Two sheets of metal are joined in such a way that the direction of material flow is perpendicular to the direction of pressure. After a material-dependent reduction of the sheet thickness, the joint is formed. A high-quality joint will not be formed unless all superfluous oil has been removed and the contact surfaces have been mechanically cleaned (for example, by scratch-brushing with a rotating steel brush). Cleaning should be performed immediately before welding. Depending on the material, sheet thicknesses between 0.1 to 15 mm (0.004 to 19/32 in.) can be welded.

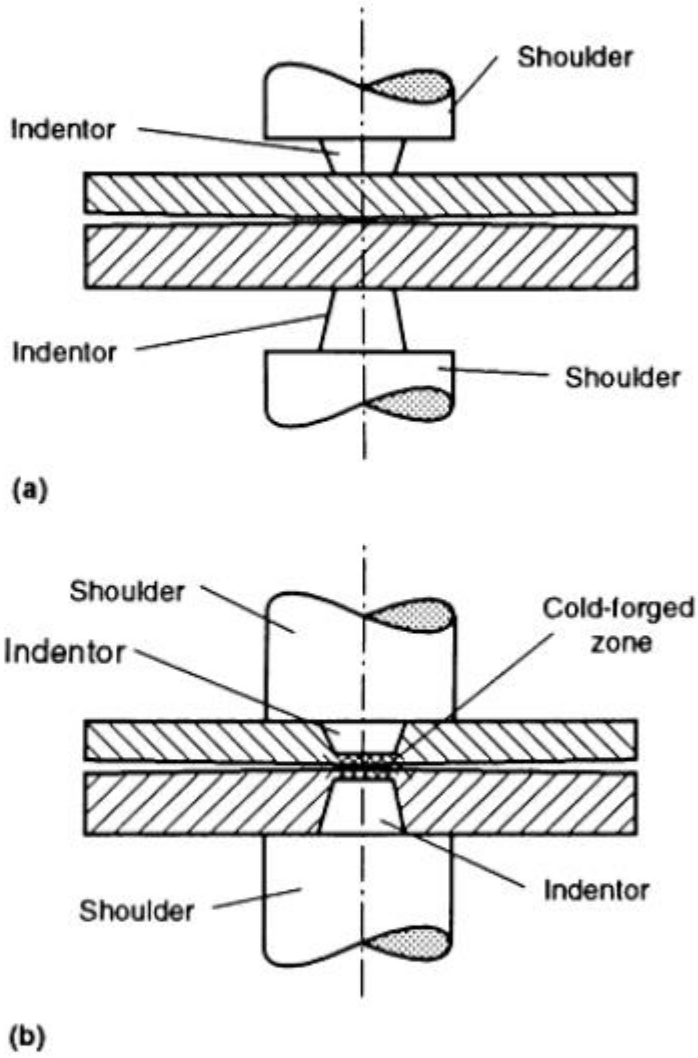


Fig. Schematic showing two dies being used for cold pressure lap welding of two metallic sheets. (a) die position before welding. (b) die position after welding

The welds are produced by annular, point, or line-shaped pressure dies in mechanical or hydraulic presses or pneumatic clamps. The reduction in thickness produced by the dies must be limited by a solid stop or deformation measurement method. The bending distortion of the sheets is small when several spots or adjacent narrow areas are welded at the same time. Dies that generate a ring-shaped area of pressure produce welds superior to dies that generate a circular area of pressure. For line welds, dies with relatively long and narrow pressure areas should be used. The width of the pressure area and its distance to an adjacent pressure area will be greater with increasing thickness of the plate.

Cold pressure butt welding:

It implies that the ends of two bars of similar or dissimilar metals are jointly upset. The two bars are placed in a device or machine having suitable clamping shoes. The compressive force applied along the axis of the bars causes an expansion of the contact surfaces and forms a bulb. Both bar ends will weld together when the contact surfaces have reached a certain size, which depends on both the material and the condition of the contact surface. The strength of the joint increases as the contact surface expands until it reaches the strength of the softer of the two materials used. The strength of the softer material is thus enhanced by cold work hardening.

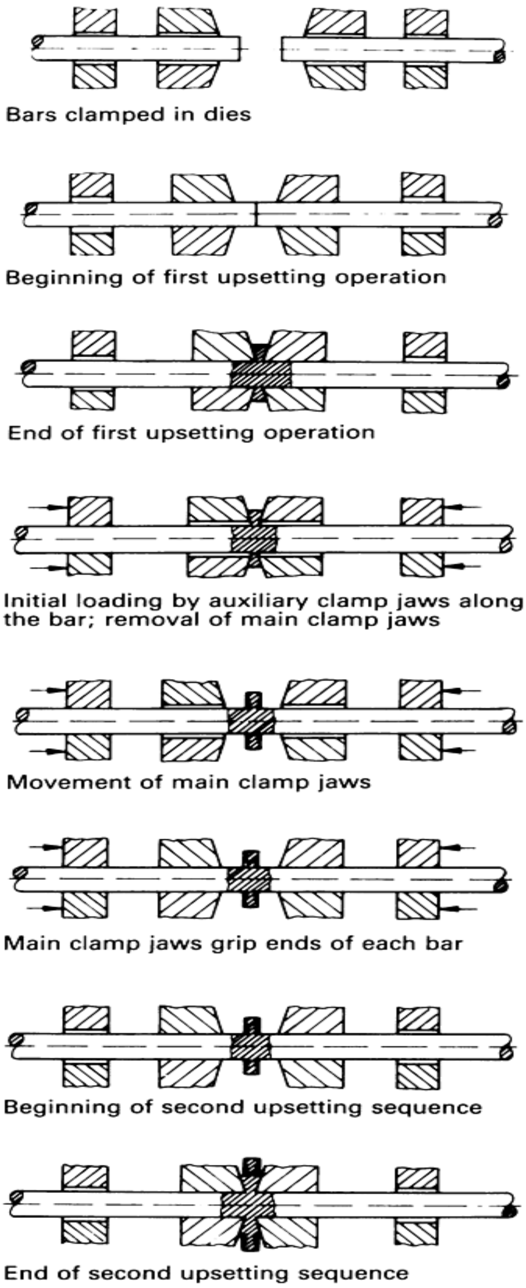


Fig. 3 Cold Pressure Butt Welding of two bars using multiple-step upsetting method

Advantages

- As the process is performed at ambient temperature, there are no thermal effects on the parts being joined
- The process is simple and fast.
- It is simple and inexpensive to operate once dies have been produced.
- The ends of the wire or rod need no preparation to welding and the alignment of the two butt ends is automatic as the material is placed in the die.

Disadvantages

- Highly specialized with respect to joint design and materials to be welded (soft iron that has no carbon content)
- Since the welds are made in the 'solid state' they are difficult to inspect.
- With the exception of butt welds, or welds where the contact surfaces are sheared together, the thickness of the parts is reduced.

Applications of Cold Welding

- Cold welded butt joints are used in the manufacturing of aluminum, copper, gold, silver, and platinum wires with continuous drawing.
- Most commonly, used in sealing heat sensitive semiconductor devices.
- Sealing of heat sensitive containers such as containing explosives.
- Used in underground wire servicing due to hostile environments (explosive gasses).

MODULE 3

EXPLOSIVE WELDING & ADHESIVE BONDING

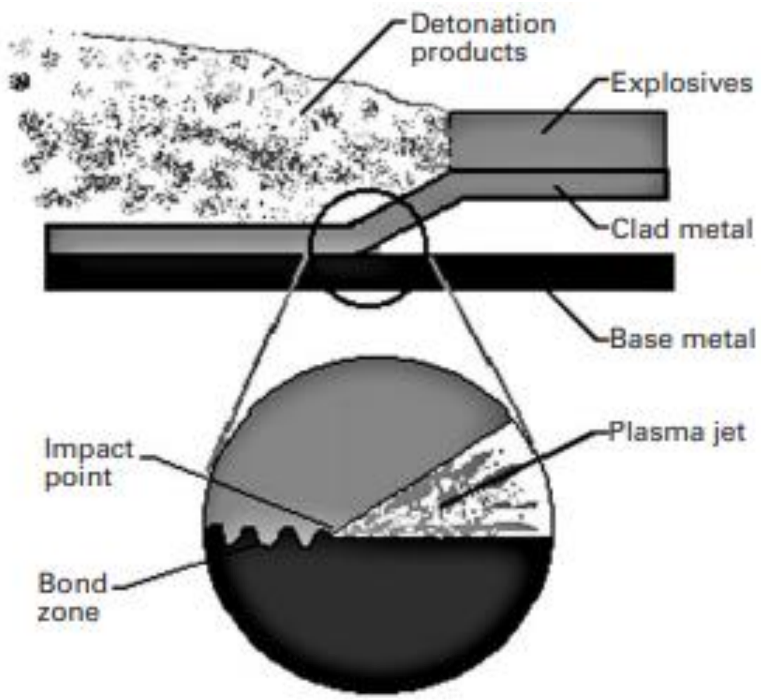
EXPLOSIVE WELDING

The explosive welding technique has found major use for cladding low cost plate (usually carbon steel) with more expensive corrosion resistant materials. This clad plate is typically used in the chemical and petrochemical industries as tube sheet for heat exchangers.

Explosive welding differs from other traditional joining processes as it does not depend on melting of two metals to be joined, or on plastic deformation of the surfaces in contact as occurs with cold or hot pressure welding. In simple terms an explosive weld is achieved by impelling the cladding plate against the substrate plate material using the considerable energy from an explosive discharge, resulting in a high energy rate impact. The high interfacial pressure at the point of contact (or collision front) between the cladding plate and the substrate plate must be greater than the yield strength of both materials, to permit plastic deformation within the surface layers to occur. A jet of highly softened metal is formed at the collision front and is projected in front of it as it progresses rapidly across the weld interface. As the jet progresses, it thoroughly cleans the surfaces, thus permitting solid phase bonding to occur between the two materials.

Because bonding occurs in the solid phase, it is possible to weld metals with different melting points and some of the common clad layers deposited onto steel plate are aluminium, copper, bronze, titanium, monel, nickel alloys and zirconium. Alternatively explosive welding can be used to repair or plug tubes in heat exchangers on-site, where conventional welding methods are difficult to use.

Explosive welding is mainly used for cladding processes. Nearly all kinds of metals and alloys allowing more than 5% of strain may be joined by this technique (Andernach und Bleck). Titanium explosive cladded tank bottoms have successfully withstood testing by use in chemical apparatus. In explosive welding, a compression force created by detonation of explosives is used to join overlapping metal sheets. The joining parts are arranged towards each other at an angle of 1–15°, depending on the material and method, and are prepared with a layer of explosive on the top. After ignition the joining areas are moved against each other at high speed. Joining happens continuously by local plastic deformation of the contact area . The thickness of the cladding may vary between 0.1 and 30mm and the detonation velocity is between 1200 and 7000m s−1". The top plate hits the bottom plate with a speed of 100–1000m s−1", and pressures are in the range of 10 to 100kbar. Under certain conditions a superheated layer of material forms in the contact area. The joint is then caused by a deformation induced melting bath. The melt layer is quite thin; for example, when cladding an aluminum alloy it is about 0.5– 4μmThe dilution of the molten zones results in plane or corrugated interfaces. In contrast to surface-layer welding, explosive welding causes no change in micro-structure, and corrosion resistance of the layers is not affected.



Explosion welding , also known as explosive bonding, is accomplished by a high-velocity oblique impact between two metals. The impact must have sufficient energy to cause the colliding metal surfaces to flow hydro dynamically when they intimately contact one another in order to promote solid-state bonding. Oblique impact is important because conservation of momentum allows for a re-entrant jetting action that is due to hydrodynamic flow of the faying metal surfaces. The jet is ejected outward from the collision apex between the metals and produces a cleaning action by scarfing or effacing the metal surfaces. The resulting virgin metal surfaces are then compressed together under high pressure from the explosion, which promotes atomistic bonding.

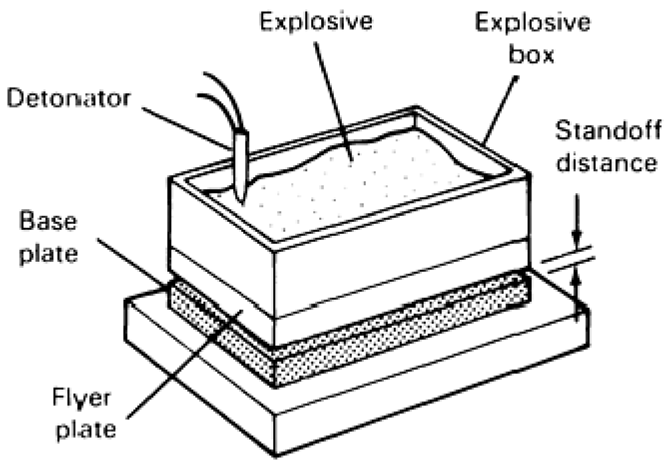
Bonding Practice

Figure below shows the arrangement used in the parallel gap explosive bonding process. The explosive charge is placed in contact with the top plate, hereafter called the flyer plate. The explosive detonation is initiated from one end to generate a linear detonation front, which runs along the flyer plate length. Pressure generated by the expansion of the explosive products accelerates the flyer plate downward at the point where the explosive is reacting and results in the desired impact on the stationary base plate. The principal parameters that affect bond success with this arrangement are:

· Detonation velocity and energy, which are characteristics of the explosive used and result in flyer plate acceleration

· Impact energy, which is a function of the flyer plate standoff distance, the detonation energy, and the energy transfer characteristics

· Dynamic bend angle and the physical and mechanical properties of the metal constituents



Flyer Plate Acceleration

Figure 2, an intermediate view of the explosive bonding process, shows an idealization of the metal deformation that result after explosive detonation. Flash radiography performed during the bonding process has been used to develop this pictorial representation. The energy produced by detonating the explosive results from a very rapid expansion of detonation products, which impacts an acceleration to the flyer plate and maintains a high-pressure region in the atmosphere behind the detonation front. Rapid flyer plate acceleration results in a dynamic bending action. The dynamic bend angle, β, results in an oblique impact between the flyer and base plates, which promotes the hydrodynamic flow of the metal surfaces and resulting jetting actions.

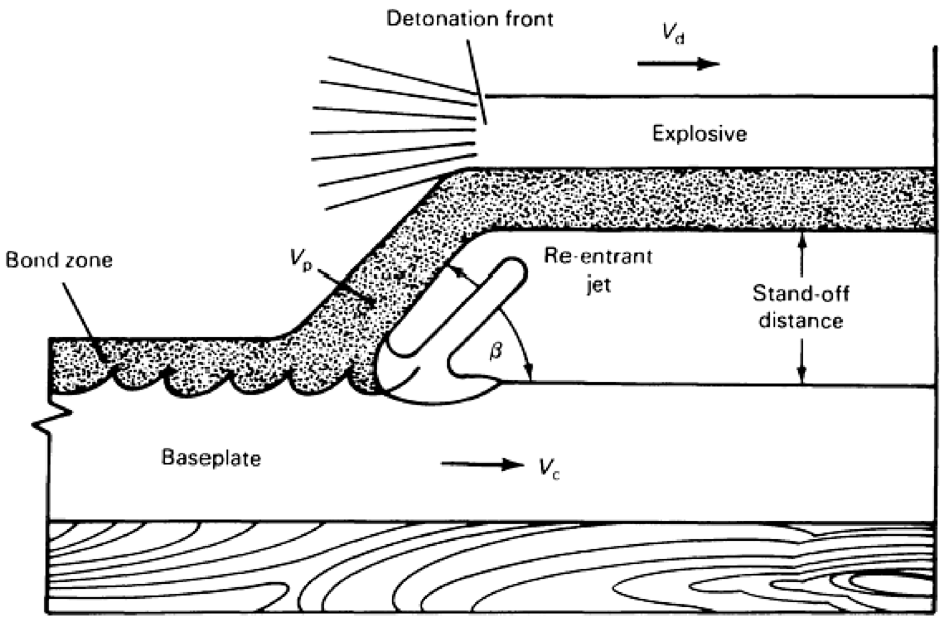


Fig. 2 Schematic showing an idealized view of the flyer plate deformation and impact

Resulting from a moving explosive detonation front

Components of Explosive Welding

1. Base component
2. Cladding metal
3. Flyer plate
4. Interlayer
5. Anvil
6. Standoff
7. Bond Window
8. Bonding Operation

Stages of Explosive Welding

Steps in the Explosive Welding

1. Plain material inspection
2. Grid mating surfaces
3. Assembly: Backer, Cladder, Explosive
4. Explosion
5. Flattering & Cutting
6. Testing & inspection

Explosive Material

- High velocity (14750-25000 ft/s)
  - ✓ Trinitrotoluene (TNT)
  - ✓ Cyclotrimethylenetrinitramine (RDX)
  - ✓ Pentaerythritol Tetranitrate (PETN)
- Mid-low velocity (4900-14750 ft/s)
  - ✓ Ammonium nitrate
  - ✓ Ammonium perchlorate
  - ✓ Amatol

Types of Detonation

1. Shock wave develops if sonic velocity is greater than 120% of material sonic velocity (type 1)
2. Detached shock wave results when detonation velocity is between 100% and 120% of material sonic velocity (type 2)
3. No shock wave is produced if detonation velocity is less than material sonic velocity (type 3).

Welding parameters

Detonation velocity is a function of:

- ✓ Explosive type
- ✓ Composition of explosive
- ✓ Thickness of explosive layer

Advantages

- No heat-affected zone (HAZ)
- Only minor melting
- Material melting temperatures and coefficients of thermal expansion differences do not affect the final product
- The shock front compresses and heats the explosive material which exceeds the sonic velocity of undetonated explosives

Limitations

This method is that extensive knowledge of explosives is needed before the procedure may be attempted safely. Regulations for the use of high explosives may require special licensing

Applications

- Can weld large areas of metal
- Can weld inside and outside surfaces of pipes
- Transition joints can be made
- Chemical Processing
- Petroleum Refining
- Hydrometallurgy
- Aluminum Smelting
- Shipbuilding

ADHESIVE BONDING

Adhesive bonding is a joining technique used in the manufacture and repair of a wide range of products. Along with welding and soldering, adhesive bonding is one of the basic joining processes. In this technique, components are bonded together using adhesives. The broad range of types of adhesives available allows numerous materials to be bonded together in products as diverse as vehicles, mobile phones, personal care products, buildings, computers and medical devices.

According to IUPAC, adhesion is the “process of attachment of a substance to the surface of another substance”. Interactions between the adhesive and substrate have a very short range of less than one nanometre. Therefore, good wetting of the materials to be joined by the adhesive in its liquid state is required to produce a high quality bond. In addition to the wetting ability, the adhesive and substrate must have compatible molecular groups so that interaction between the adhesive and substrate can take place and thus achieve adhesion.

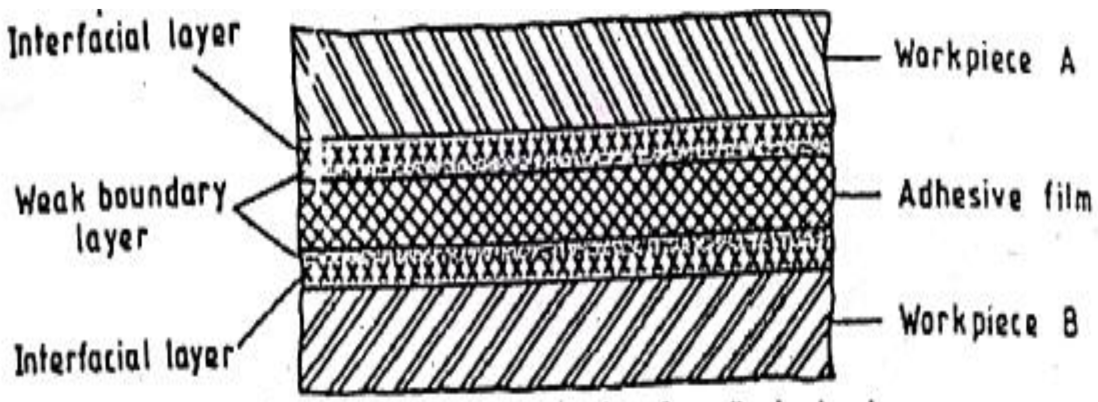


Fig. 17·12 A schematic representation of an adhesive bond.

The adhesive forces are usually based on physical interactions, for example, such as those between polar or polarisable groups, on hydrogen bonds, or van der Waals forces. When bonding plastics, in particular with solvent-based adhesives, diffusion processes can also play a role. In this case, the plastic at the substrate surface is dissolved by the solvent contained in the adhesive. This leads to an increased mobility of the plastic's polymer chains, which in turn allows penetration by those of the adhesive. Ultimately, additional interactions occur between the polymer chains of the adhesive and the substrate. After evaporation of the solvent, a solid compound is formed. Chemical bonds are also important in certain adhesive / substrate combinations, for example when bonding glass using silicone adhesives, wood using polyurethane adhesives and aluminium using epoxy adhesives. Chemical bonding leads to significantly higher adhesion than physical bonding. In addition, penetration of the liquid adhesive into undercuts may provide addition adhesion after it has hardened.

Achieving adhesion between the adhesive and substrate requires not only an adhesive of suitable composition for the substrate, but also places high demands on the substrate surface. Due to the short range of the adhesion forces, the nature of the surface layer of the substrate is crucial. It must be sufficiently firmly connected to the body of the substrate. For example, many adhesives adhere well to a corroded steel surface. However, the corrosion layer – the rust – is not firmly connected to the substrate. Under load, failure may occur in the corroded material or between the rust layer and the uncorroded steel. The same applies to coated items. The adhesive must build adhesion to the coating. The coating in turn must be sufficiently firmly connected to the substrate.

Likewise, contaminants, especially those which, due to their low surface tension, counteract wetting by the adhesive (for example, oils, release agents, etc.) hinder the adhesion interaction. Contaminants form, as it were, a barrier between the adhesive and the substrate which cannot be bridged by the adhesion forces due to their short reach.

Therefore, contaminants usually need to be removed before adhesion. Some special adhesives show a degree of compatibility with certain oils. They are able to absorb certain oils during the curing of the adhesive, which takes place at elevated temperatures, and thus to remove them from the boundary layer between the adhesive and substrate. Such adhesives are used for example in automotive body shops. They allow the gluing of sheet metal parts with corrosion protection and drawing oils without previous cleaning; The curing of the adhesive takes place in the furnaces used subsequently for hardening the lacquer at temperatures between approximately 150 and 200°C.

Pre-treatment can be used to modify surfaces in a targeted way and thus make them more adhesive. In addition to coating the substrates with an adhesion promoter (primer) to enable good adhesion, surfaces can also be modified by various methods to prepare them for gluing. The most common surface pre-treatment methods are listed in the adjacent figure.

The selection of the pre-treatment process is application-specific, taking into account

- The materials to be joined.
- Their surface condition.
- The type and amount of surface contamination.
- The adhesive to be used for bonding the substrates.
- The stresses on the glued product over its life cycle (e.g. mechanical, thermal or medial).

The selection should be validated through appropriate testing.

While adhesive bonding may sound complicated, it’s actually a relatively simple manufacturing process that consists of just a few basic steps.

Step #1) Degreasing

The first step of adhesive bonding is degreasing. As the name suggests, this step involves the removal of all grease — as well as other contaminants — on the surfaces that will be joined. While small amounts of grease may sound harmless, it can reduce the bond created by the adhesive. Therefore, manufacturing companies must degrease the surfaces before applying the adhesive.

Degreasing is often performed using a solvent. Known as vapor degreasing, the surfaces are submerged in a solvent that dissolves grease and other contaminants. In addition to vapor degreasing, another degreasing method involves wiping the surfaces with a solvent-soaked cloth.

Step #2) Abrasion

The second step of adhesive bonding is abrasion. During this step, the surfaces are prepared by exposing them to abrasive material, such as sandpaper. The purpose of abrasion is to increase the surface area to which the adhesive will be exposed. By exposing the surfaces with an abrasive material, it becomes rough and rugged. In turn, the adhesive will spread to fill the micro-sized cracks and crevasses, allowing for a stronger bond.

Step #3) Adhesive

After the surfaces have been degreased and exposed to an abrasive material, the adhesive is applied. During this step, the adhesive is carefully applied to the surfaces. Adhesives can be organic or inorganic. Regardless, they must be able to create a strong enough hold to prevent the surfaces from separating.

Step #4) Curing

The fourth and final step of adhesive bonding is curing. Not all glues or adhesives require curing, but many do. Heating, for example, is a common curing method used in adhesive bonding. The adhesive is heated, resulting in a chemical reaction that strengthens its bond. To cure the adhesive, manufacturing companies typically place the workpieces in a large commercial drying oven where they are heated to a specific temperature.

Adhesives and their Classification:

There are three main in gradients of most adhesives viz., a synthetic resin system, an elastomer or flexibilizer and inorganic materials.

Adhesives can be divided into two broad groups – structural adhesives and non-structural adhesives. The adhesives of the first group have high load carrying characteristics while the non-structural adhesives, also known as glues or cements, are used for low load applications, for example, waterproof latex adhesive used for tile flooring.

1. Structural Adhesives:

Structural adhesives like plastics are classified into two groups— thermoplastic and thermosetting; the members of the former group may be re- softened repeatedly by heat though at too high a temperature, which is decided by their chemical structures, they also lose bond strength due to decomposition.

2. Thermoplastic Adhesives:

Most commonly used thermoplastic adhesives are the polyamides, vinyls and non-vulcanizing neoprene rubber. For structural applications, the vinyls have proved very versatile, for example, polyvinyl acetate can be used to form strong bonds with metals, glass and porous materials.

3. Thermosetting Adhesives:

Thermosetting resins are the most important materials from which metal adhesives are formed. These adhesives harden or cure by chemical reactions such as polymerisation, condensation, or vulcanization. Once they harden, these adhesives cannot be remelted and a broken joint cannot be rebounded by heating. Thermosetting adhesives are generally preferred for elevated temperature service.

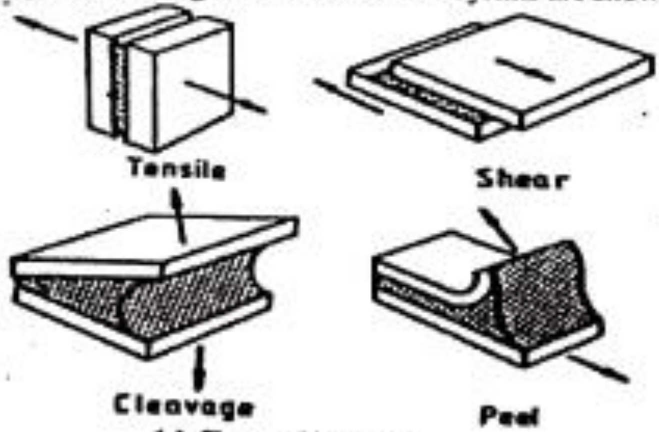
- Thermosetting resins are available to give strong, waterproof and heat- resistant joints. There are two general types of thermosetting structural adhesives viz., the phenolic-resin base and the epoxy-resin base adhesives. The phenol formaldehyde resins have proved themselves as amongst the best bonding materials for waterproof plywood.
- Resorcinol – formaldehyde resins are similar to phenolic resins but have the advantage of getting cured at room temperature.
- Epoxy resins are amongst the newest thermosetting resins and are widely acclaimed as they combine the properties of excellent action, low shrinkage, high tensile strength, toughness and chemical inertness. They can be cured at room temperature without any volatile by-products and can develop strengths between 15 to 30 MPa. Amongst the latest arrival on the scene is the 'oily metal' epoxy that bonds directly to oily metals as received with normal protective oil layer on them.
- Although epoxy-based adhesives develop high shear and tensile strengths, creep and peel strengths are low. However, peel strengths of epoxy adhesives can be improved by modifying them with nylon, carboxylic functional, and nitrile copolymer rubber. Such modified epoxy adhesives can develop joint shear strength higher than 50 Mpa with high peel strength.
- Other thermosetting adhesives are melamin-formaldehyde, polyurethanes, polysters, phenolic rubber, phenolic vinyl and buna, and neoprene rubbers.
- Structural adhesives are also made from combinations of rubbers and synthetic resins, for example nitrile-rubber-phenolic combination can develop a shear strength of 15 to 25 MPa at room temperature. These adhesives combine the strength of the phenolic resins with the flexibility and resilience of rubbers. Some of these resins can develop tensile strength of 20 to 45 MPa at room temperatures for lap joints in aluminium.
- Structural adhesives, developed to produce high strength are generally composed of synthetic resins or combinations of synthetic resins and elastomers. Common synthetic resins used are epoxy, urea, phenol and resorcinol.
- Thermosetting adhesives are generally hard and rigid when completely cured. Elastomer resin adhesives have high strength but retain flexibility to a large extent even after curing.

Flexibility of almost all adhesives can be controlled by formulation, for example, epoxy resins can be made quite flexible by modification with polysulfide rubber.

- Still another class of high-temperature-resistant structural adhesives is formulated from polybenzimidazole (PBI) and polyimide (PI) which can be used successfully for the temperature range of -220°C to 540°C. These adhesives have been found to give excellent results for bonding aluminium, stainless steels, titanium, beryllium and reinforced plastics.
- Although structural adhesives have been successfully used for bonding in aerospace applications for a number of decades, stress corrosion problems have been detected under the service conditions involving continuous or cyclic stress and a hot humid atmosphere. Adhesives cured at room temperatures degrade more rapidly in a hostile service environment than heat-cured adhesives.

Joint Design for Adhesive Bonding:

- The most important consideration in joint design for adhesive bonding is to know the kind of load or stress to which the part will be subjected during service.
- The four main types of loading encountered in such joints are shown in Fig.



(a) Types of loading

- The design must provide space enough for the adhesive to form thin bond lines in the range of 0.075 to 0.125 mm so as to achieve high bond strength

For designing an adhesive joint three important rules are:

(i) The joint should preferably be subjected to shear or tensile loading rather than cleavage or peel loading.

(ii) The static loading of the joint should not exceed the adhesive plastic strain capacity,

(iii) Adhesive joints subjected to low cyclic loads should be provided with sufficient overlap to minimise creep in the adhesive.

The main types of joints employed for adhesive bonding are lap joint and the tongue and groove configuration which can be used for butt, corner or fillet joints. The mortise and tenon are used for corner joints.

Application of Adhesive to the Surface:

- Adhesives may be applied to the prepared surfaces by hand brushing, spraying, roller coating, knife-coating and dipping. They are also applied as sheet or powder, generally on a precoated surface. Sheet or tape type adhesives are gaining in popularity because there is no need for mixing and the application will be of known uniform thickness.
- The thickness of the applied adhesive is referred to as 'lay-down' while the final thickness after the application of pressure and curing is called 'glue- line' thickness, for example, to achieve a glue-line thickness of 25 to 75 micron, a lay-down thickness of 0-125 to 0-375 mm of 20 percent solid wet adhesive must be applied.
- The adhesive can either be applied in one thick layer on one of the parts, or in one thin layer on each of the surfaces before assembly. The latter method is preferred as it leads to a stronger bond with a longer tack life.
- Adhesive bonds with optimal joint strength are achieved when 0-25 to 0-75 microns of solvent-free adhesive remains after two smooth, flat, parallel surfaces are bonded together.
- Lay-down thickness depends upon the porosity and smoothness of the surfaces to be bonded, the fit-up of the joint and the strength required. If the surface is porous allowance must be made in the lay-down solvent lo be absorbed by the surface, to achieve the desired glue-line thickness. Similarly, allowance must be made while coating rough surfaces so as to fill up all small depressions and attain the desired glue-line thickness; this is normally done in a single coat.
- Apart from the above described general bonding procedure there are certain well established procedures for achieving optimum joint strength for specific applications. One such technique is called Redux Bonding in which the metal is first given a coat of

phenol formaldehyde in a suitable solvent and then polyvinyl formaldehyde powder is scattered over the precoated surfaces before they are brought together and cured. Though polyvinyl resin is the main adhesive but precoating with phenol formaldehyde is essential to bond it to the metal. Redux Bonding is widely used, since long, for making adhesive joints for aircraft manufacture.

Assembly:

- Because the amount of flow for a good adhesive is very small therefore the components coated with solvent dispersed liquid adhesive should be assembled when they are tacky and wet enough to adhere to each other. The aim should be to assemble the parts when the applied adhesive is at its optimum consistency. Solvent evaporation rate may be increased by moderate heating using infra-red lamps or a hot air oven.
- Provision should be made for positioning the components for mating during curing and assembly fixtures are normally used for the purpose.
- Care should be taken to align the parts accurately before they are mated because a strong bond is created instantly when the coated surfaces are brought together.
- The assembly fixtures used for positioning should be light-weight for ease of handling. A heavy fixture is not only difficult to handle it may also act as a heat sink which can retard the heating and cooling rates during curing. The expansion rate of the fixture material should be as nearly as possible match with that of the expansion rate of assembly to minimise distortion of components and subsequent stressing of the adhesive.
- Sometimes adhesive bonding is combined with resistance welding or mechanical fastening to improve the load carrying capacity of the joint.
- Once the parts are assembled pressure and or heat are applied to cure or set them.

Curing the Joint:

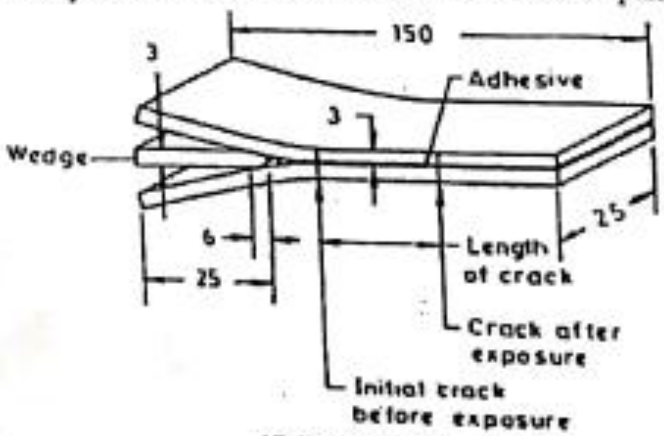
- With certain adhesives it is essential to apply and maintain adequate pressure during curing. The pressure should always be uniformly distributed over the entire joint. Generally, it is desirable to use as high a clamping pressure as the adherends can withstand without being crushed.
- Some adhesives like epoxy can be bonded under a low pressure while some phenolic rubber adhesives require high pressures to ensure adequate flow. Normally a moderate pressure of 0-1 to 10 MPa applied in a suitable press serves the purpose well. Complex parts are placed in a plastic bag which is then evacuated allowing atmospheric pressure to apply the clamping force.
- After the application of pressure, the surplus adhesive is heated through the cooling cycle preferably in an oven though electric heating pads may be lised for large components. Hydraulic platen presses are often used for applying heat and pressure to flat assemblies.
- A typical curing period is 30 minutes at 145°C though shorter times at higher temperatures may be applicable. (Heat transmitted to the adhesive being dependent upon the thermal conductivity of the adherend, the curing temperature is measured at the glue-

line.) Curing limes may be reduced at the expense of bond strength if an accelerator is added to the adhesive.

- Most of the phenolic-based structural adhesives require high curing temperatures in the range of 150 lo 205°C for curing periods of 30 minutes to 2 hours. Some epoxies, however, can be cured at as low a temperature as 120°C.
- Extremely large components like aircraft assemblies are cured by placing them in large autoclaves. The typical operating range of such autoclaves is a pressure of upto 1-4 MPa at a maximum temperature of 175°C. Pressure is provided by compressed air while heating is done by steam heated tubes or electrical elements.

Testing and Quality Control in Adhesive Bonding:

- For judging the joint quality in adhesive bonding the most commonly used destructive test is the lap shear test in which a 25 mm wide lap joint with an overlap of 12.5 mm is loaded in tension along a line parallel to the plane of the joint. Such a test is generally satisfactory for control of mixing, priming and bonding. Peel test is recommended to ascertain the adequacy of cleaning procedures; alternatively the recently developed crack extension or wedge test may be used.
- The crack extension test is designed for quickly determining the durability of the adhesive joint in an environment with controlled humidity and temperature. The test specimen and the method adopted for wedging action are shown in Fig. 17.22. The required number of specimens are cut from the adhesive bonded panel.



All dimensions in mm

Fig. 17.22 Wedge test specimen for adhesive bonds.

- The wedge is forced between the adherend at the glue- line. This separates the adhesive and produces cleavage loading at the tip opening. The location of the apex of the sheet separation is recorded. The wedged specimens are then exposed at 49°C to an environment of 95 to 100 per cent relative humidity for 60 to 75 minutes. The distance that the apex moves during exposure is measured within two hours after exposure.
- The wedge test is used for surface preparation, process control and procedures by comparing the test results with a maximum acceptable increase in adhesive crack length.

It is also used for determining the durability characteristics of the adhesive. Though the test was originally designed for adhesive bonded aluminium, it may be used for other metals with design modifications to account for differences in stiffness and yield strength.

Applications of Adhesive Bonding:

- Adhesive bonding of metal-to-metal accounts for less than 2% of the total metal joining applications. However, the bonding of metal to non-metals especially plastics is gaining utmost importance and is the major application of adhesive bonding.
- Industries involved with aircraft and automobile construction are the major users of adhesive bonding of metals. Redux bonding was developed in early 1940's as an alternative to riveting for aircraft structures and still finds extensive use in that industry. Typical applications include fastening of stiffeners to the aircraft skin and in assembling honeycomb structures wherein honeycomb core is bonded between two sheet metal skins. Many of the joints made in the fabrication of aircraft wing and tail assemblies are by adhesive bonding; increased use is also evident in the fabrication of aircraft internal structures as well as for providing the required smooth surfaces for supersonic planes, making complex designs possible.
- Adhesive bonded assemblies may comprise over 50 percent of the total area of a modern airplane. They include about 400 major assemblies including sections measuring 75 mm by 330 mm, tapered spar caps over 10 m long and panels measuring upto 1-3 m by 4-8 m. Bonded stiffeners are used on single curvature panels forming the fuselage skin. Cost of fabrication in many of these cases is reduced by 33 to 75 percent.
- The main uses of adhesive bonding in automobile industry are for attaching brake lining to shoes, automatic transmission bands, and for stiffeners and fabricated box sections. Double shell panels are bonded with a high strength vinyl plastisol adhesive. Adhesive bonding reduces the number of sub-assembly details by about 50 percent, provides a smooth exterior surface, reduces noise level, and improves corrosion resistance.
- Other major uses of adhesive bonding are in the fabrication of railway coaches, boats, refrigerators, storage tanks, and microwave reflectors for radar and space communications.

- Adequate and effective ventilation is essential to avoid suffocation due to excessive accumulation of toxic fumes.
- Strict supervision is imperative to prevent inadvertent contamination of non-operating areas, for example, the contamination of door knobs, valves, handrails, etc.

MODULE 4

ULTRASONIC WELDING & VACUUM BRAZING

USW is a quasi-solid-state process that produces a weld by introducing high-frequency vibration to the weldment as it is held under moderately high clamping forces. The weld is produced without significant melting of the base materials. In some respects, ultrasonic welding is an infant process that still awaits thorough exploration. A greater understanding is needed of the processes that occur at the bond interface. Specifically, the interaction of the process parameters, as well as their role in bond development, needs to be better understood.

The advantages of ultrasonic welding are that it:

- Permits joining of thin materials to thick materials
- Permits dissimilar metal joints
- Provides joints with good thermal and electrical conductivity
- Joins metals without the heat of fusion
- Provides efficient energy use
- Typically requires no filler material, flux, or special atmosphere
- Typically requires no special cleaning processes
- Welds through most oxides

PROCESS MECHANISM

Ultrasonic welding products a weld by oscillating shear forces at the interface between the two metals being joined while they are held together under moderate static clamping force. The resulting internal stresses result in elasto-plastic deformation at the interface. Highly localized interfacial slip at the interface tends to break up oxides and surface films, permitting metal-to-metal contact at many points. As continued oscillation breaks down, the points and the contact area grows and diffusion occurs across the interface to produce a structure similar to that of a diffusion weld.

Ultrasonic welding produces a localized temperature rise from the combined effects of elastic hysteresis, interfacial slip, and plastic deformation. The welding process is completed without having fully melted metal at the interface when the correct combination of force, power, and time parameters are used. Interface temperature rise is greater for metals with low thermal conductivity (for example, steel) than it is for metals of high conductivity (for example, aluminum or copper). Ultrasonic welding of such high-conductivity materials consumes substantially less energy than does resistance welding. In the case of alloys that have a broad melting temperature range, it is likely that as the low end of the range is reached, a slushing condition that facilitates plasticity in the weld interface is produced. An ultrasonic welding system requires a power supply that converts line power to the high frequency and high voltage needed by the transducer. The transducer transforms high-frequency electrical energy to vibratory energy and is incorporated into the welding head, which also provides the means (that is, pneumatic, hydraulic, or mechanical) to clamp the workpiece. The transducer assembly also incorporates components or waveguides to transmit the energy to the desired weld area. Welds can be made adjacent to or overlapping previous welds to form a continuous welded joint. A product clamp may be necessary to prevent the dispersion of ultrasonic energy into adjacent areas of the workpiece. The product clamp is usually concentric with the welding tip and has a slightly larger diameter than the tip.

PROCESS VARIATIONS AND LIMITATIONS

Variations of the USW process produce different weld geometries. There are spot, line, continuous seam, and ring welding machines. Two other versions of spot welding machines are used to join microelectronic components.

Spot welds: can be circular, elliptical, or rectangular, and solid or ring like in geometry. They are formed when the material is clamped between a shaped tip (sometimes called a sonotrode) and an anvil (Fig. 1). The tip vibrates as ultrasonic energy is momentarily introduced in a plane parallel to the interface and perpendicular to the clamping force. Although weld time varies according to the thickness and composition of the material to be joined and the power of the welding machine, most spot welds can be produced in less than 1.5 s

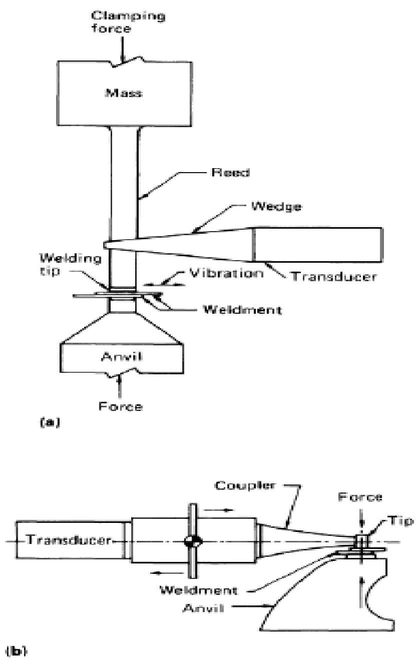


Fig. Two versions of an ultrasonic welding system used for spot welding applications. (a)

Wedge-Reed System. (b) Lateral Drive System

Line welds: are produced by a variation of spot welding in which the weld geometry is elongated by using a linear sonotrode tip and anvil. Custom multiple transducer heads have been used to produce line welds that are several inches long, but most commercially available equipment is limited to lines of 38 mm (1.5 in.) or less in length. Adjacent welds can produce a longer line. Typically, the longer welds are attainable only in thin materials (that is, less than 0.25 mm, or 0.010 in., thick). Single line welds up to 50 mm (2 in.) long have been made to join expanded nickel foil to solid foil for a lithium battery application. Line welding is also used to seal copper tubes in HVAC applications. This technique can replace seals normally produced by crimping and brazing. Continuous seam welds are produced when a disk-shaped ultrasonically vibrating roller is rotated and traversed over a workpiece that is supported on a fixed anvil. Typical uses include joining foil ends in aluminum and copper foil mills. Commercial equipment is available to weld sheet thicknesses up to about 0.15 mm (0.006 in.). High-frequency systems (typically, 50 kHz) permit excellent welds in even the thinnest of foils, such as 0.0043 mm (0.00017 in.), without tearing or puckering. This technique is also used to join 0.038 mm (0.0015 in.) aluminum interconnects to foil in photovoltaic panels.

Ring Welds: A circular tip used on a spot welder can be used to form a ring weld. Systems designed especially for ring welding often use the torsional or circular motion of an annular-shaped tip instead of a forward and backward motion. Such a system utilizes two transducers, one of each side of a hollow reed. Each transducer produces motion 180° out of phase with the other, thus causing a torsional motion at the interface of the weldment. Ring welds with diameters up to about 50 mm (2 in.) and an annular weld track of about 1.25 mm (0.050 in.) have been produced in thin aluminum or copper foils. Typical applications include the encapsulation of liquid and powder propellant or explosive materials by welding a thin foil cover on a container. Foils are usually 0.2 mm (0.008 in.) or less. The weld process does not produce much heat, which makes it suitable for use with heat-sensitive materials. Man y small, high frequency (28 kHz) systems are in operation to hermetically seal small explosive initiators or fuses for armaments.

Microelectronic Welds: fine wire bonding represents the earliest widely used USW application and still accounts for a large volume of industrial activity. Millions of wire bonds are performed daily. Fi Wire diameters range from less than 0.025 to 0.5 mm (0.001 to 0.020 in.), and the highest volume occurs in the 0.025 to 0.050 mm (0.001 to 0.002 in.) diameter range. Vibratory action at high frequency (typically, 60 kHz) removes surface contaminants, induces material flow, and permits a solid-state weld between the wire and either the metallized bond pad or the leads on the semiconductor package. A combination of ultrasonic and thermo-compression bonding techniques, known as thermo-sonic bonding, is now a popular wire bonding method. The technique involves ultrasonic welding with heated substrates, typically with interface temperatures that range from 100 to 200 °C (210 to 390 °F).

USW PROCEDURES

The USW process requires the overlapping of the materials to be welded. Generally, the materials need only be presented to the welder in proper orientation. Correct orientation is usually achieved by using a nest or anvil fixture, which supports the parts while they are being welded. When joining stranded wires to other solid or stranded wires or to a terminal, a "gathering" fixture must be used to pull the wires together and to exert a slight pressure while welding to prevent the wires from escaping from the intended weld area. This type of fixture is usually supplied by the manufacturer with machines intended for use with wires and can be adjusted to accommodate a wide range of sizes and combinations. Special considerations described below include the condition of the surface, the use of an interlayer, and the control of resonance.

Surface Condition: Most of the readily weldable materials, such as aluminum, copper, or brass, can be welded as received from the mill or must be degreased with a common solvent or detergent to remove surface lubricants. Oxide coatings will disperse during the process, unless they are very thick. Heavy surface scale should be removed by mechanical abrading or chemical etching before welding. The time lapse between cleaning and welding is generally not critical, unless the atmosphere is corrosive. Some types of coatings and insulations (for example, low-temperature magnet-wire coating) may be penetrated during the welding process, whereas other types must be mechanically removed. Fairly consistent surface cleanliness and quality must be maintained to ensure uniform weld quality.

Use of an Interlayer: A useful technique for improving the weld quality of some weldments involves placing a thin foil, usually aluminum or copper, between the metals to be bonded. This is particularly useful when materials of varying hardness are to be bonded. This interlayer is sometime more convenient and cost effective than plating the materials witha more weldable material (for example, copper or gold). In a technique known as weld bonding, a layer of adhesive is placed between the panels to be ultrasonically welded. This technique not only provides a watertight seal, but also increases the weld strength beyond that obtained by either adhesive bonding or ultrasonic welding alone. Either a paste adhesive or a fabric-supported adhesive can be used in the ultrasonic bonding process.

Control of Resonance: Complex workpieces, especially those with multiple parts or thin wall sections, may be induced to vibrate by the ultrasonic welding system, which can produce fractures in the workpiece itself and in previously made welds or can cause inconsistent weld quality. This resonance can be either eliminated or minimized by applying pressure to the vibrating section. For example, in the ultrasonic welding of aluminum foil layers to the studs of capacitor caps, the stud must be clamped tightly or else the vibration will not only prevent the formation of a good joint, but can even melt the plastic cap that surrounds the stud. Another option is to clamp the vibrating part to a comparatively large fixture or anvil. Significant pressure is required, and some machines come equipped with a product clamp for this purpose. Because resonance in the tooling can also occur, fixtures should be rugged and should not contain multiple small devices, such as springs or pins. It is best to avoid using light materials (for example, aluminum) for part fixtures, anvils, or supports. Steel is the preferred material for these components.

Tooling, Tips, and Anvils: The welding tip (or sonotrode) that contacts the weldment is usually made of the highquality heat-treated tool steel. A precision fit between the tip and the waveguides is necessary to ensure efficient transmission of the vibratory energy. A locking (Morse) taper is frequently used, and the fit should cover 75% of the contacting surface area between the tip and its matching receptacle. In lower-power systems, the tip and the waveguide (horn) can be integral and can sometimes have several surfaces for welding. Rotation of the horn provides a new welding surface. A welding tip with a taper lock fit is less expensive to replace and easier to resurface, when necessary, than an integral horn-tip combination. Certain alloys, especially the very soft aluminum alloys, may stick to the tip when welded. A mechanical stripper may be needed to pull the part free. Sometimes, a low-power, ultrasonic pulse may be sufficient to remove the stuck part from the tip. If a nugget remains on the tip, a weld pulse, with the tip clamped against a thick piece of brass, can remove the sticking nugget easier than mechanical abrasion methods. Tips composed of exotic alloys have been used to prevent particularly tenacious sticking conditions, but with limited success. A steel shim with an oxidized surface was found to be particularly effective in preventing both sticking and deformation when bonding high-strength aluminum and titanium alloys, which are extensively used by the aircraft industry. The anvil tip is subject to the same problems of wear and tip sticking that plague the sonotrode tip. The same high strength heat-treated tool steel (typically, M2 heat treated to 58 to 60 HRC hardness) is recommended. Welding tip and anvil tip surfaces with serrated or crosshatched patterns are useful in preventing slip between the tip and the weldment. Slip can result in a weld location between the metal and the tools, instead of at the required interface. A typical crosshatched pattern would be 0.5 mm (0.02 in.) peak-to-peak and about 0.2 mm (0.008 in.) deep.

Special Atmospheres: Although ultrasonic welding does not require a special atmosphere, it may be applicable under certain conditions. For example, use of an inert gas can reduce or prevent oxidation when bonding a metal such as lithium. Ultrasonic welding is not adversely affected by the presence of an inert atmosphere. Weld quality is described below in terms of influencing factors, surface appearance and deformation, and metallographic examination.

INFLUENCING FACTORS

The quality of ultrasonic welds is affected by these parameters:

- **Composition and geometry of the weldment**
- **Hardness of the workpiece**
- **Cleanliness of the weldment**
- **Selection of welding conditions, such as power, clamping force, and weld time**
- **Capacity of the tooling to properly support and clamp the parts to**
- **Prevent unwanted vibration**

Surfaces to be welded should be reasonably flat. This is especially critical for ring welding where a high degree of hermeticity is required. Some materials may be weldable in the as-received condition. However, a change in lubricants or other surface condition can require an adjustment in machine settings to maintain quality. Therefore, it is sometimes advisable to degrease or to abrade surfaces before welding to maintain a certain level of consistency.

Surface Appearance and Deformation: Depending on the material and the tip geometry, the surface of an ultrasonic weld can leave a slight scuff mark or a significant depression. This thickness deformation is more visible in soft, ductile materials, such as soft aluminum. The actual weld interface is usually smaller than the surface impression. Harder materials generally have a shallower and smaller surface depression than soft, ductile materials. A tip surface that has serrations or a cross-hatched pattern will replicate this pattern in the surface of the weldment. A spherical radius on the tip will generally produce a deeper, bowl-shaped depression than a flat tip of the same diameter. Stranded or braided wires can be welded to form a solid cross section, if required. Slightly lower power, time, or force can give a compressed, but not solid, cross section. Judicious radiusing and angling of tools is recommended to avoid sharp transitions in areas that can lead to early failure of an assembly. The metallographic examination of ultrasonic welds in a wide variety of metals reveals phenomena that occur in the microstructure, such as surface film and oxide disruption, plastic flow and extrusion, recrystallization, phase transformation, and diffusion. Diffusion across the interface is usually shallow, because of the relatively short weld times required, although significant penetration across the interface can take place. Alloying may occur when welding certain dissimilar metals and the possibility of galvanic corrosion should be considered.

APPLICATIONS

Commercially successful applications generally have certain characteristics. First, joints must be lap joints, not butt joints. Second, thin sections are required adjacent to the welding tip. Third, better results are obtained with nonferrous alloys. Production applications include electrical wire harnesses for the appliance and automotive industry; buss bars; fuses; circuit breakers; contacts; ignition modules; starter motors; aluminum and copper foil; battery foils; capacitors; encapsulation of explosives; microelectronic wires; heating, ventilation, and air conditioning (HVAC) tubing; and many others.

VACUUM BRAZING

Brazing is a process for joining solid metals in close proximity by introducing a liquid metal that melts above 450 °C (840 °F). A sound brazed joint generally results when an appropriate filler alloy is selected, the parent metal surfaces are clean and remain clean during heating to the flow temperature of the brazing alloy, and a suitable joint design is used. Like the other joining processes, brazing encompasses a variety of scientific disciplines (for example, mechanics, physics, and chemistry).

Recently, the demands of more-sophisticated structures have forced technicians and engineers to encourage metal producers to apply their metallurgical knowledge to produce brazing filler metals that meet more-specific needs. To ensure the production of good brazed joints, the technicians and engineers also had to appeal to mechanical engineers for improved joint design, to chemical engineers for solutions to corrosion problems, and to metallurgists and ceramists for proper material selection. Brazing has been embraced by the engineering community and has now reached a very successful plateau within the joining field. This has come about because of the:

· Development of new types of brazing filler metals (rapid solidification amorphous foils and titanium-added filler metals for ceramic joining

· Availability of new forms and shapes of filler metals

· Introduction of automation that has brought brazing processes to the forefront in high-production situations

· Increased use of furnace brazing in a vacuum, as well as active and Inert-gas atmospheres

Since the early 1980s, other developments, such as aluminum-clad foils for fluxless aluminum brazing, copper-nickel titanium filler metals for brazing titanium and some of its alloys, cadmium-free silver filler metals, and vacuum-grade metal brazing foils, have evolved to be used in production applications.

Physical Principles

Capillary flow is the dominant physical phenomenon that ensures good brazements when both faying surfaces to be joined are wet by the molten filter metal. The joint must be properly spaced to permit efficient capillary action and coalescence. More specifically, capillarity is a result of the relative attraction of the molecules of the liquid to each other and to those of the solid. In actual practice, brazing filler metal flow characteristics are also influenced by dynamic considerations involving fluidity, viscosity, vapor pressure, gravity, and, especially, by the effects of any metallurgical reasons between the filler metal and the base metal. Capillary attraction makes the brazing of leak-tight joints a simple proposition. In a properly designed joint, the molten brazing filler metal is normally drawn completely through the joint area without any voids gaps when processed in a protective atmosphere. Solidified joints will remain intact and gas will remain tight under heavy pressures, even when the joint is subjected to shock or vibrational type of loading. Capillary attraction is also the physical force that governs the action of a liquid against solid surfaces in small, confined areas. The phenomena of wetting and spreading are very important to the formation of brazed joints. Other significant factors that also must be considered include the condition of the solid surface in terms of the presence of oxide films and their effects on wetting and spreading, surface roughness, alloying with between the brazing filler metal and base metal, and the extent to which alloying is affected by the thermodynamic properties of the brazing atmosphere. A number of studies have been conducted on surface activation, contact angle, equilibrium, and surface energies. Some of these alloy systems have a finite contact angle that is thermodynamically unstable, because the solid-vapor surface energy exceeds the sum of the liquid-solid surface energies, that is, an alloy system in which thermodynamics would predict complete spreading. In actual fact, spreading may or may not occur in this type of alloy system, and the rate of spreading can be markedly dependent on surface chemistry.

Wetting is only one facet of the brazing process. Another factor that affects wetting is the cleanliness of the surface to be wetted. Oxide layers inhibit wetting and spreading, as do grease, dirt, and other contaminants that prevent good contact between the brazing filler metal and the base metal. One of the functions of a flux the oxide layer on the joint area and thereby expose clean base metal. Good wetting and spreading of the liquid filler metal on the base metal are necessary in brazing because the mechanics of the process demand that the filler metal be brought smoothly, rapidly, and continuously to the joint opening. If the conditions within the capillary space of the joint do not promote good wetting, then the filler metal will not be drawn into the space by capillary attraction.

Elements of the Brazing Process

An engineer must consider reliability and cost when designing the braze joint. Joint strength, fatigue resistance, corrosion susceptibility, and high-temperature stability are additional concerns that determine the selection of joint design, braze filler materials, and processing parameters.

A careful and intelligent appraisal of the following elements is required in order to produce satisfactory brazed joints:

- **filler-metal flow**
- **base-metal characteristics**

- **filler-metal characteristics**
- **surface preparation**
- **joint design and clearance**
- **temperature and time**
- **rate and source of heating**
- **protection by an atmosphere or flux**

Filler-Metal Flow: As mentioned previously, wetting is only one important facet of the brazing process. A low contact angle, which implies wetting, is also necessary, but is not a sufficient condition itself for flow. Viscosity is also important. Brazing filler metals with narrow melting ranges that are close to the eutectic composition generally have lower viscosities than those with wide melting ranges. Thus, a high surface tension of liquid filler metal, a low contact angle, and low viscosity are all desirable.

Flowability is the property of a brazing filler metal that determines the distance it will travel away from its original position, because of the action of capillary forces. To flow well, a filler metal must not gain an appreciable increase in its liquidus temperature even though its composition is altered by the addition of the metal it has dissolved. This is important because the brazing operation is carried out at temperatures just above the liquidus of the filler metal. The composition and surface energy of liquids and solids are assumed to remain constant. In real systems, however, these interactions occur:

- alloy formation between liquid and base metal
- diffusion of base metal into brazing filler metal
- diffusion of filler metal into grains of base metal
- penetration of filler metal along grain boundaries
- formation of intermetallic compounds

In practice, interactions are usually minimized by selecting the proper brazing filler metal; keeping the brazing temperature as low as possible, but high enough to produce flow; and keeping the time of brazing temperature short and cooling the brazed joint as quickly as possible without causing cracking or distortion. When diffusion brazing is desired, higher brazing temperatures and longer times at brazing temperatures are employed.

Base-Metal Characteristics: The base metal has a prime effect on joint strength. A high-strength base metal produces joints of greater strength than those made with softer base metals (other factors being equal). When hardenable metals are brazed, joint strength becomes less predictable. This is because more-complex metallurgical reactions between hardenable base metals and the brazing filler metals are involved. These reactions can cause changes in the base-metal hardenability and can create residual stresses in cases where different materials make up the assembly and gaps may open or close as heating proceeds to the joining temperature, the coefficient of thermal expansion becomes vitally important. Several metallurgical phenomena influence the behavior of brazed joints and, in some instances, necessitate special procedures. These base-metal effects include alloying by brazing filler; carbide precipitation; stress cracking; hydrogen, sulfur, and phosphorus embrittlement; and oxidation stability. The extent of interaction varies greatly, depending on compositions (base metal and brazing filler metal) and thermal cycles. There is always some interaction, except in cases of mutual insolubility. The strength of the base metal has a profound effect on the strength of the brazed joint. Therefore, this property must be carefully considered when designing the joint to have specific properties. Some base metals also are easier to braze than others, particularly by specific brazing processes.

Filler-Metal Characteristics: The second material involved in joint structures is the brazing filler metal. Unfortunately, it cannot be chosen to provide a specific joint strength. Actually, strong joints can be brazed with almost any good commercial brazing filler metal if correct brazing methods and joint design are implemented. Necessary characteristics of brazing filler metals are:

- proper fluidity at brazing temperatures to ensure flow by capillary Action and to provide full alloy distribution
- stability to avoid premature release of low-melting-point elements in the brazing filler metal
- ability to wet the base-metal joint surface
- low volatilization of alloying elements of the brazing filler metal at brazing temperatures
- ability to alloy or combine with the base metal to form an alloy with a higher melting temperature
- control of washing or control of erosion between the brazing filler metal and the base metal within the limits required for the brazing operation

It should be noted that the strength of the brazed joint is not directly related to the method of filler-metal melting. For example, if constructional metals are produced by vacuum melting, and then there is a definite relationship between the vacuum-melting practice and the final strength of the ingot, bar, or rolled sheet. With a brazing filler metal, however, joint strength is dependent on joint design, brazing temperature, amount of brazing filler metal applied, location and method of application, heating rate, and many other factors that constitute the brazing technique. The degree to which brazing filler metal interacts with and penetrates the base metal during brazing depends on the intensity of mutual diffusion processes that occur between both those materials. In applications that require strong joints for high-temperature, high-stress service conditions (such as turbine rotor assemblies and jet-engine components), it is generally wise to specify a brazing filler metal that has high diffusion and solution properties with the base metal. When the assembly is constructed of extremely thin base metals (as in honeycomb structures and some heat exchangers), good practice entails specifying a brazing filler metal that contains elements with a low-diffusion characteristic relative to the base metal being used. Diffusion, a normal part of the metallurgical process, can contribute to good brazed joints when brazing, for example, high-temperature metals with nickel-base brazing filler metals.

Brazing Temperature: When choosing a brazing filler metal, the first selection criterion is the brazing temperature. Some brazing-temperature ranges are given in Table 5. Very few brazing filler metals possess narrow melting ranges. Brazing filler metals in which the solidus and liquidus temperatures are close together do not usually exhibit a strong tendency to coexist as a mixture of liquid and solid phases or to liquate. They flow readily and should be used with small joint clearances. As the solidus and liquidus temperatures diverge, the tendency to liquate increases, requiring greater precautions in brazing filler metal application. The mixture of solid and liquid metal can aid gap filling.

Liquidation: During melting, the composition of the liquid and solid filler metal phase changes as the temperature increases from the solidus to the liquidus point. If the portion that melts first is allowed to flow out, then the remaining solid phases have higher melting points than the original composition and may never melt, remaining behind as a residue, or "skull." Filler metals with narrow melting ranges do not tend to separate, but flow quite freely in joints of extremely narrow clearance as long as the solution and diffusion rates of the filler metal with the base metal are low (as in aluminum brazing, the use of silver filler metal on copper, and so on). The rapid heating of filler metals with wide melting ranges or their application to the joint after the base metal reaches brazing temperature will minimize the separation, or liquation. However, liquation cannot be entirely eliminated and wide-melting-range filler metals, which tend to have more sluggish flow, will require wider joint clearances and will form larger fillets at the joint extremities. A few brazing filler metals become sufficiently fluid below the actual liquidus temperature, and satisfactory joints are achieved, even though the liquidus temperature has not been reached. When sluggish behavior is needed, such as in filling large gaps, brazing can be accomplished within the melting range of the filler metal. However, the brazing temperature is usually 10 to 93 °C (20 to 170 °F) above the liquidus of the filler metal. The actual temperature required to produce a good joint filling is influenced by factors such as heating rate, brazing environment (atmosphere or flux), and thickness of parts, thermal conductivity of the metals being joined, and type of joint to be made.

Large-scale mechanical properties: properties of brazing filler metals can be a guideline for their suitability (in terms of strength, oxidation resistance, and so on) for use in different capillary joining applications. However, designers cannot use the mechanical properties of brazed assemblies that are related to different joint configurations brazed at given cycles of time and temperatures.

The placement of the brazing filler metal is an important design consideration, not only because the joint must be accessible to the method chosen, but because, in automatic heating setups, the filler metal must be retained in its location until molten. Brazing filler metals are available in different forms (Table 6) and filler-metal selection may depend on which form is suitable for a particular joint design.

Surface Preparation: A clean, oxide-free surface is imperative to ensure uniform quality and sound brazed joints. All grease, oil, dirt, and oxides must be carefully removed from the base and filler metals before brazing, because only then can uniform capillary attraction be obtained. Brazing should be done as soon as possible after the material has been cleaned. The length of time that the cleaning remains effective depends on the metals involved, atmospheric conditions, storage and handling practices, and other factors. Cleaning operations are commonly categorized as being either chemical or mechanical. Chemical cleaning is the most effective means of removing all traces of oil or grease. Trichloroethylene and trisodium phosphate are the usual cleaning agents employed. Oxides and scale that cannot be eliminated by these cleaners should be removed by other chemical means. The selection of the chemical cleaning agent depends on the nature of the contaminant, the base metal, the surface condition, and the joint design. Regardless of the nature of the cleaning agent or the cleaning method used, it is important that all residue or surface film be adequately rinsed from the cleaned parts to prevent the formation of other equally undesirable films on the faying surfaces.

Objectionable surface conditions can be removed by mechanical means, such as grinding, filing, wire brushing, or any form of machining, provided that joint clearances are not disturbed. When grinding the surfaces of the parts to be brazed, care should be exercised to ensure that the coolant is clean and free from impurities to avoid grinding these impurities into the finished surfaces. When faying surfaces of parts to be brazed are prepared by blasting techniques, several factors should be considered. There are two purposes behind the blasting of parts to be brazed. One is to remove any oxide film and the other is to roughen the mating surfaces in order to increase capillary attraction of the brazing filler metal. The blasting material must be clean and must not leave any deposit on the surfaces to be joined that restricts filler-metal flow or impairs brazing. The particles of the blasting material should be angular rather than spherical, so that the blasted parts are lightly roughened, rather than peened, after the scale is removed. The operation should not distort or otherwise harm delicate parts. Vapour blasting and similar wet blasting methods require care, because of the possibility of surface contamination. Mechanical cleaning may be adequate, in which case it should be permitted (by the design) during manufacture. In those cases that require chemical cleaning, the cleaning operation may be followed by protective electroplating, which necessitates access to the faying surface by the liquids involved.

Temperature and Time: The temperature of the brazing filler metal has an important effect on the wetting and alloying action, which increases with increasing temperature. The temperature must be above the melting point of the brazing filler metal and below the melting point of the parent metal. Within this range, a brazing temperature that is most satisfactory overall is generally selected. Usually, low brazing temperatures are preferred in order to economize on the heat energy required, minimize the heat effect on the base metal (annealing, grain growth, or warpage, for example), minimize base-metal/filler-metal interactions, and increase the life of fixtures, jigs, or other tools. Higher brazing temperatures may be desirable so as to:

- Enable the use of a higher-melting, but more economical, brazing filler metal
- combine annealing, stress relief, or heat treatment of the base metal with brazing
- permit subsequent processing at elevated temperatures
- promote base-metal/filler-metal interactions in order to change the composition of the brazing filler metal (this technique is usually used to increase the remelt temperature and ductility of the joint)
- Effectively remove surface contaminants and oxides within protective atmospheres brazing (also applies to pure dry hydrogen, to argon, and to vacuum) · avoid stress cracking

The time at brazing temperature also affects the wetting action. If the brazing filler metal has a tendency to creep, the distance generally increases with time. The alloying action between filler metal and parent metal is, of course, a function of temperature, time, and quantity of filler metal. For production work, temperature, time, and quantity of filler metal are generally kept at a minimum, consistent with good quality, where diffusion is not required.

Brazing types based on heating methods

The numerous heating methods available for brazing often represent constraints on the designer or engineer when selecting the best type of capillary joint. However, because effective capillary joining requires the efficient transfer of heat from the heat source into the joint, one cannot braze a 0.025 mm (0.001 in.) dia wire to a 2.3 kg (5.1 lb) lump of copper with a small torch.

Brazing Technologies

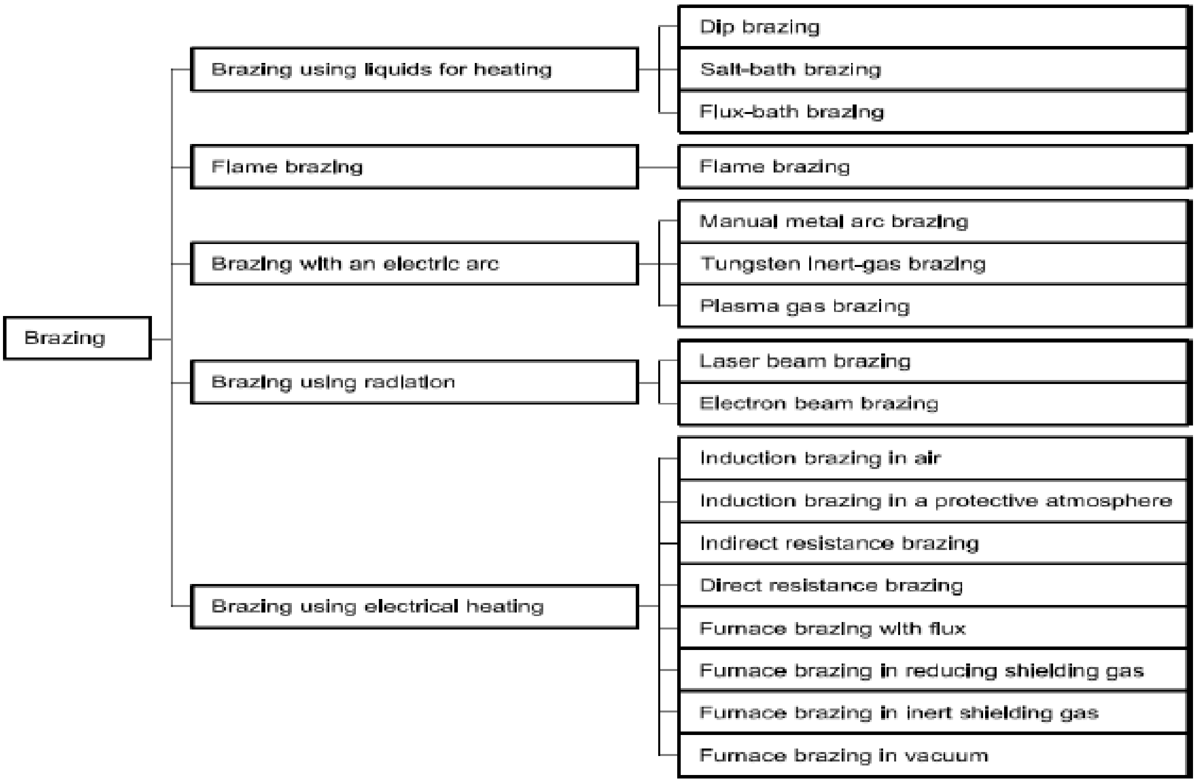


Table below shows the relative rating of selected brazing process heating methods:

METHOD	CHARACTERISTICS[A]					
	CAPITAL COST	RUNNING COST	BASIC OUTPUT	FLUX REQUIRED	VERSATILITY	OPERATOR SKILL REQUIRED
Torch (flame)	L/M	M/H	L	YES	H	YES
Electrical resistance	M	M	M/H	YES	L	NO
Induction	M/H	M	M/H	Y/N	M	NO
Furnace (atmosphere)	M/H	M/H	H	Y/N	M	NO
Furnace (vacuum)	H	L	H	NO	M	NO
Dip (flux bath)	L/M	M/H	L/M	YES	L	YES
Infrared	M	L	M	Y/N	L	NO

(A) H, HIGH; M, MEDIUM; L, LOW

Torch Brazing:

Torch Brazing (TB) utilizes a fuel gas flame as the heat source for the brazing process. The fuel gas is mixed with either air or oxygen to produce a flame, which is applied to the workpiece until the assembly reaches the proper brazing temperature. Then, preplaced filler metal will be melted or hand-fed wire can be introduced.

Advantages and Limitations

Torch brazing is used with various base metals and on many different sizes of assemblies. The process offers many advantages, including:

- Flexibility, in that one torch with multiple tips can be used to braze a variety of assemblies
- Low capital equipment cost (manual torch brazing)
- Entire assembly does not have to be heated; small joints on large assemblies can be heated locally
- Automation is possible in many cases
- Most base metals and combinations of base metals can be torch brazed if a suitable flux is available

Although the process provides versatile, low-cost heating for brazing, its limitations include:

- Oxidation/discoloration can occur on surfaces of the assembly not
- Covered with flux, because process is conducted in air flux residues need to be removed after brazing
- Highly reactive materials, such as titanium and zirconium, cannot be
- Torch brazed, because no flux is available large assemblies can be difficult to heat, because of the localized
- Nature of flame heating

Applications

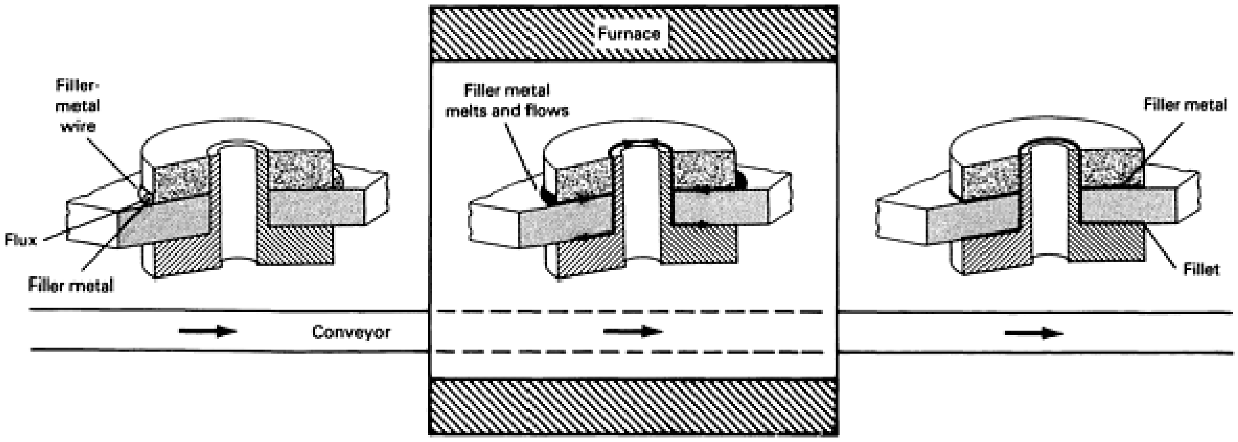
Torch brazing is commonly used on copper, brass, and other copper alloys, as well as steel, stainless steel, aluminum, carbides, and various heat-resistant materials. Most combinations of these materials can also be torch brazed. It is necessary to use flux with these materials, except when a phosphorus brazing alloy is used to braze pure copper parts. In this case, the phosphorus acts as the flux. The low-temperature silver-base and silver/copper/phosphorus filler metals are commonly used with torch brazing. Various other copper-base and gold-base filler metals can also be used with this process.

Torch brazing is often used to join copper and Bundy steel tube assemblies for the heating, air conditioning, and refrigeration industries. The process is also commonly used when brazing heat exchangers, bicycles, furniture, carbide tools, plumbing components, automotive subassemblies, medical instruments, and many other workpiece types. A wide range of components can be torch brazed, including small joints for jewelry parts, large-diameter (75 mm, or 5 in.) tubes, and fitting joints. The process provides strong, leak-tight joints on a wide variety of base materials.

Furnace brazing

It is a mass production process for joining the components of small assemblies with a metallurgical bond, using a nonferrous filler metal as the bonding material and a furnace as the heat source. Furnace brazing technology was initiated in the 1920s and was first used commercially circa 1930, primarily to provide a brazing process that did not require a chemical flux, thereby eliminating the flux entrapment problem.

Currently, furnace brazing is widely applied in a variety of industries. The automatic nature of the process and its use of unskilled labor account for its popularity.



In the furnace brazing process, cleaned parts and brazing filler metal are assembled, placed in a furnace, and heated to the brazing temperature. Furnace brazing is only practical if the filler metal can be placed on the joint before brazing and retained in position during brazing. Heating rate, brazing temperature and time, and cooling rate are controlled. Furthermore, in most cases, the brazing is carried out in a controlled atmosphere, which may be reducing, inert, or vacuum. The advantages and limitations of furnace brazing are identified below.

Process Advantages

There are at least five advantages to using the furnace brazing process:

· It is a method in which many variables can be easily controlled to ensure repeatability of the process and guarantee a high-quality joint. Brazing temperature and process duration, as well as heating and cooling rates, can be controlled and monitored. In addition, the brazing atmosphere can be easily regulated.

· When all the brazing procedures are well established, relatively unskilled operators can carry out every day manufacturing operations.

· The absence of flux entrapment allows more flexibility in joint design. The post-braze cleaning of the brazed part and the furnace are unnecessary.

· Because a whole assembly is heated, distortion of the parts can be minimized or eliminated. In some cases, heat treatment of the part can be incorporated into the brazing cycle.

· More than one joint per workpiece can be brazed in a brazing cycle. Several different assemblies requiring the same brazing conditions can also be brazed simultaneously.

Process limitations:

- The initial investment in furnace brazing equipment is relatively high. Furthermore, the maintenance of the equipment is critical and can be more expensive than other brazing techniques. The cost of a special atmosphere must also be considered.
- Because the whole assembly is heated, the cost of heating exceeds that of other brazing operations. In addition, microstructural changes in the base material can occur, depending on the material being brazed and the brazing temperature.
- Because brazing is performed inside the furnace, joint design is important. The fixtures for holding a brazed assembly require extra heat mass, which increases the manufacturing cost. Proper joint design can minimize or even eliminate fixture complexity.

Vacuum Brazing

Vacuum brazing is a term for various metal joining or brazing processes that take place in a chamber or retort below atmospheric pressure, otherwise known as a vacuum furnace Vacuum brazing is brazing in a furnace using a vacuum atmosphere Furnaces are categorized as hot wall or cold wall, depending on the location of the heating and insulating components Assemblies are bright and clean (after vacuum brazing because the extremely low amount oxygen in a vacuum atmosphere prevents oxidation of parts. Vacuum brazing is particularly useful where base metals are processed that adversely react with other atmospheres, or where entrapped fluxes or gases are intolerable. Vacuum brazing is widely used to braze base metals of stainless steel, super alloys and carbon low alloy steels. Vacuum brazing offers the combination of high cleanliness and uniform heating and cooling or rapid cooling. Vacuum brazing is ideal for oxidation sensitive materials such as those used in the aerospace industry. The reaction that takes place in a vacuum is a physical one in which the low pressures (high vacuum), combined with sufficiently high temperatures dissociates the metallic oxides and produces atomically clean surfaces. Clean, oxide free surfaces are imperative to ensure sound brazed joints of uniform quality. Uniform capillary attraction may be obtained only when all grease, oil, dirt, and oxides have been removed from both the filler metal and the base metal before brazing. Chemical and Mechanical methods can be employed for cleaning.

The vacuum furnace can ensure reaching the melting temperature with extreme precision and without over shoot. The problems of resistance to oxidation and corrosion of the alloy itself become negligible in the vacuum furnace. For the brazing to be successful the filler must melt (whether in the form of a paste or as a metallic wire or tape) at its own specific melting temperature and not at a higher temperature This primarily avoids the liquid being at a temperature at which its surface tension would be lower, and therefore wetting a greater surface area, with the resulting joint lacking the correct filling. The liquid must spread precisely within the joint cavity between the metals, creating an intermediate layer.

Capillary action ensures the alloy penetrates into the joint spaces in its liquid state. These are created by mechanical processing, exactly where the joint is required. Mechanical processing is required to obtain the right tolerances in the elements of the joint and must determine the exact bed dimension for the bond. The gap must be created so as to avoid too restrictive tolerances, in which case the bond could be difficult to fill and, at the other end of the spectrum, a weak joint would result from too great a tolerance, potentially with gaps or porosity. In fact, the alloy is drawn inside the surfaces to be joined at the wettability temperature against the force of gravity.

An alloy is required with a melting temperature far from the melting temperature of the metals being joined, but at the same time with suitable mechanical characteristics for the joint. In order to achieve perfect brazed joints the joint surface must be clean, without traces of processing oils or greases, in order to have good wettability. Brazing is simple and easy in a vacuum furnace Due to the nature of the vacuum, heat is evenly distributed and part production is consistent.

Production Cycle of Vacuum Brazed Parts Design

The following are to be considered during the Production Cycle of Vacuum Brazed Parts Design:

1. **Materials choice has to be besides functional requirements as well in accordance with vacuum brazing needs:**
   a. Copper with low oxygen content mandatory (OF/OFE copper)
   b. Thermal stress release of materials must be considered especially for high accuracy if necessary, usage of 3 D forged blanks (OFE copper, 316 LN stainless steel)
   c. Materials/alloys must not contain volatile elements (high vacuum at brazing temperature), i e Zn, Mn, Cd etc.
2. **Adequate gap clearance must be ensured by design and tolerances**
   a. Depending on the used BFM, certain gap clearances and surface roughness values for the areas to be brazed must be kept
   b. For flat joints, planarity has to be tolerated according to max gap requirements
3. **Design features for placement of BFM**
   a. Depending on form of applied BFM, i e wires (placed in grooves, chamfers), foils or paste
4. **Special cases**
   a. Metallization coatings for Al_2O_3 ceramics
   b. Ni plating etc

Materials joined

- Nickel and Iron based alloys containing aluminium and/or titanium
- Refractory metals
- Reactive metals
- Ceramics metal to ceramics
- Exotic base metals such as Aluminum Titanium,
- Zirconium, Niobium, Molybdenum, and Tantalum
- Beryllium brazing

MODLUE 5

PLASMA ARC WELDING & UNDERWATER WELDING

Plasma Arc Welding (PAW) can be defined as a gas-shielded arc welding process where the coalescence of metals is achieved via the heat transferred by an arc that is created between a tungsten electrode and a workpiece. The arc is constricted by a copper alloy nozzle orifice to form a highly collimated arc column. The plasma is formed through the ionization of a portion of the plasma (orifice) gas. The process can be operated with or without a filler wire addition.

Plasma Arc Welding is the welding process utilizing heat generated by a constricted arc struck between a tungsten non-consumable electrode and either the work piece (transferred arc process) or water cooled constricting nozzle (non-transferred arc process). Plasma is a gaseous mixture of positive ions, electrons and neutral gas molecules.

Transferred arc process produces plasma jet of high energy density and may be used for high speed welding and cutting of Ceramics, steels, Aluminum alloys, Copper alloys, Titanium alloys, Nickel alloys.

Non-transferred arc process produces plasma of relatively low energy density. It is used for welding of various metals and for plasma spraying (coating). Since the work piece in non-transferred plasma arc welding is not a part of electric circuit, the plasma arc torch may move from one work piece to other without extinguishing the arc

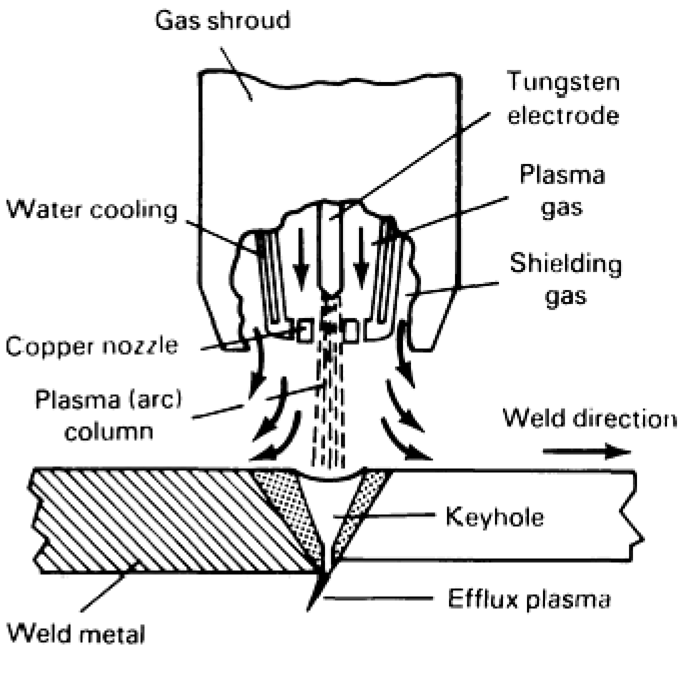


Fig. PAW Principle

Principles of Operation:

Once the equipment is set up and the welding sequence is initiated, the plasma and shielding gases are switched on. A pilot arc is then struck between a tungsten alloy electrode and the copper alloy nozzle within the torch (non-transferred arc mode), usually by applying a high-frequency open-circuit voltage. When the torch is brought in close proximity to the workpiece or when the selected welding current is initiated, the arc is transferred from the electrode to the workpiece through the orifice in the copper alloy nozzle (transferred arc mode), at which point a weld pool is formed. The PAW process can be used in two distinct operating modes, often described as the melt-in mode and the keyhole mode. The melt-in-mode refers to a weld pool similar to that which typically forms in the gas-tungsten arc welding (GTAW) process, where a bowl-shaped portion of the workpiece material that is under the arc is melted.

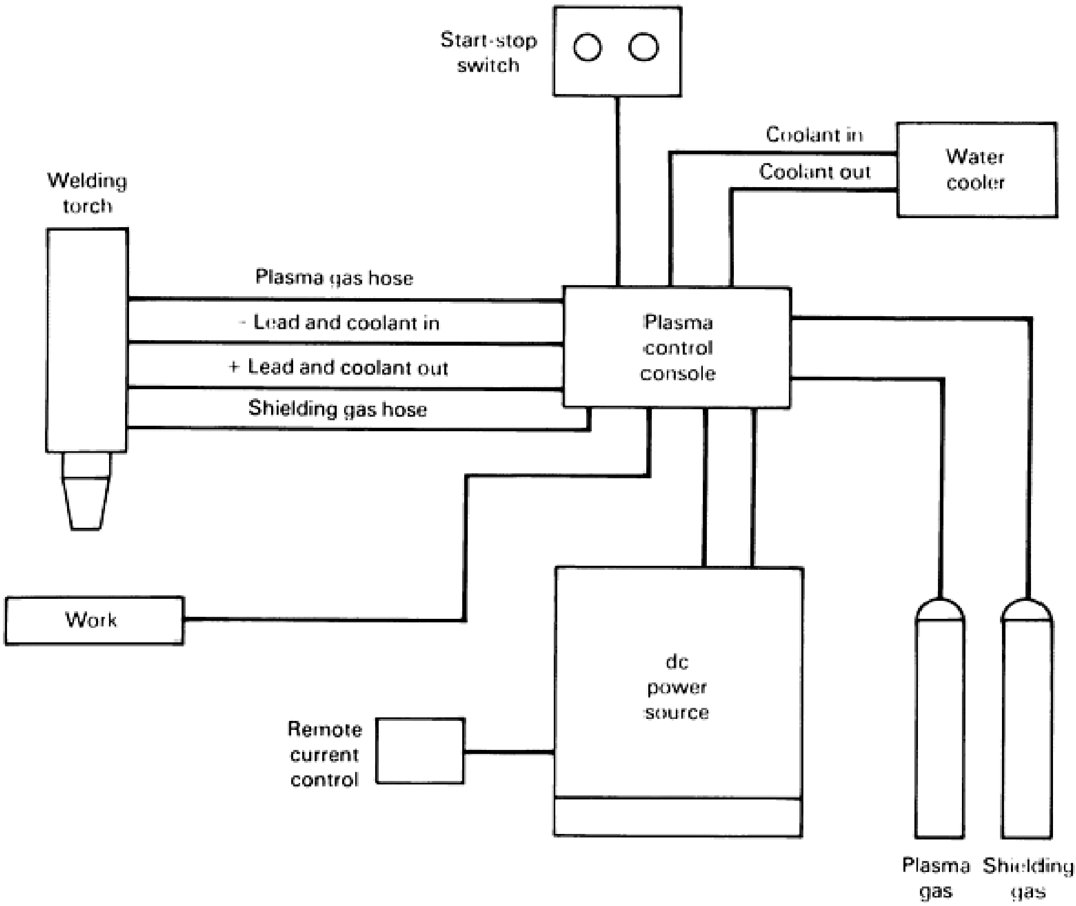


Fig. Typical PAW machine structure

Equipment and Tooling

Power Source: The power source, which supplies the main power for the welding system, is usually supplemented with a sequence controller and control console. The sequence controller sequences the timing of gas flow, arc initiation, main welding current control, and any up-slope and downslope parameters. In its simplest form, the plasma control console controls the gas flow for plasma and shielding gases from separate flow-meters and incorporates the high-frequency pilot arc initiation circuit. The welding torch can be manual or mechanized and is water cooled to avoid torch overheating and to maximize component life.

In most PAW installations, plasma and shielding gases are supplied from separate gas cylinders, although bulk gas can readily be used. The gas supply is usually routed through the plasma control console, where the individual flow rates are set by the operator. The power source should be of a constant-current design. Transistorized power sources are most common, although inverter power supplies are also available. It should have a minimum open-circuit voltage of 80 V to ensure the reliable initiation and transfer of the main arc current. The power source can be adjusted for welding current and it should have the capability to adjust the up slope and down slope of the current. It may be equipped with thumbwheels or potentiometers to select the parameters for pulse current operation, that is, peak and background current levels, as well as peak and background times.

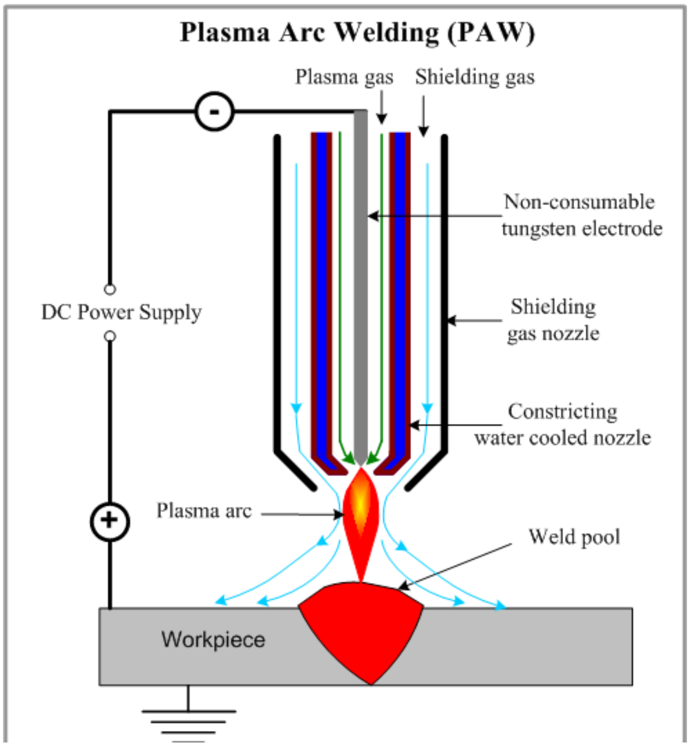


Fig. PAW Equipment

Welding Torches: Like those of the other arc welding processes, PAW torches are available in a range of sizes for different power ratings and in manual and mechanized versions. The design principles are the same in each case. A tungsten alloy electrode is held in a collet within the torch body. To avoid one of the most common defects in plasma torches, it is critical to hold concentricity between the tungsten electrode and the orifice in the design and manufacture of the torch. The electrode assembly is set inside a plenum chamber and the plasma gas is supplied to this chamber. A threaded copper alloy nozzle forms the front of this chamber and contains the nozzle orifice that is used to constrict the plasma arc. A shielding gas nozzle, usually of an insulating ceramic material, is threaded onto the front end of the torch and surrounds the constricting nozzle, creating an annulus through which the shielding gas is supplied. The torch is connected electrically to the power source and the electrode forms the negative pole of the circuit for dc welding. The gas hoses that supply the plasma and shielding gases and the water hoses that supply and remove water from the torch are all connected to the torch body or handle. These hoses are enclosed in a flexible sheath that extends from the torch to the components of the welding system. Most constricting nozzles have a single orifice in the center. However, multiple-nozzle orifices can be used with higher power torches to achieve further arc constriction. The most common version of this type of nozzle has a central orifice flanked by a smaller orifice on each side. The common centerline of the three orifices is arranged at 90° to the weld line during operation.

Electrodes: The non-consumable electrode employed is usually a 2% thoriated tungsten electrode, that is, tungsten with 2% thorium oxide. The electrode specification is covered in AWS A5.12-92. The electrode size is selected according to the welding current level that will be used. The electrode is ground with a tapered point on the end, the angle of which depends on the selected welding current level. There are two different approaches to PAW.

1. Transferred Plasma Arc Welding

This process uses a straight polarity DC current. The workpiece is connected to the positive terminal while the tungsten electrode to the negative terminal. The arc is maintained between the workpiece and the tungsten electrode. Heating of a co-axial gas maintains it in a plasma state. Both the arc and plasma are transferred to the workpiece to increase the heating processes. This process features a high-density plasma arc that conducts through the ionization of argon gas that's passed through the electric arc. The transferred arc is throttled to achieve high temperatures, gaining a plasma column with temperatures between 8000- 18000 degrees Celsius.

Application of Transferred Plasma Arc Welding

This process is suitable for workpiece that are subject to wear and tear or corrosion.

Transferred plasma arc welding is applied in the following processes;

- forging matrix dies
- plasticizing screw
- making hydraulic cylinders
- making moulds and accessories for the glass industry

- forging industrial blades and knives
- making automotive valves

Advantages of Transferred Plasma Arc Welding

- **High Levels of Structural Quality:**

  Transferred plasma arc welding is different from other welding methods. It maintains metallurgical homogeneity, and the controlled penetration allows single-pass coating that translates to high-quality welding.

- **High Welding Speeds**

Transferred arc welding can weld up to 500mm in a minute, more than cool wire TIG welding. If you want a fast welding process, this might be an ideal option for you.

- **High Energy Efficiency**

High welding speeds limit thermal addition, thus saving much on energy. An average of 12KW of electric energy is capable of depositing six kos/h of metal. Additionally, this energy reduces the deformation of metal workpieces while maintaining the metallurgical structure.

- **Low Pollution**

Compared to traditional welding methods, transferred arc welding produces fumes with low atmospheric pollution.

2. Non-Transferred Plasma Arc Welding

In this process, the plasma arc torch has two electrodes, a rear and a front one. A direct current (DC) between the two electrodes create an iodized-gas plasma that's constricted at the end of the torch.

The heat generated from non-transferred plasma arc welding is more dispersed than the transferred plasma arc. This makes the non-transferred arc welding process suitable for a wide range of applications. Current flows from the electrode inside the torch to the orifice-containing nozzle and back to the power supply.

Advantages of Non-Transferred Plasma Arc Welding

This process is suitable for large surface areas due to plasma spraying. Its main advantages include the following;

- **Precise Welding on Thin Metal Sheets**

One of the benefits of this process is the production of precise welds. Unlike in the transferred plasma arc, products appear more clear-cut and robust.

- **Lower Energy Consumption**

Compared to the transferred plasma arc, this method consumes relatively lower energy.

Application of Non-Transferred Plasma Arc Welding

The primary purposes of this process its plasma spraying. This is a thermal coating process whereby heat-softened particles that form a coating are applied onto a substrate. This reduces corrosion damage and gives materials a longer life.

Plasma (Orifice) and Shielding Gases: The plasma gas is used to generate the arc, whereas the shielding gas is used to provide the weld pool with supplementary shielding from atmospheric contamination while it solidifies and cools. The plasma gas is almost always argon. Gas properties affect both weld shape and quality. Flow rates, particularly of the plasma gas, are also important, because they control the extent of plasma constriction. The flow rate can vary from 0.1 L/min (0.026 gal/min) for micro-plasma welding up to 10 L/min (2.6 gal/min) for keyhole plasma welding. Considerable care is needed to regulate the gas flow rate if keyhole closure is required, because the flow rate must be sloped out to 1 to 2 L/min (0.26 to 0.52 gal/min) within about 1 s. Gas flow control is best achieved by electronic means. The design and current rating of welding torches are based on argon plasma gas. Argon provides effective shielding, being heavier than air, and is cheaper than helium. Shielding gas selection is based on the type of base metal (refer table below)

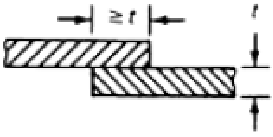
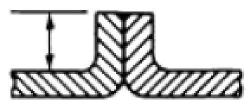
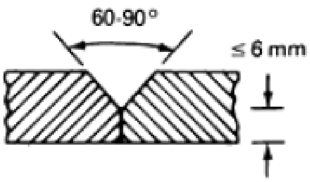
TABLE 2 PLASMA AND SHIELDING GAS COMPOSITIONS

MATERIAL	PLASMA GAS	SHIELDING GAS
MILD STEEL	ARGON	ARGON ARGON-2-5% H_2 (A)
LOW-ALLOY STEELS	ARGON	ARGON
AUSTENITIC STAINLESS STEEL	ARGON	ARGON-2-5% H_2 HELIUM (A)
NICKEL AND NICKEL ALLOY	ARGON	ARGON ARGON-2-5% H_2 (A)
TITANIUM	ARGON	ARGON 75HE-25AR (A)
ALUMINUM AND ALUMINUM ALLOYS	ARGON	ARGON HELIUM (A)
COPPER AND COPPER ALLOYS	ARGON	ARGON 75HE-25AR (A)

(A) ALSO USED

Typical Components and Joints

The most common joint configuration used with the PAW process is a butt joint. The micro-plasma mode is used with overlapped butt (micro-lap) joints and with joints that have integral weld metal as a result of flanged, butted edges on very thin metals (Table 3). Corner joints with edge welds are also commonly welded using the micro-plasma and medium current modes.

Thickness range						
mm	**in.**	**Joint type**	**Joint configuration**	**Process variant**	**No. of runs**	**Comments**
0.5–1.0	0.02–0.04	Micro-lap		Microplasma	1	Edges fully fused to produce additional weld metal; good clamping essential
0.5–1.5	0.02–0.06	Flanged edge		Microplasma	1	Edges fully fused to produce additional weld metal
3.0–6.0	0.12–0.24	Square butt		Keyhole plasma	1	Grooved backing bar required to prevent disturbance of the efflux plasma. Additional (cosmetic) run using melt mode may be employed
6.0–15	0.24–0.60	Single-V butt		Keyhole plasma	2 or more	Keyhole technique used for root run only. Joint completed with the melt mode plus filler wire

Because the keyhole operating mode fully penetrates the workpiece, it is used exclusively on square-grooved butt joints and single-V joints with a root face (Table 3). For square-grooved butt joint preparation, the thickness that can be welded in a single pass depends on the fluid flow characteristics of the workpiece material for a given heat input from the plasma torch. Thus, alloys of titanium and zirconium can be butt welded with square-grooved preparation at greater thicknesses than steels and stainless steels. Generally, it is an industry-accepted practice to use square-grooved preparation without edge bevelling for stainless steels up to 6 mm (0.24 in.) in thickness.

Procedures

Process Operating Procedure: Welding parameters, such as welding current, arc voltage, travel speed (for mechanized/automatic operation), and plasma and shielding gas flow rates, are set by the procedure and implemented by the welder. Torch parameters include the correct electrode vertex angle and set-back distance, as well as the correct orifice diameter for the welding current level. The operating sequence for the PAW process was described in the section "Principles of Operation" at the beginning of this article. After the weld pool or keyhole is formed, the torch is traversed across the workpiece at the pre-set welding speed. Welding is terminated by the down slope of the welding current, with simultaneous sloping of the plasma gas flow rate if keyhole welding and keyhole closure are desired. Most plasma arc welding is done in a mechanized or automated operation that does not require much operator intervention, except initially to set the parameters and to position the workpiece and torch. When current pulsing and keyhole closure operations are involved, numerous parameters must be set, which requires strict attention to detail, accurate part fit-up, and careful alignment of the torch relative to the joint.

Inspection and Weld Quality Control: All of the common non-destructive evaluation (NDE) techniques are applicable to plasma arc welds. Radiography and ultrasonic inspection are the most common techniques used. The fact that most plasma arc welding is carried out in the keyhole mode means that there is a penetration bead on the root side of the joint. Visual inspection for full penetration, as well as for correct width and profile of both the penetration bead and the weld surface profile, can readily be accomplished. Smooth, even under beads can be achieved through good procedure development with tolerances improved through current pulsing.

Troubleshooting: When troubleshooting a PAW operation, all of the previously defined basic parameters of the welding schedule should be checked. Welding discontinuities can result from incorrect electrode set-back or from a worn or damaged nozzle orifice. The concentricity of the diameter of the nozzle orifice and the alignment of the electrode and nozzle orifice are very important. Worn nozzles should be replaced. The condition of the tungsten electrode tip should also be checked. An undercut is one of the most common defects in the PAW process. Depending on material type, thickness, and pre-set welding parameters, a two-sided undercut can occur above certain threshold welding speeds. This can only be eliminated by increasing welding current. A one-sided undercut can result from misalignment of the torch, the electrode/orifice and multiport nozzles, or from the mismatched fit-up of the workpieces. Correct alignment is essential.

MICRO PLASMA ARC WELDING

Principle of Micro Plasma Arc Welding (MPAW)

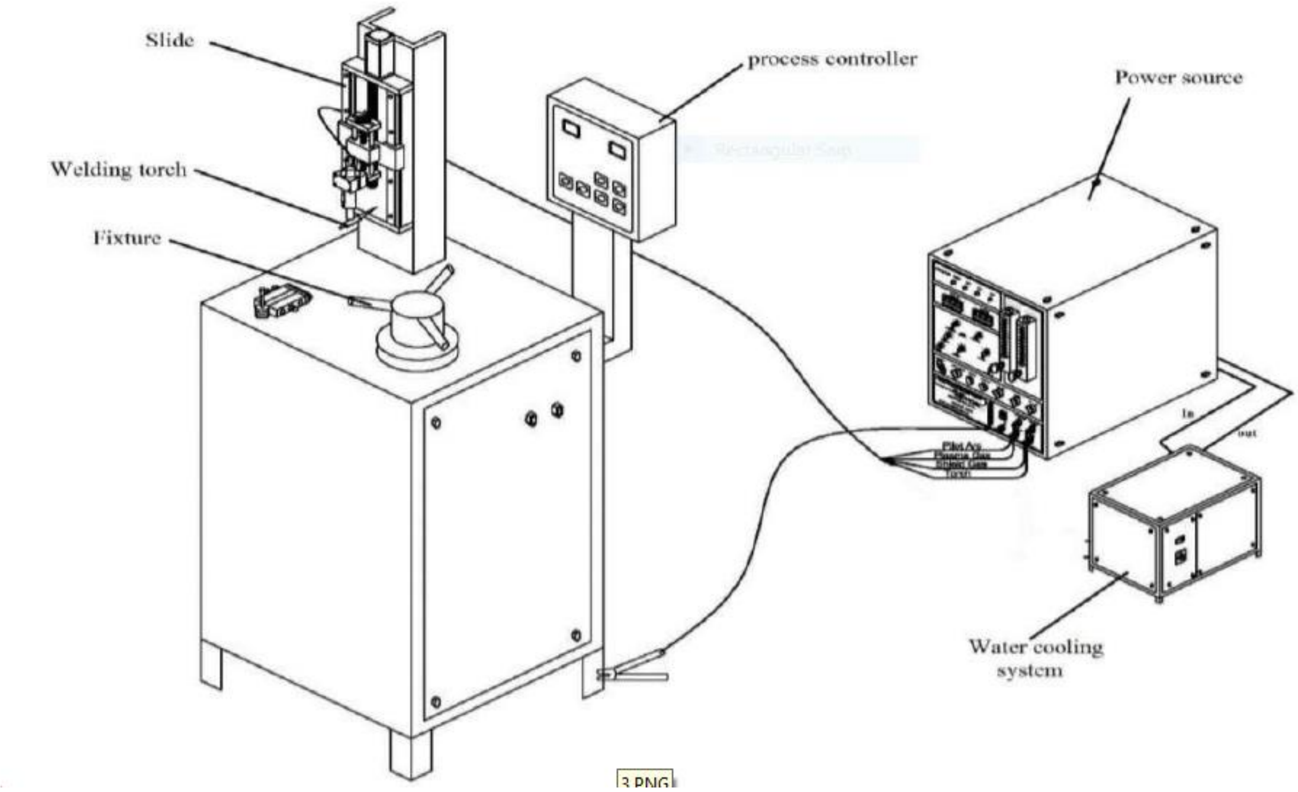
An arc is formed between the electrode and the work piece in an inert atmosphere to fuse metal in a joint area and produce a molten weld pool. The uniqueness of MPAW from other welding processes is the electrode is positioned within the body of the torch and the plasma forming gas is separated from the shielding gas envelope where in the other processes the electrode is exposed to the atmosphere during the process. It has a mechanism called the ‘pilot arc’ that is struck between the electrode and nozzle to initiate the main welding arc. The pilot arc can be shut off after the main arc starts or can be kept on all the time. This helps when welding mesh or similar jobs where the main arc shuts down when there is no metal for the current to flow. The current range of micro plasma arc varies from 0 1 A 15 A. Even at welding current at 0 1 A the length can be varied possibly up to 10 mm without affecting stability of the arc and the columnar nature of the arc transfers the arc without excessive spreading. Highest quality welds can be produced by welders who had never learnt the fundamentals of plasma arc welding as it is an easy process to learn.

Equipment

The Micro Plasma Arc welding machine consist of basic equipment such as

1. Power Source
2. Plasma Console
3. Process controller
4. Plasma Welding Torch
5. Fixture
6. Table to hold the fixture
7. Pilot arc control
8. Gas cylinders
9. Water cooling system

Fully Automated Micro Plasma Arc Welding Equipment



Power source

Generally in Micro plasma arc welding DC current source is used Micro plasma arc welding current generally can vary from a range of 0 01 amp to 15 amp. Optionally it can vary up to 50 amps. Pulsing facility is provided. The pulsed arc has the ability to produce highest and precise weld quality. Up slope and down slope of current is provided. Coolant flow rate is monitored in order to protect the plasma torch from overheating. High performance cooling is done by circulating water through the welding torch. Variable pulse mode operation is available. Flow meters are available to ensure precise setting of both plasma and shielding gas flow rate. Various parameters such as pilot current, main current, gas flow rate are controlled to ensure good results.

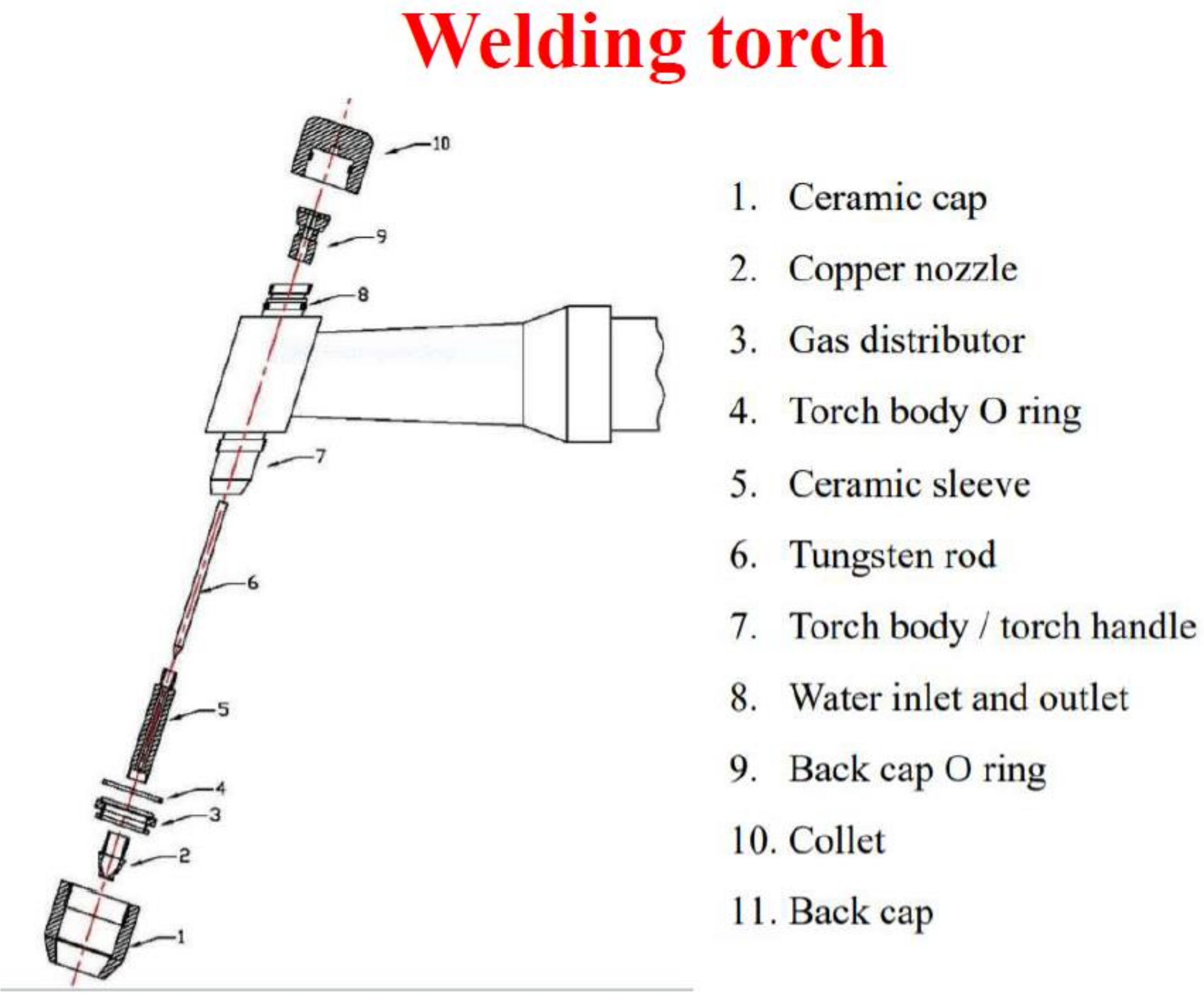
Welding torch

Micro Plasma Arc Welding Torches are available both in manual and fully automated mode.Manual MPAW generally can work in all position where in fully mechanized MPAW is done in the flat and horizontal positions. The arc is transferred from the electrode to the work piece through the orifice which is of 2 types,

1. Cylindrical Orifice

2. Divergent Orifice

The Micro Plasma Welding most commonly uses cylindrical orifice where the current conducting capacity is 0.1A and above.



Advantages & Disadvantages

- It can be done very fast and it does not produce any heat affected zone around the weld where loss of alloying element can occur.
- The plasma arc is highly stable and consistent when compared to other welding processes.
- The welding speed is high.
- It has minimal heat affected zone.
- The pilot arc ignition ensures welding arc is struck consistently even on jobs like wire mesh.
- Pilot arc can be adjusted according to work done

- Variable connection option for standard torches are provided
- DC power source is available which can be used depending on the application of the job
- Welding current is low as 0 1 Amp for very small delicate jobs
- It can be fully automated system which results in precise repeatable welding for mass production
- The cost of the equipment is very high when compared to TIG welding but economical when compared to laser beam and electron beam welding

Applications

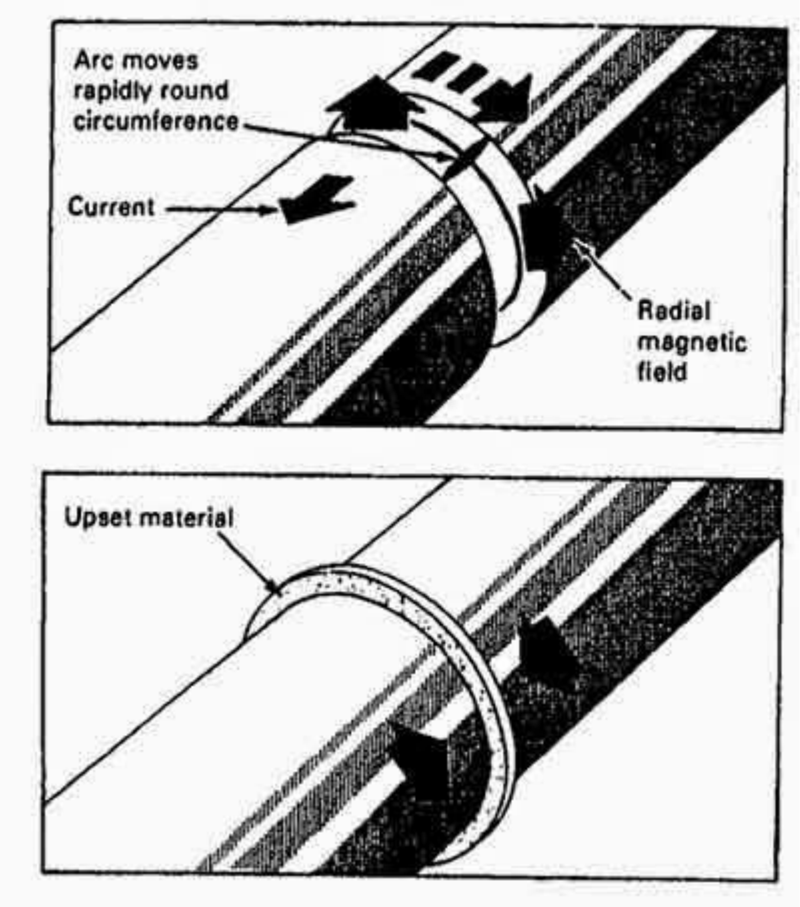
- It is used in aerospace and nuclear industries
- It is used in large number of medical industries including Bio implants such as stainless steel canister of the electronic pace maker, stents, orthopaedic implants, etc.
- It is used in automobile industries especially in exhaust pipes of formula one racing cars, high performance motorcycles, etc.
- It is used in everyday items like coffee pots, stainless steel water storage pots, table counters in canteens, kitchen sinks, etc.
- In industries it can be used for Precision instruments, Pressure and load sensor, batteries, metal seals, hydraulic and pneumatic systems, Bellows, thin sheets, tool and die mould, thermocouple, etc.
- The suitable materials that can be welded using Micro Plasma Welding are stainless steel, nickel based alloys, heat resistant alloys, non-ferrous metals, silver, titanium, etc.

MAGNETICALLY IMPELLED ARC BUTT (MIAB) WELDING

Magnetically impelled arc butt (MIAB) welding (sometimes referred to as rotating arc welding) is a rapid, clean, and reliable arc welding process that employs forging to produce the finished weld. As such, it is classified as an electric arc welding process since that is the energy source for producing melting or fusion, even though pressure from forging is needed to complete the weld. It is thus a fusion arc pressure welding process, and, in that way, is related to arc stud welding. The MIAB welding process is well established in Europe (especially Eastern Europe) and the independent states of the former Soviet Union, finding application in the automotive industry for the fabrication of tubular-section butt welds and, to a lesser extent, tube-to-plate welds. Tubes can have circular or non-circular cross sections, with walls ranging from 0.5 to 5 mm or more (0.020 to 0.200 in.) thick. Steel as well as aluminum alloy has been welded successfully in mass production, producing welds with exceptional quality even for safety-critical applications.

Magnetically Impelled Arc Butt Welding Principles

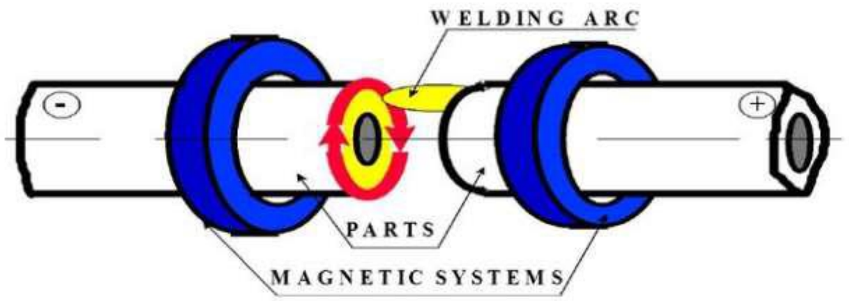
In practice, MIAB welding is fully automated. An arc drawn between aligned but properly gapped tube ends is impelled to move (rotate) around the joint line by an interaction of the arc current and an externally applied magnetic field , hence the name. Once the arc has heated the ends of the tubes to cause localized melting and adjacent softening in the heat-affected zone, the parts are forged together. This expels most of the molten metal present and a solid-phase bond is formed. The principle of operation is shown schematically in Figure 1; typical placement of the magnets used to apply the propelling force to the arc is shown in Figure 2



Schematic of the operation of the magnetically impelled arc butt (MIAB) welding process

Figure 1: MIAB principles, Schematic of the typical placement of magnets for propelling the arc in MIAB welding,

Principle of MIAB welding



MIAB welding is a forge welding process that relies on an electric arc to generate necessary heating to melt the surfaces being welded.

How MIAB welding works?

- *Welding arc rotate in the gap between tubes due to the presence of external magnetic field generated with permanent or electromagnets.*
- *The maximum Linear Speed of the arc movement is 870 km/hour.*
- *The spinning arc in combination with thermal conductivity of the welded metal creates very uniform heating at the joint.*
- *On completion of welding, the welded parts are rapidly brought under pressure.*

Benefits of MIAB

The major benefits of MIAB welding are

(1) No rotation of either component (thereby overcoming problems with asymmetrical parts encountered with many friction welding processes),

(2) Short welding times (e.g., 2-4 s for 2 to 4-mm CO.040 - to 0.080-in. thick low-carbon steel tube),

(3) Low material loss,

(4) Low fumes and spatter, and

(5) Relatively low required arc current.

As opposed to flash and upset welding, MIAB welding does not use resistance to accomplish heating at the joint, but, rather, an electric arc. This makes it an arc rather than a resistance welding process. The fact that forging removes most molten metal suggests that the process could be considered non-fusion; after all, the role of the liquid is largely fluxing . The process is considered a non-consumable electrode arc process because the intent is not to consume the parts being welded and used as electrodes, but to preserve those parts.

UNDERWATER WELDING

Underwater Welding or Hyperbaric welding is the process of welding at elevated pressures, normally underwater. Hyperbaric welding can either take place wet in the water itself or dry inside a specially constructed positive pressure enclosure and hence a dry environment. It is predominantly referred to as "hyperbaric welding" when used in a dry environment, and "underwater welding" when in a wet environment. The applications of hyperbaric welding are diverse it is often used to repair ships, offshore oil platforms, and pipelines. Steel is the most common material welded.

Dry welding is used in preference to wet underwater welding when high quality welds are required because of the increased control over conditions which can be exerted, such as through application of prior and post weld heat treatments. This improved environmental control leads directly to improved process performance and a generally much higher quality weld than a comparative wet weld. Thus, when a very high quality weld is required, dry hyperbaric welding is normally utilized. Research into using dry hyperbaric welding at depths of up to 1,000 metres (3,300 ft) is on-going. In general, assuring the integrity of underwater welds can be difficult (but is possible using various non-destructive testing applications), especially for wet underwater welds, because defects are difficult to detect if the defects are beneath the surface of the weld. Underwater hyperbaric welding was invented by the Russian metallurgist Konstantin Khrenov in 1932.

Dry welding

Dry hyperbaric welding involves the weld being performed at raised pressure in a chamber filled with a gas mixture sealed around the structure being welded. Most arc welding processes such as shielded metal arc welding (SMAW), flux-cored arc welding (FCAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), plasma arc welding (PAW) could be operated at hyperbaric pressures, but all suffer as the pressure increases. Gas tungsten arc welding is most commonly used. The degradation is associated with physical changes of the arc behaviour as the gas flow regime around the arc changes and the arc roots contract and become more mobile. Of note is a dramatic increase in arc voltage which is associated with the increase in pressure. Overall degradation in capability and efficiency results as the pressure increases. Special control techniques have been applied which have allowed welding down to 2,500 m (8,200 ft) simulated water depth in the laboratory, but dry hyperbaric welding has thus far been limited operationally to less than 400 m (1,300 ft) water depth by the physiological capability of divers to operate the welding equipment at high pressures and practical considerations concerning construction of an automated pressure / welding chamber at depth.

Methods of Dry Welding:

Pressure Welding: Working in a pressure vessel measuring one atmosphere unit of pressure (same as pressure at sea level).

Habitat Welding: Using a chamber in ambient pressure (same as surrounding pressure at working depth) about the size of a small room to weld. Before entering, the chamber displaces its water the surrounding ocean or lake.

Dry Chamber Welding: It is habitat welding, but with a smaller chamber The chamber holds the head and shoulders of a diver (dressed in diving gear) and is open at the bottom for the to fit in.

Dry Spot Welding: Here the habitat is even smaller. The habitat shrinks to the size of about the welder diver's head, and it's completely clear. It is placed on the weld site and the welder inserts his or her electrode inside the habitat, which seals around

Advantages of Dry Welding

- Better diver safety
- Better quality welds
- No build-up of hydrogen and oxygen pockets
- Allows for heat treatment before and after welding
- Surface monitoring possible

Disadvantages of Dry Welding

- Requires large, complex equipment.
- Chamber has to be fabricated differently for different applications
- Cost is very high and increases with depth
- More energy requirement

Wet welding

Wet underwater welding directly exposes the diver and electrode to the water and surrounding elements. Divers usually use around 300–400 amps of direct current to power their electrode, and they weld using varied forms of arc welding. This practice commonly uses a variation of shielded metal arc welding, employing a waterproof electrode. Other processes that are used include flux-cored arc welding and friction welding. In each of these cases, the welding power supply is connected to the welding equipment through cables and hoses. The process is generally limited to low carbon equivalent steels, especially at greater depths, because of hydrogen-caused cracking.

Wet welding with a stick electrode is done with similar equipment to that used for dry welding, but the electrode holders are designed for water cooling and are more heavily insulated. They will overheat if used out of the water. A constant current welding machine is used for manual metal arc welding. Direct current is used, and a heavy duty isolation switch is installed in the welding cable at the surface control position, so that the welding current can be disconnected when not in use. The welder instructs the surface operator to make and break the contact as required during the procedure. The contacts should only be closed during actual welding, and opened at other times, particularly when changing electrodes.

The electric arc heats the workpiece and the welding rod, and the molten metal is transferred through the gas bubble around the arc. The gas bubble is partly formed from decomposition of the flux coating on the electrode but it is usually contaminated to some extent by steam. Current flow induces transfer of metal droplets from the electrode to the workpiece and enables positional welding by a skilled operator. Slag deposition on the weld surface helps to slow the rate of cooling, but rapid cooling is one of the biggest problems in producing a quality weld.

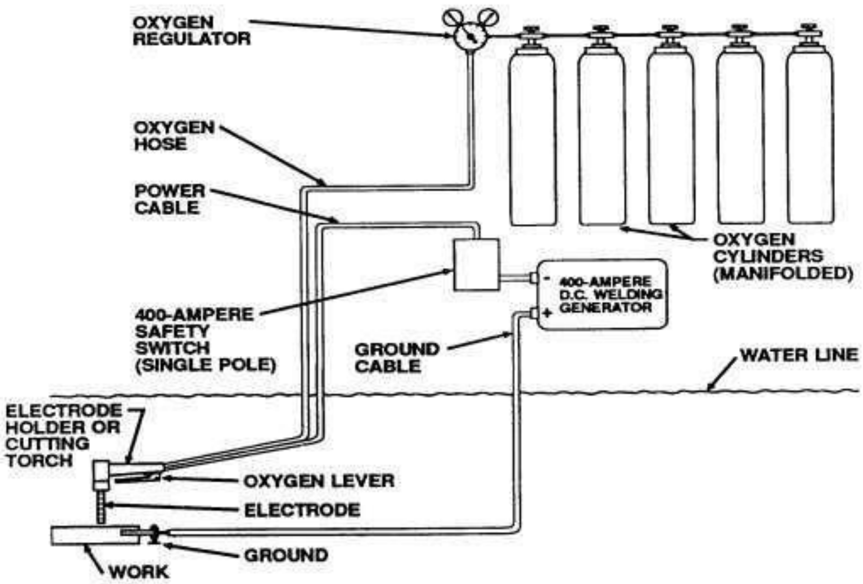


Fig. Schematic of Underwater welding

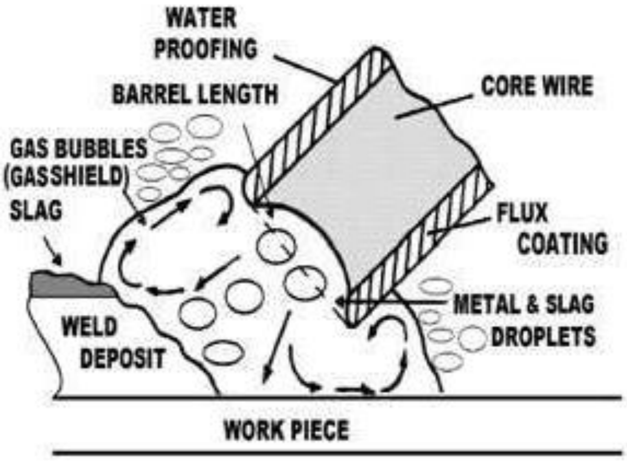


Fig. Weld Environment in underwater welding

Advantages of wet welding

- The versatility and low cost of wet welding makes this method highly desirable
- Other benefits include the speed with which the operation is carried out
- It is less costly compared to dry welding
- The welder can reach portions of offshore structures that could not be welded using other methods
- No enclosures are needed and no time is lost building
- Readily available standard welding machine and equipment are used
- The equipment needed for mobilization of a wet welded job is minimal

Disadvantages of wet welding

- There is rapid quenching of the weld metal by the surrounding water
- Although quenching increases the tensile strength of the weld, it decreases the ductility and impact strength of the weldment and increases porosity and hardness
- Hydrogen embrittlement: Large amount of hydrogen is present in the weld region, resulting from the dissociation of the water vapour in the arc region. The $H2$ dissolves in the Heat Affected Zone and the weld metal, which causes Embrittlement cracks and microscopic fissures Cracks can grow and may result in catastrophic failure of the structure
- Another disadvantage is poor visibility. The welder sometimes is not able to weld properly

Application of underwater welding

The important applications of underwater welding are

(a) Offshore construction for tapping sea resources,

(b) Temporary repair work caused by ships collisions or unexpected accidents

(c) Salvaging vessels sunk in the sea

(d) Repair and maintenance of ships

(e) Construction of large ships beyond the capacity of existing docks

(f) Repair and maintenance of underwater pipelines

Dangers of Underwater Welding

- Chances of an Electric Shock: This happens when the welding equipment that is used is not adapted to work under the water. The equipment should be tested properly, well insulated and a waterproof electrode should be connected to it
- Possibility of an Explosion: The chances of such explosions are more in processes, wherein both, hydrogen and oxygen are involved, and may lead to the formation of numerous gas pockets. During hyperbaric welding, the formation and combination of hydrogen and oxygen pockets is dangerous because they are explosive, when ignited.
- Decompression Sickness: Decompression sickness, also known as 'diver's disease. Diver inhales harmful gases such as nitrogen, when he dives quickly from a high pressure zone to a low pressure zone. If the welder dives too fast to the surface of the water, nitrogen bubbles enter his bloodstream. These bubbles then spread inside the diver's body, and start showing numerous adverse symptoms. Decompression sickness may lead variably to rashes, joint pain, paralysis or even death of a person.
- Breakdown of Dental Amalgam: As a result a metallic taste in the mouth. Recent studies have shown that in the process of electric welding and cutting under the water, a magnetic field with alternating current gets created This magnetic field, in turn, induces a secondary current in the oral tissues of the welders, due to which their dental amalgam breaks down.

MODULE 6

FRICTION WELDING TECHNIQUES

FRICTION WELDING (FRW)

FRW in its simplest form involves two axially aligned parts. While one part is rotated, the other stationary part is advanced to make pressure contact. Axial force then increases to generate the frictional heat necessary for welding at the abutting surfaces in order to form a solid-state joint. Friction welding can be divided into two major process variations, depending on the manner by which rotational energy is converted into frictional heat. The first process, direct-drive, or continuous-drive, FRW, has been used commercially since the 1940s. It requires constant energy from a source for any desired duration. The second process, inertia-drive FRW, which was developed in the early 1960s, uses the kinetic energy stored in a rotating flywheel.

Direct-Drive Friction Welding (DDFW)

Figure 1 shows the layout of a direct-drive FRW system. The spindle is first driven to a predetermined constant speed, and the two parts are brought together under a preset axial force. Both rotation and force are maintained for a specific period determined either by a time or a distance, so that the frictional heat will raise temperatures at the abutting surfaces enough to render the material plastic and suitable for welding. (However, direct-drive friction welds are almost never made using a single level of axial load. The vast majority of welds are made using a minimum of two axial force levels. The second axial load is basically added to the beginning of the weld cycle to yield a preheating phase. In fact, direct drive friction welds using three axial loads are more commonly applied than those using a single load.) The spindle is then disengaged from the driving unit, and a brake is applied to bring the spindle to rest. At the same time, axial force either remains unchanged or is raised to complete the weld.

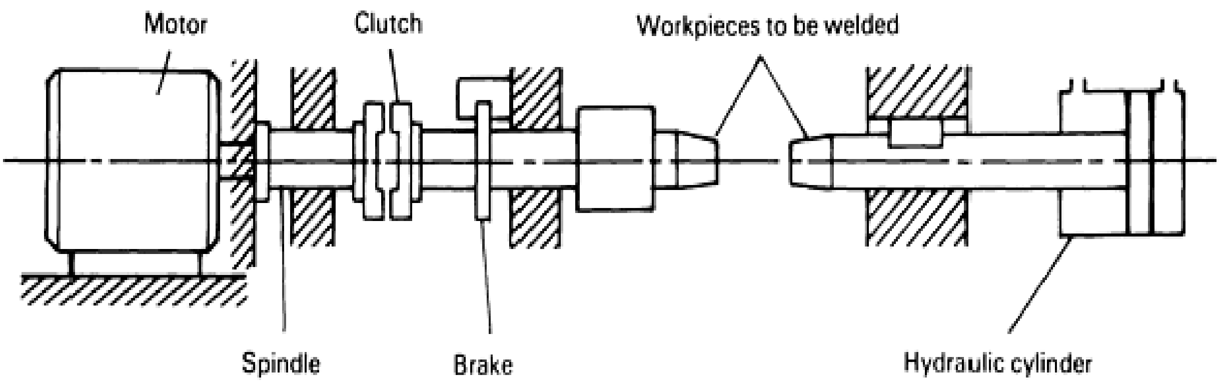


Fig.1 Schematic showing relation of workpiece to key components of a Direct-Drive FRW System

Inertia-Drive Friction Welding (IDFW)

In inertia-drive FRW (Fig. 2), a flywheel and the rotating part are mounted in a spindle, which is driven to the desired speed. The drive source is then disengaged, and the two parts make contact under a pre-set axial force. The free-rotating flywheel decelerates under either the same applied force or later under a larger force. Meanwhile, kinetic energy stored in the flywheel and spindle is converted to frictional heat at the abutting surfaces. The weld is complete when the flywheel comes to a stop. A subsequent higher forging force may be used after the flywheel has stopped.

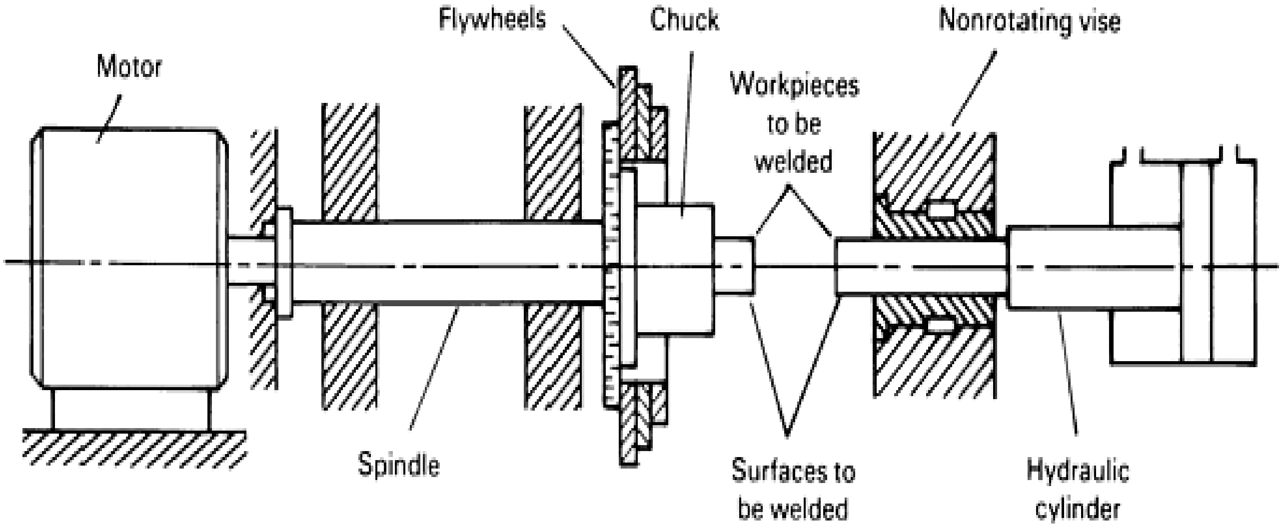


Fig. 2 Schematic showing relation of workpieces to key components of an Inertia-Drive FRW System.

WELDING PARAMETERS

Direct-Drive FRW Variables:

Three parameters control the character of a weld in direct-drive FRW: rotational speed, duration of rotation, and axial force. During welding, there is not only an axial shortening of the part length, often called axial displacement or upset, but also a resisting torque of friction to rotation, which also undergoes change. Figure 3 shows the change in various events occurring throughout the whole process. Based on the shape of the friction torque curve, it is convenient to divide direct-drive FRW into three phases:

- Phase 1: **Initial Friction** (break-in or first friction) Phase
- Phase 2: **Heating** (friction) Phase
- Phase 3: **Forging** (upsetting) Phase

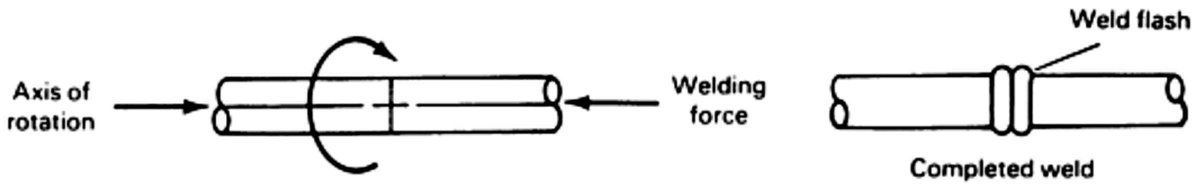
In phase 1, the torque rises rapidly after the start of the process. It then peaks and drops before levelling off when phase 1 ends. The rapid rise and gradual fall of torque is associated with the interlocking and breaking of asperities and subsequent softening of the material at the faying surfaces by frictional heating.

Friction torque remains somewhat constant in phase 2, indicating that the process reaches a balance of effects between strain hardening and thermal softening. Both the faying surfaces and material immediately behind are by then sufficiently heated to permit the two parts to be forged together.

Forging takes place in phase 3 which starts at the time of declutching and braking. Spindle rotation is immediately retarded, and the deceleration depends on braking time. Because the brake force itself can be set, braking time can also be a variable. Deceleration varies in the welding of different materials. However, the torque may not rise at all but drops abruptly at the onset of phase 3 if braking is sudden. This brings the rotating spindle to rest almost instantly, and the larger force is applied after spindle rotation stops. In this case, there is no torsional forge, and forging is brought about by upsetting.

Axial force in phase 3 is usually increased to effect forging. The friction torque again rises after the onset of this phase, reaching another peak before sharply falling off to zero. This peak varies with deceleration and applied axial force. Under some circumstances, this final peak can be omitted by delaying the onset of the forging force. This is done only at or after the stoppage of spindle rotation by braking. In this case, forging is carried out by upsetting without torsional forging. Although two-stage welding is applied more frequently in direct-drive friction welding, one stage welding is sometimes used, especially in research work.

When the axial force remains unchanged, slower deceleration (longer braking time by reduced braking) leads to higher peak. If the axial force is increased in phase 3, braking time is shortened, but the peak still rises because of the larger applied force. Rising friction torque in phase 3, characteristic of FRW, contributes to torsional forge, which is more effective than conventional forge by upsetting. Phase 3 ends shortly after spindle rotation stops. This period of forging or upsetting time can also be considered a fourth welding parameter.



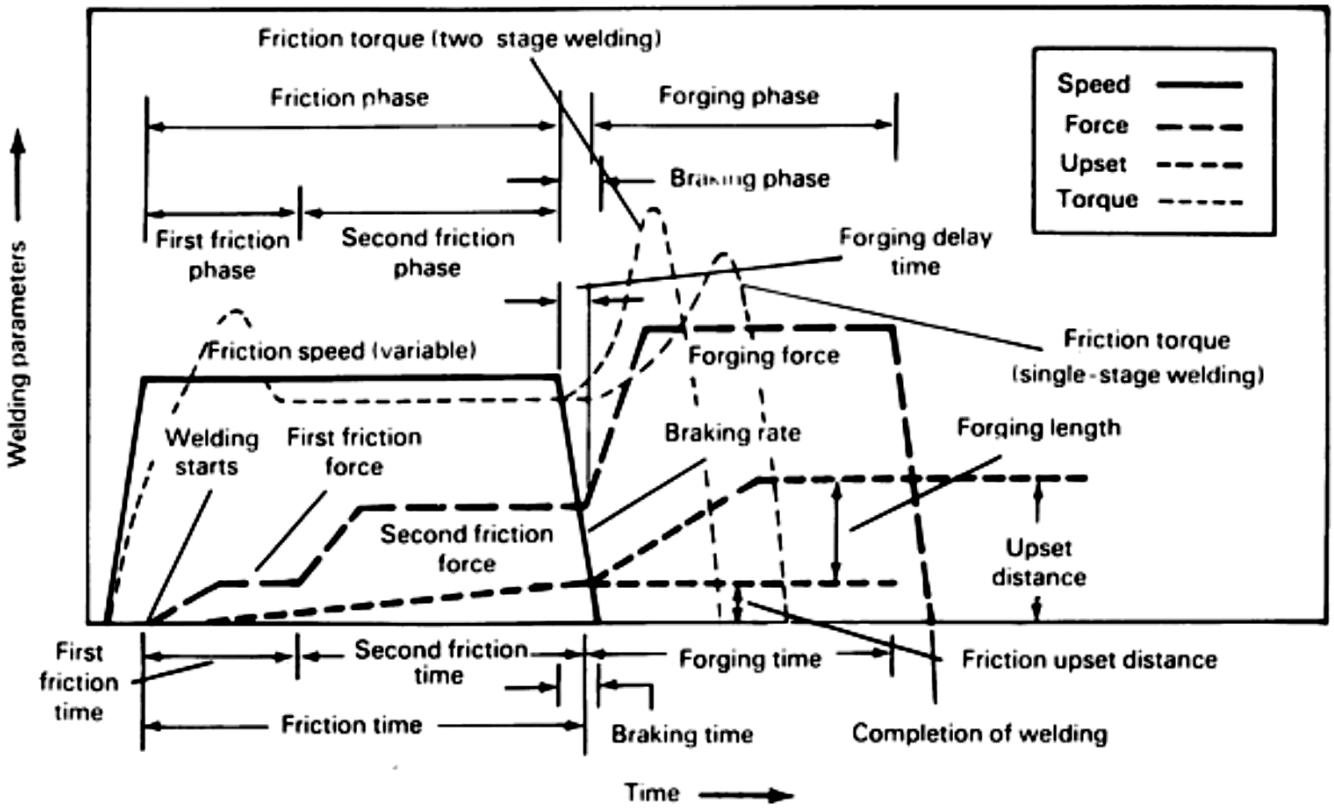


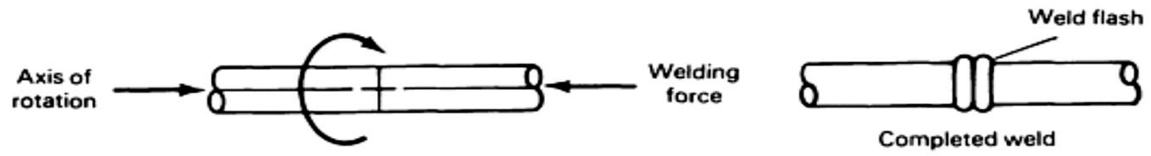
Fig. 3 Plot of Welding Parameters versus Time for a Direct-Drive FRW System

Inertia-Drive FRW Variables

There are three welding parameters in Inertia-Drive FRW: **flywheel mass (expressed by moment of inertia), rotational speed, and axial force.** The events described for direct-drive FRW also occur in Inertia Drive FRW. Except for rotational speed, the curves shown in Fig. 4 are similar to those shown in Fig. 3. The process can also be divided into three phases based on the shape of the friction-torque curve. Unlike direct-drive FRW, duration of rotation and forging time in phase 3 are not predetermined but controlled by the three welding parameters.

If axial force differs in phases 2 and 3, the process is called two-stage welding, and the forces, called heating force and forging force, respectively, are both included as a welding parameter of axial force. On the other hand, when the force remains constant throughout the process, it is called one-stage welding. The second friction-torque peak in two-stage welding is generally higher than that in one-stage welding because of the larger axial force applied in phase 3. As stated in the section "Direct-Drive FRW Variables" in this article, the peak in one-stage welding depends on

braking time: It rises with longer braking time. In two-stage welding, the larger axial forging force is applied when the flywheel rotational speed decreases to a fraction of the initial value--for example, 0.1 to 0.5. Friction torque again rises to a second peak, which as in direct-drive FRW is higher than in one-stage welding. This phase is prolonged beyond cessation of the flywheel rotation. This extra time, called dwell time, is used for cooling of the joint to avoid debonding by the release of stored strain energy. Although dwell times can range from 0 to 30 s, 1 to 2 s is typical. The kinetic energy used for inertia-drive FRW depends on the product of the flywheel moment of inertia and the square of rotational speed. The frictional heat generated at the faying surfaces, however, is determined by the rate of change of this energy (or the energy delivery rate), which is influenced by the moment of inertia of the flywheel and the axial force. For a given kinetic energy input and a given axial force, a smaller flywheel (with smaller moment of inertia) delivers the energy at the faying surfaces faster than a larger flywheel (with larger moment of inertia). For a given energy input using the same flywheel, a larger axial force increases flywheel deceleration rates, intensifies heat generation, and raises temperatures at the faying surfaces. A rapid energy input and a high rate of heat generation, typical of inertia-drive FRW, result in very short weld cycles. There is little time for heat to dissipate in the axial direction, so the heat-affected zone
(HAZ) remains narrow.



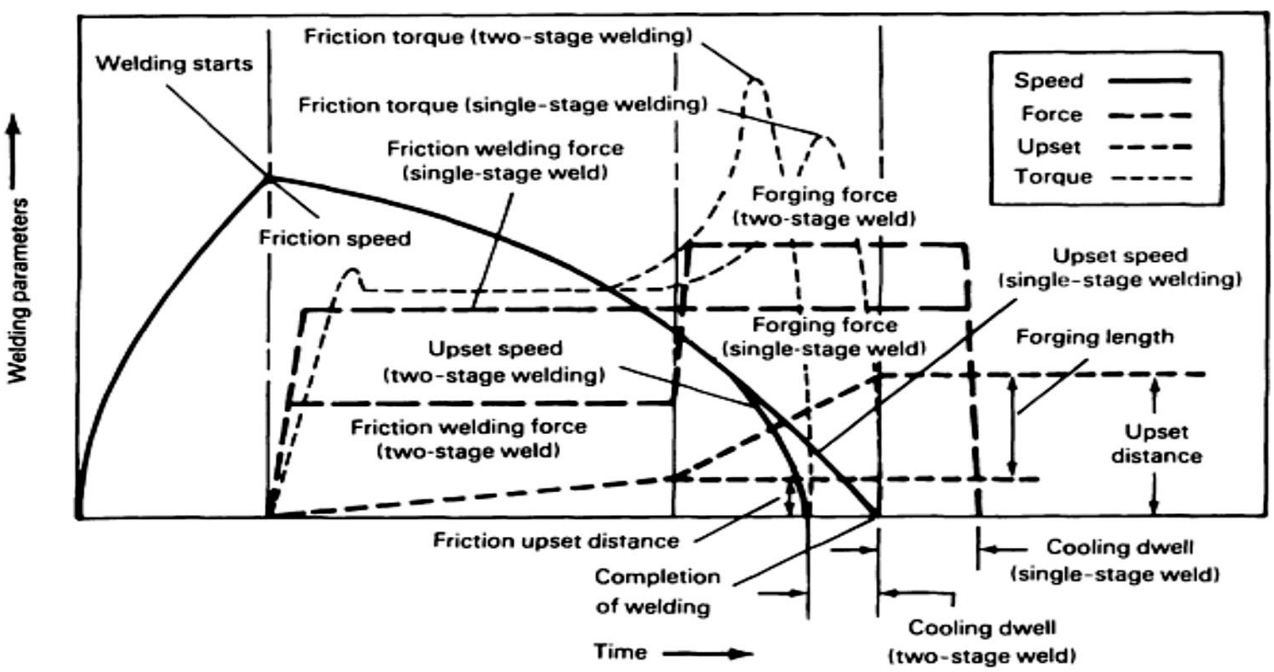


Fig. 4 Plot of Welding Parameters versus Time for an Inertia-Drive FRW System.

Direct-Drive versus Inertia-Drive FRW

Lower rotational speed and smaller axial force are generally used in direct drive FRW. Direct-drive FRW also offers greater latitude in process variables, because heating time in phases 1 and 2 is pre-set as duration of rotation or upset distance, which is a welding parameter, and because forging phase can be controlled by braking time, axial force, and forging time. Nevertheless, both processes do produce welds of equal quality when proper welding parameters are implemented. Torsional forging is required when forging by upsetting with inertia-drive friction welding; it is not required when forging by upsetting with direct-drive friction welding. A comparison of the two processes is presented in Table 1.

TABLE 1 PROCESS PARAMETERS OF DIRECT-DRIVE FRW SYSTEMS RELATIVE TO INERTIA-DRIVE FRW SYSTEMS

It is assumed that similar or dissimilar metals of the same size are being joined.

PROCESS PARAMETER	DIRECT-DRIVE FRW	INERTIA-DRIVE FRW
WELDING PARAMETERS	ROTATIONAL SPEED	FLYWHEEL MOMENT OF INERTIA
	DURATION OF ROTATION OR FRICTION BURNOFF DISTANCE	ROTATIONAL SPEED
	AXIAL FORCE	AXIAL FORCE
CONVERSION OF ENERGY TO FRICTIONAL HEAT	CONSTANT ENERGY IN A PRESET DURATION OF ROTATION	FIXED ENERGY IN FLYWHEEL; DURATION OF ROTATION DETERMINED BY WELDING PARAMETERS
ENERGY INPUT	LOW	HIGH
HEAT GENERATION RATE	LOW	HIGH
CYCLE TIME	SIMILAR	SIMILAR
HAZ WIDTH	WIDE	NARROW
MACHINE SYSTEM SPINDLE RIGIDITY	LESS RIGIDITY	GREATER RIGIDITY AND MORE POWERFUL CLAMPING FORCES REQUIRED

FSW PROCESS

The working principle of Friction Stir Welding process is shown in Fig below. A welding tool comprised of a shank, shoulder, and pin is fixed in a milling machine chuck and is rotated about its longitudinal axis. The work piece, with square mating edges, is fixed to a rigid backing plate, and a clamp or anvil prevents the work piece from spreading or lifting during welding. The half-plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side. The rotating welding tool is slowly plunged into the work piece until the shoulder of the welding tool forcibly contacts the upper surface of the material. By keeping the tool rotating and moving it along the seam to be joined, the softened material is literally stirred together forming a weld without melting. The welding tool is then retracted, generally while the spindle continues to turn. After the tool is retracted, the pin of the welding tool leaves a hole in the work piece at the end of the weld. These welds require low energy input and are without the use of filler materials and distortion.

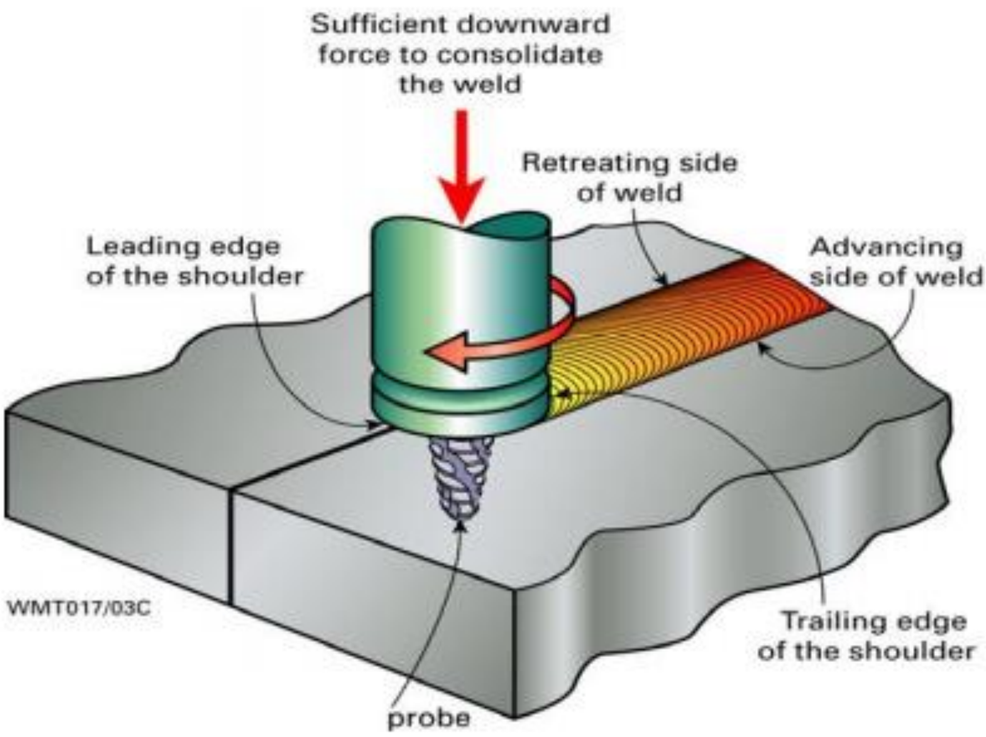


Fig. The principle of Friction Stir Welding

WELDING VARIABLES

FSW involves complex material movement and plastic deformation. Welding parameters, Tool geometry and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material. Therefore, welding speed, the tool rotational speed, the tilt angle of the tool, tool material and the tool design are the main independent variables that are used to control the FSW process. The main process parameters and there effects in friction stir welding are given below Table 2 (FSW-Technical Handbook).

Table2
Main process parameters in friction stir welding.

Parameter	Effects
Rotation speed	Frictional heat, "stirring", oxide layer breaking and mixing of material.
Tilting angle	The appearance of the weld, thinning.
Welding speed	Appearance, heat control.
Down force	Frictional heat, maintaining contact conditions.

- **Tool rotation and Transverse speed**

For FSW, two parameters are very important: tool rotation rate (v, rpm) in clockwise or counter clockwise direction and tool traverse speed (n, mm/min) along the line of joint. The motion of the tool generates frictional heat within the work pieces, extruding the softened plasticized material around it and forging the same in place so as to form a solid-state seamless joint. As the tool (rotates and) moves along the butting surfaces, heat is being generated at the shoulder/work-piece and, to a lesser extent, at the pin/work-piece contact surfaces, as a result of the frictional-energy dissipation. The welding speed depends on several factors, such as alloy type, rotational speed, penetration depth, and joint type. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force.

- **Tool tilt and Plunge depth**

In addition to the tool rotation rate and traverse speed, another important process parameters are tool tilt with respect to the work piece surface and plunge depth. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. The tool is usually characterized by a small tilt angle (θ), and as it is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to the tool shoulder. Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders.

- **Tool Design**

Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe length, probe shape and shoulder size are the key parameters because it would affect the heat generation and the plastic material flow The tool is an important part of this welding process. It consists of a shoulder and a pin. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process. The shoulder generates most of the heat and prevents the plasticized material from escaping from the work-piece, while both the shoulder and the tool pin affect the material flow. Friction stir welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used. The commonly used five pin profiles i.e., straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pins to fabricate the joints, in FSW are shown schematically in Fig.

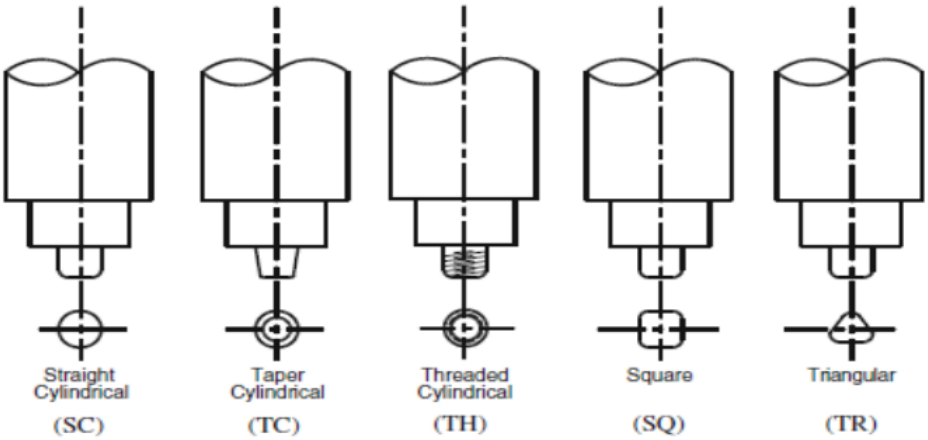


Fig. Schematic drawing of the FSW tool.

WELD QUALITY AND PRODUCT EVALUATION

At present, there is no satisfactory non-destructive method for detecting a friction weld of poor strength. (X-rays are used to identify defects that can cause welds of poor quality.) Weld quality control and product evaluation must rely on the control of the process and the machine that is used to produce the welds. In direct-drive FRW, both rotational speed and axial force affect axial shortening or upset in addition to the mechanical properties of the weld produced. There can be a correlation between the upset and the quality of the weld. Further, upset in phase 2 increases almost linearly with time. The upset of this phase, often called friction burn off, and its rate, the friction burn off rate, have been believed to control weld quality. Indeed, some researchers use burn off instead of duration of rotation as a welding parameter.

In inertia-drive FRW, because duration of rotation is not pre-set but controlled by the three welding parameters, the total upset, instead of friction burn off, is supposed to indicate weld quality. This presumes that the same amount of kinetic energy and axial force will produce the same amount of upset at the end of the process (given the same materials and cross sections).

The welding parameters of either direct-drive or inertia-drive FRW are set using a particular machine. So once this machine is properly calibrated, the process becomes almost entirely machine-dependent. Regardless of the process used to evaluate the product of friction welding under a given set of parameters, once variations in machine components and dimensional tolerances for a particular weld are determined, an acceptable tolerance band of the total upset can be established as a standard. A monitor will compare the upset of each weld relative to this reference. The machine will automatically stop to indicate a defective weld when its upset falls outside the proven band of the standard.

ADVANTAGES AND LIMITATIONS

Advantages of FRW:

Friction welding has a number of advantages over other joining processes (such as fusion welding, brazing, and diffusion bonding):

- Special attention to surface cleanliness is not necessary, because FRW tends to disrupt, displace, and finally remove surface films in weld flash (this does not apply to heavy mill or heat-treat scales, which can interfere with frictional heating).
- Filler metal, flux, and shielding gas are not required. Unlike fusion welding, friction welding is not hazardous to operator health and is safer, because there is no metal spatter, radiation, fume, or electric hazard involving high voltage, arcs, and sparks.
- Defects associated with melting-solidification phenomena are not present in FRW, because it is a solid-state process.
- It is possible to make transition joints of dissimilar metals that are difficult or even impossible to weld by other processes (for example, refractory and exotic metals).
- Lower labour costs, simple part design, simpler weld fixtures, lower energy requirements, and a short weld cycle (a matter of seconds) make the process cost effective for producing components normally made by other processes.

Limitations of FRW:

- The welding area of at least one part must be rotationally symmetrical, so that the part can rotate about the axis of the welding plane.
- Typical part geometries that can be friction welded are: bar to bar, bar to tube, bar to plate, tube to tube, and tube to plate. This process is normally limited to making flat and angular (or conical) butt joints.
- The material of at least one component must be plastically deformable under the given welding conditions. For example, alumina can be joined to aluminum, but alumina cannot be joined to alumina. Another example is the joining of polymers (that is, plastics). Thermoplastics, unlike thermosetting plastics, can be friction welded because thermoplastics are softened by frictional heat but thermosetting plastics decompose.

PROCESS APPLICATIONS

The applications of FRW fall into two categories:

Batch and jobbing work: used when a relatively low volume of parts is required, especially when expensive dies must be used but cannot be justified

Mass production: applications that span a wide range of industries (agricultural, aircraft engine, automotive, earthmoving, electrical, petroleum, and so on) producing components ranging from simple butt joints of drive shafts and oil drilling pipes to complicated or critical Aircraft engine components.

FRICTION STIR WELDING

Friction Stir Welding (FSW) was invented by Wayne Thomas at TWI (The Welding Institute), and the first patent applications were filed in the UK in December 1991. Initially, the process was regarded as a “laboratory” curiosity, but it soon became clear that FSW offers numerous benefits in the fabrication of aluminium products. Friction Stir Welding is a solid-state process, which means that the objects are joined without reaching melting point. This opens up whole new areas in welding technology. Using FSW, rapid and high quality welds of 2xxx and 7xxx series alloys, traditionally considered unweldable, are now possible.

Friction Stir Welding is a novel solid-state joining process that is both efficient, environmental friendly and versatile in its applications. Counted as one of the most significant developments in this age, Friction Stir Welding is used in the joining of high strength alloys which present difficulties with the conventional fusion techniques. As one most significant developments as far as metal joining is concerned, Friction Stir Welding is a green technology that requires less energy as compared to conventional welding methods; no flux or gas is required hence making the Friction Stir Welding process environmentally safe. Being an efficient method, Friction Stir Welding process does not involve the use of any filler metal hence any alloy can be joined without consideration of compatibility of composition as opposed to conventional welding methods where compatibility is an issue.

In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two pieces of sheet or plate material. The parts have to be securely clamped to prevent the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the workpieces causes the latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticised material, transferred to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling, a solid phase bond is created between the workpieces. Friction Stir Welding can be used to join aluminium sheets and plates without filler wire or shielding gas. Material thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration, without porosity or internal voids. In terms of materials, the focus has traditionally been on non-ferrous alloys, but recent advances have challenged this assumption, enabling FSW to be applied to a broad range of materials. To assure high repeatability and quality when using FSW, the equipment must possess certain features. Most simple welds can be performed with a conventional CNC machine, but as material thickness increases and “arc-time” is extended, purpose-built FSW equipment becomes essential.

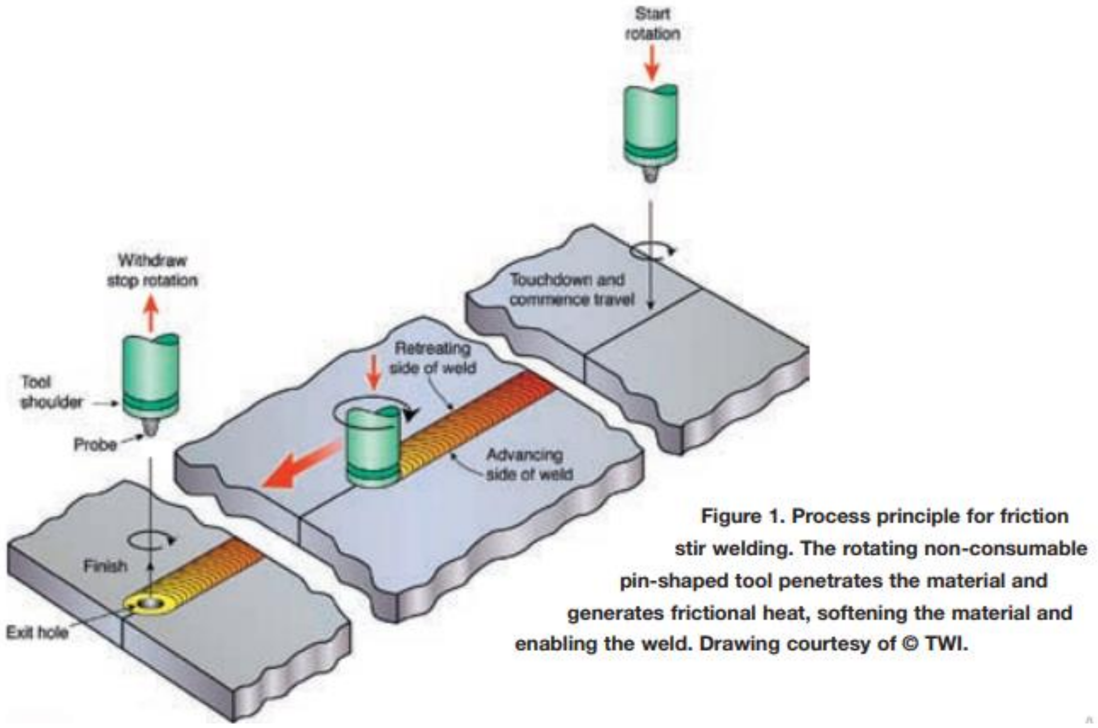


Figure 1. Process principle for friction stir welding. The rotating non-consumable pin-shaped tool penetrates the material and generates frictional heat, softening the material and enabling the weld. Drawing courtesy of © TWI.

Weldable alloys

In terms of high-temperature materials, FSW has been proven successful on numerous of alloys and materials, including high-strength steels, stainless steel and titanium. As what is weldable refers to the material by which the welding tool is made and how the process is applied there are really no limits to what can be achieved.

Process characteristics

The FSW process involves joint formation below the base material’s melting temperature. The heat generated in the joint area is typically about 80-90% of the melting temperature. With arc welding, calculating heat input is critically important when preparing welding procedure specifications (WPS) for the production process. With FSW, the traditional components – current and voltage – are not present as the heat input is purely mechanical and thereby replaced by force, friction, and rotation. Several studies have been conducted to identify the way heat is generated and transferred to the joint area. A simplified model is described in the following equation:

$$\mathbf{Q = \mu \Omega f k}$$

In which the heat (Q) is the result of friction (μ), tool rotation speed (ω) down force (F) and tool geometry constant (K). The quality of an FSW joint is always superior to conventional fusion-welded joints. A number of properties support this claim, including FSW’s superior fatigue characteristics.

Design principles

The simple pin-shaped, non-profiled tool creates frictional heat and is very useful if enough downforce can be applied. Unfortunately, the oxide-layer breaking characteristics are not very good, and as material thickness is increased, welding heat at the lower part of the joint may be insufficient. With parameter adjustment and tool geometry optimisation, the oxide-layer could be broken more effectively. The need to generate more frictional heat and break the oxide-layer more effectively has been a driving force in tool development for light-metals

Tools for steels

To apply FSW in steel or other high-temperature materials, the difficulty is mainly associated with finding proper tool material; a material that can withstand the high temperatures that are experienced during the process. Resistance to wear (durability) is one important aspect, especially as many of the intended applications are considered critical; hence there can be no traces of the tool left in the seam. One of the most promising tool materials so far is the so called PCBN.

Retractable pin tool

The Retractable Pin Tool (RPT) or Adjustable Probe Tool is a machine feature in which the pin of the FSW tool may be moved independently of the tool’s shoulder. This permits adjustments of the pin length to be made during welding, to compensate for known material thickness variations or to close the exit hole of the weld. The advantages of RPT may be summarized as follows:

• Ensures full root closure of the weld

• Increases joint quality properties at the exit

• Increases the joint’s aesthetic properties

Bobbin tool

The bobbin tool employs a technique that enables double-sided welding. The solution is a special designed tool, consisting of two shoulders, one on each side of the workpiece to be joined. The two elements of the tool are connected with the pin, which here runs through the material. Bobbin tool welding can be applied in several ways, but there are two main alternatives:

• Fixed bobbin tool, in which the distance between the two shoulders is fixed.

• Self-reacting bobbin tool, in which a retractable pin feature allows the distance between the two shoulders to be adjusted during the weld.

There are, of course, benefits and drawbacks with both solutions. The first offers a simple mechanical solution (for the welding head), as the tool differs in no way from a conventional FSW tool at the tool interface. In contrast, the second allows us to control the contact conditions for the two shoulders independently, to compensate for variations in material thickness. Initiating a bobbin weld either involves first drilling a hole in the material in which the tool is inserted, or by employing a run-on preparation of the material. The end of the weld is normally welded through, leaving the exit unbounded, for removal at a later stage. The bobbin tool is typically used to join extruded profiles, where the technique eliminates the need for a backing bar or advanced fixtures.

To summarize the advantages of bobbin tool welding, we find:

- No backing bar needed.
- Less complex fixtures.
- No root flaws from incomplete penetration.
- Less (or zero) down force needed.

Process speed

Not so long ago, one of the main "excuses" for not using FSW was the claim that its welding speed was too slow for production, even though the mechanical properties of FSW welds outclass conventional joining processes for aluminium. The typical stated welding speed for 5 mm AA6082 was between 250 mm/min and 400 mm/min. This was typical for a CNC machine, not designed for the high down forces needed in FSW or the high travel speeds. With production machines, welding speeds for the above-mentioned alloy are (and have been for a number of years) almost ten times higher – with 2000 mm/min a typical production speed when joining extruded profiles. In a medium-size welding workshop (between 200 and 400 blue-collar workers), time spent in welding and related functions represents roughly 15% to 20% of total manufacturing time.

This suggests three alternatives for improving productivity:

1. Increase the welding speed of conventional processes (GMAW, GTAW),
2. introduce a new welding process that offers a speed similar to conventional arc welding but that generates significant cost savings in other aspects of production, or
3. Introduce FSW, which welds 3-4 times faster than GMAW and generates significant cost savings at a later phase of the production process.

FRICTION STIR PROCESSING

Friction stir processing (FSP) is a method of changing the properties of a metal through intense, localized plastic deformation. This deformation is produced by forcibly inserting a non-consumable tool into the workpiece, and revolving the tool in a stirring motion as it is pushed laterally through the workpiece. The precursor of this technique, friction stir welding, is used to join multiple pieces of metal without creating the heat affected zone typical of fusion welding.

When ideally implemented, this process mixes the material without changing the phase (by melting or otherwise) and creates a microstructure with fine, equiaxed grains. This homogeneous grain structure, separated by high-angle boundaries, allows some aluminium alloys to take on superplastic properties. Friction stir processing also enhances the tensile strength and fatigue strength of the metal. In tests with actively cooled magnesium-alloy workpieces, the microhardness was almost tripled in the area of the friction stir processed seam (to 120–130 Vickers hardness).

Process

In friction stir processing (FSP), a rotating tool is used with a pin and a shoulder to a single piece of material to make specific property enhancement, such as improving the material's toughness or flexibility, in a specific area in the micro-structure of the material via fine grain of a second material with properties that improve the first. Friction between the tool and workpieces results in localized heating that softens and plasticizes the workpiece. A volume of processed material is produced by movement of materials from the front of the pin to the back of the pin. During this process, the material undergoes intense plastic deformation and this result in significant grain refinement. FSP changes physical properties without changing physical state which helps engineers create things such as "high-strain-rate super plasticity". The grain refinement occurs on the base material improving properties of the first material, while mixing with the second material. This allows for a variety of materials to be altered to be changed for things that may require other difficult to acquire conditions. The processes branches off of friction stir welding (FSW) which uses the same process to weld two pieces of different materials together without heating, melting, or having to change the materials' physical state.

Tool

The tool has a crucial part to creation of the final product. The tool consists of two main functions:

1. **Localized heating**
2. **Material flow**

The tool at its most simplest form consist of a shoulder, a small cylinder with a diameter of 50 mm, and a pin, a small threaded cylinder similar to a drill. The tool itself has been modified to reduce displaced volume of the metals as they merged. Recently two new pin geometries have arisen:

- Flared-Triflute – introducing flutes (large carving vertically on the pin)
- A-skew – the pin axis being inclined to the axis of the spindle.

APPLICATIONS

The FSP is used when metals properties want to be improved using other metals for support and improvement of the first. This is promising process for the automotive and aerospace industries where new material will need to be developed to improve resistance to wear, creep, and fatigue. Examples of materials successfully processed using the friction stir technique include AA 2519, AA 5083 and AA 7075 aluminum alloys, AZ61 magnesium alloy, nickel-aluminium bronze and 304L stainless steel.

- **Casting**

Metallic parts produced by casting are comparatively inexpensive, but are often subject to metallurgical flaws like porosity and microstructural defects. Friction stir processing can be used to introduce a wrought microstructure into a cast component and eliminate many of the defects. By vigorously stirring a cast metal part to homogenize it and reduce the grain size, the ductility and strength are increased.

- **Powder metallurgy**

Friction stir processing can also be used to improve the microstructural properties of powder metal objects. In particular, when dealing with aluminium powder metal alloys, the aluminium oxide film on the surface of each granule is detrimental to the ductility, fatigue properties and fracture toughness of the workpiece. While conventional techniques for removing this film include forging and extrusion, friction stir processing is suited for situations where localized treatment is desired.

- Fabrication of metal matrix composites

FSP can also be used to fabricate metal matrix composites at the nugget zone where we need the change of properties. Al 5052/SiC and some other composites were successfully fabricated. Even nano composites can also be fabricated by FSP.

- **Aluminium Surface Composites with Superior Properties**

Aluminium surface composites with enhanced surface properties can be fabricated using FSP. Aluminium surface composites fabricated with the optimum friction stir processing parameters show better mechanical properties and corrosion resistance. The processing parameters such as tool rotational speed and tool shoulder diameter affects the surface properties. Higher surface hardness is exhibited by the surface composites fabricated at higher tool rotational speed and lower tool shoulder diameter. The properties of the composite materials can be altered by changing the type of reinforcement. Reinforcement particles aids in the grain size refinement as well as the property enhancement in the processed materials. The surface composite properties can be varied by changing the reinforcement particles based on the end application. The reinforcement phases can be metallic, ceramic, or polymer materials.

BENEFITS

FSP has benefits for when two materials' would be needed to be mixed. FSP is a short route, solid state processing technique with one-step processing that achieves microstructural refinement densification and homogeneity. FSW helps modify materials so that metaling down or changing the material drastically does not have to take place. FSP, for example, can easily change the form of a piece of material as sheets of metal, where before it may have had to be melted down before and put into a mold for it to cool and form. The microstructure and mechanical properties of the processed zone can be accurately controlled by optimizing the tool design, FSP parameters an active cooling/heating. The same sheet of metal can be modified to fit various situations with the proper modification of the tool. FSP has shown to make metallic alloys bendable as for example an alloy modified with FSP would be able to bend to 30 degrees as before it could only bend to seven.

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Reg No.:________________ Name:________________________

APJ ABDUL KALAM TECHNOLOGICAL UNIVERSITY

SIXTH SEMESTER B.TECH DEGREE EXAMINATION, APRIL 2018

Course Code: ME366

Course Name: ADVANCED METAL JOINING TECHNOLOGY

Max. Marks: 100 Duration: 3 Hours

PART A

Answer any three full questions, each carries 10 marks. Marks

1	a)	Explain working of Electron beam welding (EBW) with help of a diagram	(7)
	b)	List major process parameters of EBW	(3)
2	a)	Compare advantages of Laser beam welding over EBW	(7)
	b)	Explain how key hole formation is achieved in LBW.	(3)
3	a)	Explain working principle of diffusion welding.	(7)
	b)	List and explain process parameters in diffusion welding	(3)
4	a)	Compare the joints formed by EBW, LBW and diffusion welding	(7)
	b)	What are the major limitations of diffusion welding?	(3)

PART B

Answer any three full questions, each carries 10 marks.

5	a)	Explain explosive welding procedure with help of a diagram	(7)
	b)	List different types of explosives used in explosive welding	(3)
6	a)	Draw the schematic representation of Ultrasonic welding and list major processes parameters.	(7)
	b)	Explain the major advantagent of Ultrasound welding over conventional welding methods.	(3)
7	a)	Explain major adhesive bonding theories.	(7)
	b)	Describe the adhesive bonding procedure	(3)
8	a)	Explain advantageous, disadvantageous and application of vacuum brazing.	(7)
	b)	List major equipment's used for vacuum brazing.	(3)

PART C

Answer any four full questions, each carries 10 marks.

9	a)	Differentiate TIG Torch and Plasma torch with help of diagrams	(7)
	b)	Explain transferred and non-transferred arc techniques in PAW	(3)
10	a)	Explain effect of various process parameters of PAW on weld quality	(7)

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	b)	Write a short note on under water welding methods	(3)
11	a)	Explain the magnetically impelled arc butt welding process	(7)
	b)	Draw different types of joints that can be welded using PAW	(3)
12	a)	Differentiate friction welding and Friction Stir welding with examples	(7)
	b)	Explain mechanism of boning in friction stir welding	(3)
13	a)	List and explain different types of friction welding	(7)
	b)	What are the major process parameters in friction welding	(3)
14	a)	Explain friction stir welding processes	(7)
	b)	List major application of friction welding	(3)

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