WELDING AND ALLIED PROCESSES

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Keywords: welding, manual arc welding, gas welding, powder welding, electric resistance welding, electrode, plasma arc welding, electron beam welding, laser beam welding, keyhole mode, energy density, friction welding, welding of polymers, brazing, manual brazing, gas brazing, induction brazing, arc brazing, thermal spraying, thermal cutting

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Summary

The joining process is typically the final step in assembly and plays the major role in ensuring structural performance. Additionally, the emergence of near-net-shape processes to produce sub-components has raised the importance of assembly processes as the next area for increased production efficiency. To solve all the joining needs that require welding, many different processes have been developed along the years. This chapter contains coverage of the most common welding processes in joining industry and all other allied processes. Background concepts and basic techniques are also covered. Subchapters on resistance spot and seam welding, projection welding, flash and high-frequency welding, basic principle of brazing, thermal spraying and thermal cutting processes are also included. The most recent developments in beam technology are discussed in the chapters about laser beam welding and electron beam welding.

1. Introduction

Welding is a precise and reliable joining process that produces a local coalescence of materials. This is often done by local melting the workpieces and adding a filler material to form a pool of molten material that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. In essence, the welding process fuses the surfaces of two distinct elements to form a single unit. Welding technologies also include methods for welding metals, dissimilar metals, polymers, and ceramics, as well as emerging composite and engineered materials.

Welding dates back to the earliest days of metalworking, and continues to be widely applied today due to its cost effectiveness, reliability and safety. More than 100 processes and process variants comprise the family of welding technologies. These various technologies allow a great deal of flexibility in the design of components to be welded. Most of the familiar objects in modern society, from buildings and bridges, to vehicles, machines, and industrial facilities, could not be produced without the use of welding technology. Welding goes well beyond the bound of its simple description. The future of welding holds even greater promise as methods are devised for joining dissimilar and non-metallic materials, and for creating products of innovative shapes and designs.

2. Welding Technology

Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by causing fusion. Welded parts are heated on the joint location to a plastic or semi-molten state, or are melted and then joined by fusion, with or without the addition of filler material. In addition to heat, pressure is often used in welding. On the other hand, welding without the use of heat is carried out very rarely. The welded joint consists of the weld (the part of the material that has been molten during the welding process) and the surrounding zone in which some structural changes occur due to high temperature and afterward cooling. Welding is a very important process in the construction of steel structures (in shipbuilding, bridge construction, and heavy machine-building), but almost all other metals, glass and some polymers (thermoplastics) can also be welded.

2.1. Welding and Allied Processes

The joining of materials by a solid joint or the cutting of materials without the use of mechanical cutting tools, usually by means of heat, comprise the following processes: welding, brazing, thermal spraying and thermal cutting.

Soldering and brazing involve melting a lower-melting-point material between the workpieces to form a bond between them, without melting the workpieces. In this process, the melting point of solder should be at a temperature of at least 50^{o}C lower than the melting point of base material to be joined.

Thermal spraying is a process in which a molten metal is sprayed onto a surface. The equipment and power source used in the process are similar as those used for welding.

Thermale cutting (oxy-fuel gas cutting) is a process used for the cutting of materials by means of heat. No cutting tools are used in the process. It is an allied process to welding, although its purpose is just the opposite, because the same or similar power sources and working equipment are used.

An allied process to welding may be adhesive bonding because it also involves the joining of materials by a solid joint. However, adhesive bonding is distinctly different from welding in terms of operating conditions and equipment.

2.2. History of Welding

Welding and brazing processes were developed concurrently with forging and casting. An iron cart dating from the times Before Christ has been found in China. The components of the cart were joined by fusion welding, i.e. by casting molten iron which formed a solid joint when it hardened. One of the oldest welding procedures is forge welding, a process in which two metal parts, heated in the blacksmith's fire, are joined by hammering. Pieces of jewellery found in Egyptian royal tombs have shown that components had been joined by brazing. The iron piping system found in Pompeii had pipe sections joined by a kind of forge welding.

Welding and allied processes have become fully developed since early 1900s when electric arc came into use as a source of heat. In 1885, N. de Bernardos and S. Olszewski patented a welding process using a coal electrode, and in 1888, N. G. Slavjanov patented electric arc welding using coated electrodes. It was a major breakthrough as the electric arc was not used solely as a heat source since the consumable electrode was used as an electrode and as a filler material.

At the same time, resistance welding processes were also developed. An American, E. Thompson, obtained a number of patents from the field of resistance welding in the period from 1885 to 1900. Around the year 1900, gas welding was developed in Germany and France. A German, Prof. Goldschmidt, introduced the Thermit welding process (a welding process which makes use of the aluminothermic reaction).

During the 1920s, major advances were made in welding technology, including the introduction of automatic welding in 1920, in which electrode wire was fed continuously. Shielding gas became a subject receiving much attention, as scientists attempted to protect welds from the effects of oxygen and nitrogen in the atmosphere. Porosity and brittleness were the primary problems, and the solutions that developed included the use of hydrogen, argon, and helium as welding atmospheres.

The first merchant ship with all hull sections welded together was built in Charleston, USA, in 1930. The powder welding process carried out in shielding atmosphere with consumable and non-consumable electrodes and the plasma arc welding were developed in the the period between 1930 and 1953.

During the middle of the century, many new welding methods were invented. Submerged arc welding was invented in 1930. and continues to be popular today. In 1932 a Russian, K. Khrenov successfully implemented the first underwater electric arc welding.

The first all-welded bridge in South-eastern Europe was the bridge over the Sava River in Zagreb (Figure 1.), the Sava bridge, with 234 m in length and 9 m in width. It was built in 1938. During the construction of the bridge, welding was monitored by D. Kunstelj, an engineer who founded the Technical College in Zagreb.

Gas tungsten arc welding, after decades of development, was finally perfected in 1941, and gas metal arc welding followed in 1948, allowing for fast welding of non-ferrous materials but requiring expensive shielding gases. Shielded metal arc welding was developed during the 1950s, using a flux coated consumable electrode, and it quickly became the most popular metal arc welding process. In 1957, the flux-cored arc welding process debuted, in which the self-shielded wire electrode could be used with automatic equipment, resulting in greatly increased welding speeds, and that same year, plasma arc welding was invented. Electroslag welding was introduced in 1958, and it was followed by, electrogas welding, in 1961. In 1953 the Soviet scientist N.F. Kazakov proposed the diffusion bonding method.

Figure 1. Sava bridge in Zagreb (1938.), a bridge constructed solely by welding

A number of other processes were introduced later, in the fifties and the sixties of the twentieth century, and the main impetus came from the industry involved in space research. In 1958. Electron Beam Welding (EBW) was developed, making deep and narrow welding possible through the concentrated heat source. Following the invention of the laser in 1960, Laser Beam Welding debuted several decades later, and has proved to be especially useful in high-speed, automated welding. In 1991 friction stir welding was invented in the UK and found high-quality applications all over the world. All of these three new processes, however, continue to be quite expensive due the high cost of the necessary equipment, and this has limited their applications.

2.3 Advantages and Limitations of Welding Process

Advantages of welding are the capability of producing lighter structures than those produced by casting and riveting and savings that may be achieved by the reduction in the mass of the material or in fuel consumption. New sources of energy, e.g. electron beam and laser beam, have speeded up the development of new welding processes and enabled the previously unweldable materials to be welded (Table 1).

Property of the process or joint*	Arc welding	EBW or LBW	Resistance welding (lap joint)	Resistance seam welding (butt joint) and friction welding	Welding of polymers	Brazing
Loading capability	5	5	4	5	5	4
Static load-bearing capacity	5	5	4	5	4	4
Dynamic load-bearing capacity	4	4	3	4	4	3
Resistance to high temperatures	5	5	5	5	4	3
Resistance to corrosion	4	4	3	5	5	3
Shape accuracy	2	4	3	3	3	4
Sealing	5	5	1 ... 5	5	5	4
Vibration damping	4	4	2 ... 3	4	5	4
Costs of joining	4	2	4	4	4	4
Costs of material	3	5	5	4	4	2 ... 4
Costs of subsequent treatment	3	5	4	3	4	4

* assessment: from very favourable (mark 5) to completely unfavourable (mark 1)

Table 1. Comparison of various welding and allied processes

After 1985 welding equipment and materials have been significantly improved, which has allowed a more extensive use of mechanization, automation and robotics in welding. The weight of power sources has been reduced by 10 times. The net weight of standard power sources used in the past was from 200-300 kg, while the net weight of power sources used in welding today and having the same nominal power is less than 20 kg. Also, pulse power supplies to be used in welding have emerged. Welding techniques have been also improved by devices in which only one parameter, e.g. power, instead of four or five independent parameters with conventional devices, has to be set, while the remaining parameters are adjusted to the optimal value. The development of sensors for the automatic guidance of the welding head contributed to the automatic welding development. New filler materials have been adapted to automatic and robotic welding, and a major breakthrough has been made in the field of manufacturing electrodes used for gas-shielded welding processes.

According to the International Organization for Standardization, a metal for an intended purpose is weldable if a certain welding process can produce a homogenous joint which has mechanical properties that satisfy local requirements and which has the ability to deal with all the consequences caused by welded joints in a metal structure. The weldability of a material depends on its chemical composition, the content of alloying elements and contaminants, the size of parts to be welded, the type of filler material, and the preparations completed before the welding process. The dependence of weldability on these factors is complex and cannot be determined clearly and expressed numerically.

In most welding processes, the material is heated locally to its melting point. The heating process can cause structural changes due to the diffusion of atoms of one element into the lattice of the other element and due to a harmful chemical reaction.

The ability to make the weld and the properties of the weld are influenced by the speed of welding, the amount and motion of molten metal, the degree of mixing between the base metal and the filler material, gases that are introduced into the molten material at higher temperatures, and the uneven temperature distribution, with high temperatures on some spots and with large temperature gradients. The molten filler material and the molten metal react with the local atmosphere and the molten slag. Generally, all chemical reactions of the molten metal with oxygen, hydrogen and nitrogen have a negative effect on the mechanical properties of the joint as they either reduce its strength, toughness and ability of plastic deformation or increase porosity, tendency for cracking, aging and brittle fracture.

The homogeneity of a welded joint may be adversely affected by the phenomenon of microcracking and macrocracking and also by the adherence of inclusions (harmful additions, compounds created by the addition, intentional or unintentional, of some elements). The most serious defects are cracks, which can be classified according to the temperature at which cracking occurs and according to their characteristics as: hot cracks, cold cracks, annealing-induced cracks and lamination cracks. The propagation of a crack in a material with low plastic deformation or without plastic deformation is called a brittle fracture. Fracture often occurs at low loads, below the yield stress, due to the transition of the material from a plastic state to a brittle state. A brittle fracture is typical for non-alloyed and low-alloyed steels which have a body centered cubic crystalline structure.

The testing of the weldability of a material is carried out in an indirect way by testing the tendency of the material towards increased hardness, aging, brittle fracture, laminate rupturing, development of cold and hot cracks, and development of cracks in high-strength materials.

Local heating and cooling during a welding process cause stresses in the material, which remain after the forming process has been completed. Particularly high stress occurs during fusion welding when reaching the yield stress of the material. These stresses without the presence of an external force are called tensions. Tensions caused by welding can be reduced by applying the following: postweld heat treatment, vibrations, rolling, forging and explosion.

Deformations of welded joints and structures can be identified as changes in the shape and dimensions due to stresses induced by welding. These deformations can be very severe so that special devices are required in order to prevent them.

Postweld heat treatment is applied in order to reduce defects and tensions in the weld. Preheating to a temperature of 100-600^{o}C can prevent the development of cold cracking, and heating after welding enables the escape of hydrogen from the welded joint. Annealing at a temperature of 550-800^{o}C reduces residual stresses. Normalization is carried out after welding processes which result in a coarse-grained structure of the weld (powder welding or electroslag welding). The temperature of normalization depends on the type of the material. Other types of heat treatment depending on the type of the material are carried out with the purpose of homogenization, i.e. equalizing the properties of the welded joint and those of the base material.

Protective measures need to be taken during welding and other related processes in order to prevent power surge, danger of ultraviolet and infrared radiation of electric arc, air pollution by smoke or gases, fire, explosion, lack of oxygen, etc. The protective measures include the wearing of protective clothing (welding helmets or headshields, leather gloves, aprons and overalls, safety footwear, clothes and gloves providing thermal insulation), the use of low voltages during welding in confined metal spaces, the use of respirators (filters), and working conditions with a local ventilation system or a comprehensive one.

3. Basic Principle of Welding Processes

Welding processes can be classified according to the power source or to the way the energy, to be converted into heat required for creating a welded joint, is transmitted (gas flame, electric arc, plasma, laser, electron beam, ultrasound). Power sources can be classified according to their power, the amount of energy supplied to the base metal, maximum operating temperature and the density of heat flow (Figure 2.).

Today, there are more than fifty different welding processes. However, more than 90% of the total mass of materials subjected to welding processes are processed by only a few welding processes. These include electric arc welding processes in the first place (manual welding with a coated electrode, a consumable or non-consumable electrode, and powder welding) and electric resistance welding processes.

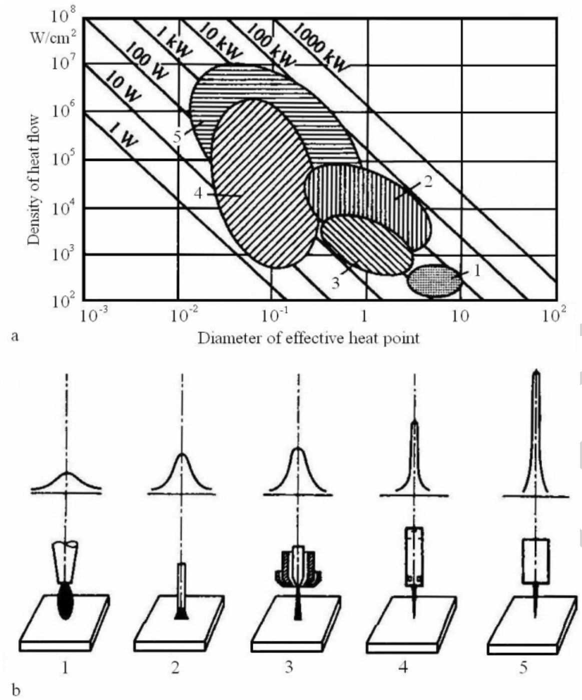

Figure 2. Density of heat flow, diameter of effective heat point and the power (*a*) and concentration of heat on the surface (*b*) for different power sources used for welding: 1 gas flame, 2 electric arc, 3 plasma, 4 laser, 5 electron beam

Gas welding is also often applied, while other welding processes are used for parts and structures of complex shapes or of very small or very big sizes, and for creating welds that cannot be created by common welding processes. The suitability of different welding processes for welding particular metals is given in Table 2.

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Biographical Sketch

Mr. Slobodan Kralj was born in 1945 in Subotica. He acquired graduate degree at Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, in 1971. He has finished postgraduate studies in 1979, and in 1985 he was awarded PhD degree at the same Faculty. He has undertaken specialization in Germany in ZIS, Halle (6 months), at TU Berlin (3 months), and in United Kingdom at University of Cambridge-Engineering Department (6 months). He also made study-visits to companies Hobart and Lincoln Electric in USA.

From 1971 to 1973 he was employed in company "Koncar- Division Large Rotating Units" in Zagreb. Since 1973 he is employed at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, in positions of assistant professor, docent and currently full professor. Since 1980 he was a head of Welding Laboratory and since 1989 head of Chair for welded structures. Also, in the period from 1996 to1998 he was holding position of dean of Faculty.

In the period from 1990 to 1994 he was the president of Governing Board of Croatian Welding Society and since 1994 is the president of the same society. Since 1992 he is Croatian representative to European Welding Federation and International Institute of Welding. In period from 2006 to 2008 he was serving vice-president of the International Institute of Welding.

He had published more than 40 articles in journals in 8 countries. On international conferences he had presented more than 60 lectures. He is member of Croatian Society for Materials and Tribology, American Welding Society and Croatian Society for Robotics where he was one of the society founders.

He was the president of number of international conferences devoted to welding. He was a leader of number of international projects within frame of European Programs such as TEMPUS, EURECA and Leonardo.