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Electron Beam Welding – Characteristics

Abstract: The article presents the characteristics of electron beam welding and describes phenomena taking place during the interaction between an electron and an atom of a material being bombarded. The study also presents the basic electron beam welding parameters and structural material weldability characteristics as well as enumerates the advantages of the technology and indicates its possible areas of application.

Keywords: electron beam welding, welding parameters, material weldability;

Introduction

Industry, permanently developing, continues to search for new technological solutions ensuring the reduction of production costs, market introduction of new products or the improvement of those existing. One of such solutions is electron beam welding.

Electron beam welding dates back to January 1951 when an electron device for perforation was patented, and to September 1951 when electron beam welding was patented in Great Britain [1]. At Instytut Spawalnictwa electron beam welding was first used in the 1970s, when an EUS 25/6 electron beam welding machine produced by Przemysłowy Instytut Elektroniki /Industrial Electronics Institute/ was put into operation.

An electron beam as a welding heat source has been utilised for many years. However, its use in various technological processes, particularly in welding and surface modification, is still dynamically developing both in terms of research and industrial applications.

In spite of quickly developing competitive laser welding technologies, electron beam welding remains indispensable in many applications due to the possibility of obtaining greater penetration depth and the metallurgical purity of a weld, as well as because of its greater welding rate.

What is important is that the technology is improved primarily as regards welding devices. Companies manufacturing electron beam welding machines such as Cambridge Vacuum Engineering (Great Britain), Sciaky (USA), PTR Precision Technologies (USA) and Pro Beam (Germany) offer either universal devices or machines for specific applications. The long-appreciated electron welding advantages cause the electron beam to be presently used also in overlay welding, remelting, alloying, quick prototyping, perforating, making gradient materials and many others. In relation to welding, the advantages of this method include very high power density, lack of detrimental effect of external

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factors on molten and heated material (as a rule, such a process is carried out in vacuum), and very small deformations of workpieces.

Characteristics

The essence of electron beam welding (often referred to as electron welding) lies in using the kinetic energy of electrons moving at a great velocity (approximately 200 km/s) in vacuum. During the bombardment of a metal surface the principal part of electron kinetic energy transforms into metal-melting heat. Electron beam welding requires the use of devices equipped with an electron gun generating an electron beam and with a vacuum working chamber (Fig. 1).

An electron beam of specific current intensity adjusted by the potential of a control electrode, is accelerated in an electrostatic field between a cathode and anode, and next focused in the magnetic field of a focusing coil and dynamically or statically deflected (if need be) in the magnetic field of deflecting coils [2]. An electron beam generated and formed in this manner in the electron gun enters the working chamber area and hits the surface of an element being welded, fixed in special clamps and usually performing working motion. The schematic design of an electron device is presented in Figure 1.

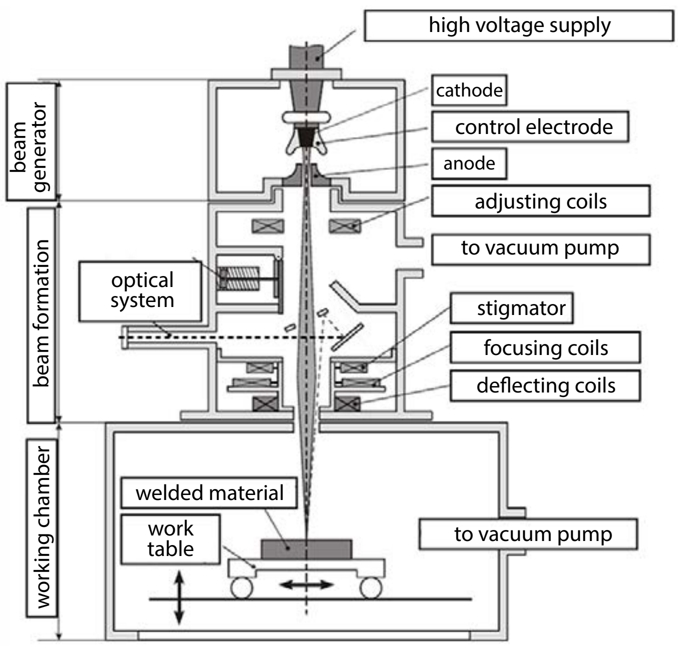

Fig. 1. Schematic design of an electron device [3]

Electron welding, depending on power density, can be carried out using so-called melt-in welding (heating of metal being welded as in the classical arc welding process with the formation of a shallow weld pool) or, typical of this process, so-called key-hole welding (formation of a deep gasodynamic channel – "key-hole"), usually with melting a material right through.

Figure 2 presents the schematic effect of an electron with the atom of a material being bombarded.

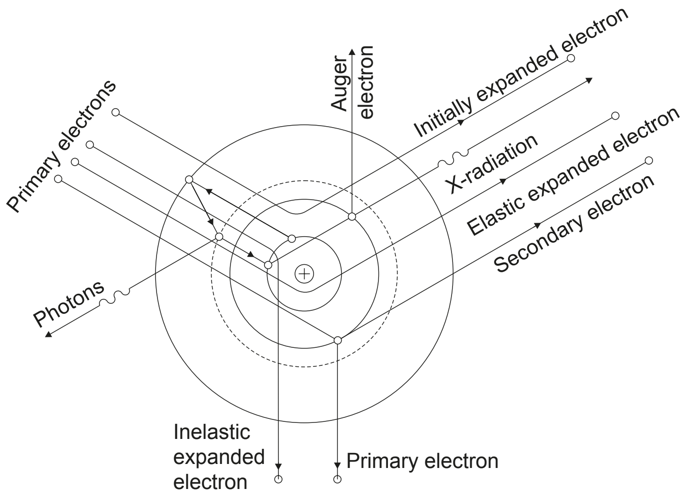

Fig. 2. Collision of primary electrons with the atom of a material being bombarded [3]

The scattering of an electron beam in a material is an issue of great complexity including many processes dependent on many parameters, particularly upon the energy of primary electrons E_0, atomic number Z of chemical element bombarded, density ρ of material bombarded, thickness of material d and the angle of incidence of primary electrons φ. The scattering of electrons is caused mainly by elastic collisions with the nuclei of medium atom, in turn the braking of electrons (energy losses) is caused by collisions with material electrons (inelastic collisions). In the latter case, not only the direction of the primary electron changes but its energy also changes. As a result of numerous collisions the energy of the primary electron decreases to a level insufficient for causing the excitation or ionisation of the atom and the process of electron penetration in the material ends. Part of the primary electrons leaves the material – these are back-scattered electrons or penetrating electrons (depending on the surface through which they leave the material). Other types of electron-atom interactions, presented in Figure 3, generate energy losses of primary electrons, yet they account for only a small part general energy losses in the thermal process [4].

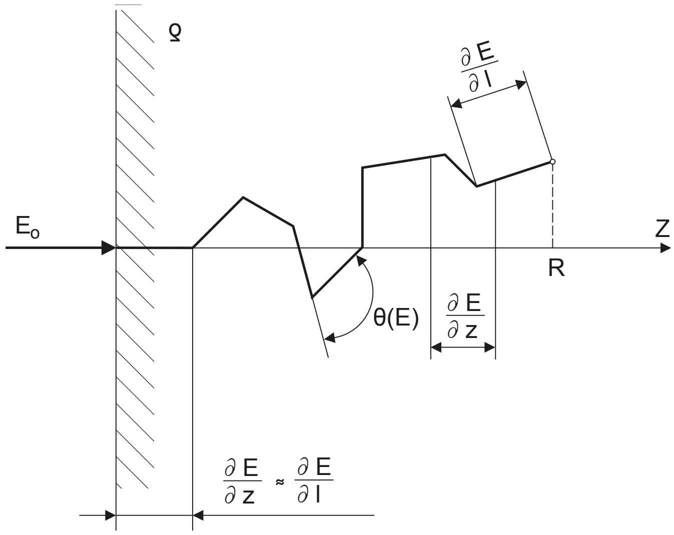

Fig. 3. Electron trajectory in material [4]

If the primary electron of energy E_0 moving along the z-axis hits the surface of a material having density ρ (Fig. 3), the kinetic energy of the electron becomes equal to zero at the distance *R* from the material surface. Such a distance is referred to as the depth of penetration. The length *L* of the real distance covered by the electron is greater than the penetration depth *R*. One of the basic scattering parameters is the angle of scattering Θ(E) and the probability of scattering at the angle Θ in the range dΘ. The losses of energy δE/δL along the real electron travel distance differ from the quantities δE/δz, referred to the z-axis. It should be noted that for low values of "z", δE/δz≈δE/δL. As scattering and energy losses are stochastic processes, these quantities undergo statistical distribution [4]. Figure 4 presents a model of inelastic scattering. Inelastic collisions cause the energy losses of primary electrons and change the direction of the motion of these electrons[4].

In the case of the scattering of electrons in the solid body due to a great number of collisions, the motion of electrons becomes purely accidental from a certain depth. There are several definitions of electron penetration depth, where part of them is connected with the beam of electrons and part with the energy of electrons [3]. From a practical point of view the most often referred to is the practical penetration depth, which can be calculated as follows [5]:

$$R = 2100 \cdot 10^{-12} \frac{U^2}{\rho}$$

where:

- *R* – practical penetration depth [μm],
- *U* – accelerating voltage [V],
- *ρ* – material density [g/cm³].

Figure 5 presents estimate calculations of the practical electron penetration depth for accelerating voltage of 150kV.

It should be emphasized that the formation of a gasodynamic channel ("key hole") extending on the whole thickness of a material welded has not been fully clarified until today due to many mutual physical phenomena and parameters present during electron welding. On the basis of the analysis of photographs of

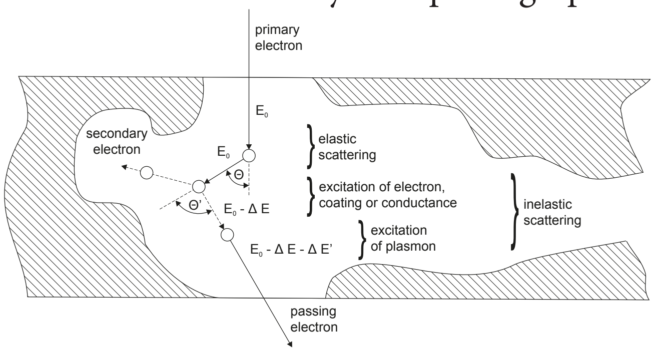

Fig. 4. Model of inelastic scattering [4]

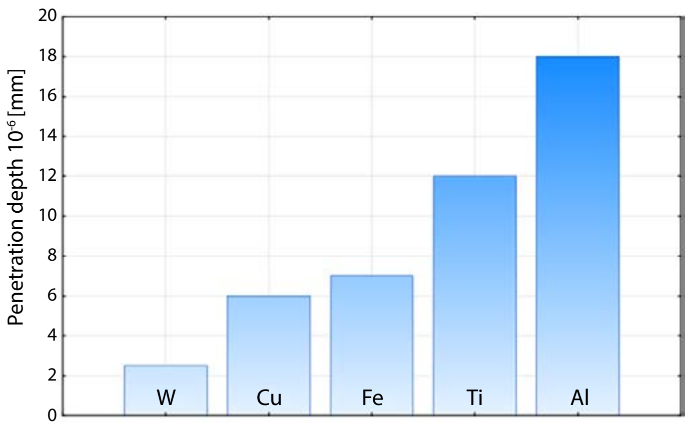

Fig. 5. Practical penetration depth during accelerating voltage 150kV

an electron welding area (made with a quick camera), the model of the formation of pits, cylindrical channel and welded joint was proposed [6]:

- by bombarding the metal surface in the joint area, the electron beam melts this surface with the heat generated as a result of the conversion of electron kinetic energy and a shallow weld pool is formed (Fig. 6a);
- further bombarding with the electron beam increases the volume of the weld pool (Fig. 6b) until reaching the thermal state in which almost the whole volume of the molten metal in the pool evaporates. Significant pressure of metal vapours pushes the molten metal onto the walls of the deep channel being formed. For some time this channel remains open due to the specific distribution of the temperature field in the channel and many forces, particularly of surface tension, affecting the liquid metal film (Fig. 6c), which enables increasingly deep penetration of the electron beam into the material. Due to the permanent effect of the electron beam, the volume of molten metal forming the film surrounding the channel interior increases until the inlet of the channel closes up. The thickness of the film closing up the inlet to the channel is a fraction of μm (Fig. 6c); the temperature of the film surface is 1800÷1900°C for aluminium alloys and 1800÷2300°C for steels. The pressure of metal vapours and gases in the pit reaches several hundred kPa [6];
- electron beam easily penetrating the liquid metal film closing up the inlet to the channel causes further metal evaporation in its interior and increases metal vapour pressure to the value exceeding that of the surface tension, causing the film to break (Fig. 6d);
- pressure of vapours and gases released from the channel decreases and the liquid metal film closing the channel inlet due to the effect of surface tension, forces is formed again (Fig. 6e).

The channel ("key-hole") formation process repeats cyclically, the channel depth increases until reaching a state of equilibrium, in which the whole electron beam energy is absorbed by metal vapours, gases and liquid metal surrounding the channel interior.

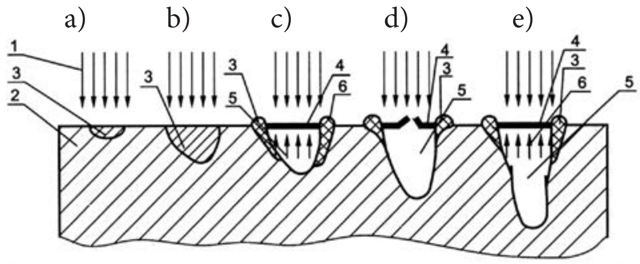

Fig. 6. Formation of a cylindrical weld pool – weld key-hole, during electron beam welding of butt joint; 1 – electron beam, 2 – workpiece, 3 – liquid weld metal, 4 – thin metal film; 5 – metal vapours and gases, 6 – stream of metal vapours and gases [7]

Electron Welding Parameters

The basic parameters of electron welding include accelerating voltage, welding current, welding rate, beam diameter on the workpiece surface, electromagnetic lens focal length, electromagnetic lens current and vacuum in the working chamber [6].

Electron beam accelerating voltage [kV], depending on a device type, is between 10 and 200 kV. The higher the accelerating voltage, the greater the beam power (for constant beam current) and the greater the penetration depth. It is also possible to observe the improvement of the weld shape factor – welds become narrower and deeper, and fusion boundaries become more parallel, which reduces welding strains. Too high accelerating voltage can cause undercuts, weld face irregularities or weld excess penetration beads.

Electron energy can be expresses as

$$E=U\cdot I \tag{1}$$

where

- U – accelerating voltage,
- I – beam current.

Figure 7 presents the effect of welding rate and accelerating current on penetration depth for 40NiCrMo6 steel.

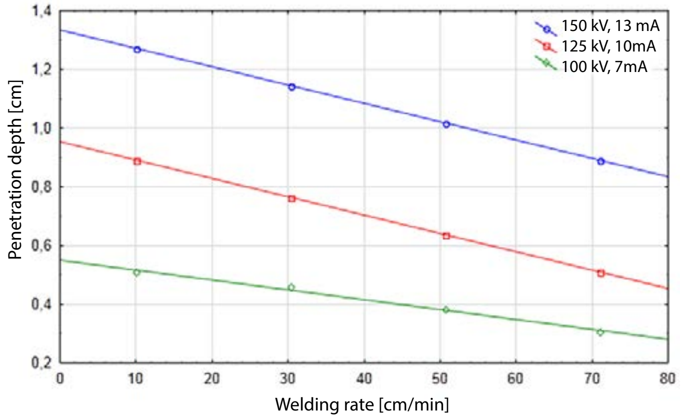

Fig. 7. Effect of welding rate and accelerating current on penetration depth for 40NiCrMo6 steel [8]

For instance, with an accelerating voltage of 80kV it is possible to obtain the following penetration depth values [9]:

- steel – 40 mm,
- titanium – 40 mm,
- copper – 60 mm,
- aluminium – 80 mm.

Higher accelerating voltage enables the use of greater working distances, and thus greater process flexibility and possibility of welding elements having more complicated shapes.

Electron beam current [mA] affects the change of power density, and as a result, influences the depth of penetration into a material being welded and a weld shape (Fig. 8). An increase in electron beam current is accompanied by a greater penetration depth. For low electron beam current values, approximately 1÷10 mA (Fig. 8), welding results are practically the same as those obtained using conventional arc welding processes.

A welding rate [m/min] properly adjusted to electron beam power is decisive for the linear energy of the process, therefore affects the process heat input, influences the geometry of a weld, namely, penetration depth and weld face width. An increase in welding rate is accompanied by a decrease in penetration depth and weld width.

The diameter of a beam focused on the workpiece surface [mm] is decisive for the electron beam power density and, consequently, influences penetration depth and weld shape. It can be adjusted by the current of the control cathode and the current of the magnetic focusing coil within the range 0.01÷10 mm.

The electron beam focal length [mm] is decisive for the depth of penetration into a material being welded as well as for the shape and quality of a weld. Changing the position of the beam focus in relation to the workpiece surface without changing other welding parameters alters the beam diameter on the workpiece surface and, as a result, changes the beam power density.

The current of electron beam focusing lens [mA] is decisive for the beam diameter and the beam focus location, for constant working distance and beam power.

The vacuum in the working chamber [mbar or Tr] is decisive for joint quality. A high vacuum ensures the highest joint quality due to accurate weld metal evaporation. Welding conducted in a vacuum is also accompanied by the

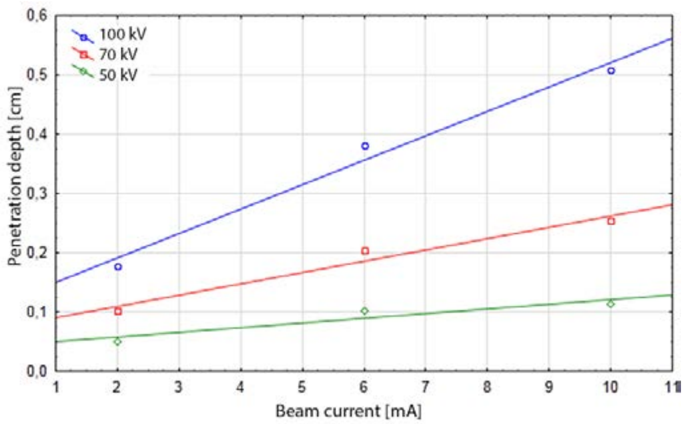

Fig. 8. Effect of electron beam current on penetration depth for constant accelerating voltage [8]

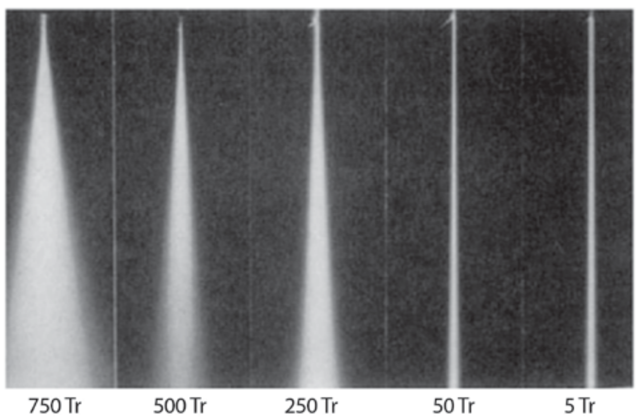

Fig. 9. Effect of pressure in a chamber on the diameter of a beam [10], 1 Tr=133.3 Pa

evaporation of alloying components of high vapour pressure, which can reduce the content of these constituents in the weld. A decrease in working chamber pressure reduces the beam diameter and decreases power density (Fig. 9).

Weldability of Electron Beam Welded Structural Materials

Depending on the geometry of a focused electron beam and on the operating mode of an electron gun (stationary or oscillating beam), heat input to a material being welded changes within a wide range. As a result, it is possible to weld elements made of various metals and alloys, having different thicknesses and shapes. The flexibility of electron beam welding enables welding of weldable and poorly weldable materials as well as materials entirely unweldable by means of arc methods.

Small welding strains and stresses cause the electron technology to be useful for welding, among others, AlCu alloys susceptible to hot cracking. On the other hand, when it is necessary to weld steels having a high carbon content, heat treatment, due to high hardness in HAZ, also becomes necessary. The heat treatment is carried out simultaneously with the welding, using the multiple-beam operating mode (beam is switched over and deflected with a great frequency, i.e. frequency sufficiently high to be invisible to the human eye, which provides the effect of the presence of many beams). In electron beam welding without a filler metal it is not possible to compensate the evaporation of alloying elements from the weld area. However, taking into consideration the fact that the weld is narrow, in many cases the change of chemical composition is so low that it can be viewed as negligible [11].

Aluminium alloys

Electron beam welding of aluminium alloys characterised by low density and good thermal conductance is widely used, even for producing daily necessities. During welding, the layer of high-melting oxides is removed, thus weld porosity is reduced. In addition, the method can be used in welding materials strongly reflecting radiation. Achievable penetration depth amounts to 200 mm and more, while maintaining the advantageous ratio of weld width to weld height. Aluminium alloys of 5000 series (AlMg) are readily weldable using the electron beam, whereas alloys of 2000 (AlCu), 4000 (AlSI) and 6000 (AlMgSi) series require additional procedures aimed at hot cracking reduction. It should be noted that hot crack risk depends on the content of alloying elements, thermal conductance and stresses generated during or after welding, therefore formulating general principles is difficult. However, it is possible to assume that in the case of the aforementioned alloys the change of chemical composition is negligible. Quite different is the situation with alloys of 7000 (AlZnMg) series, in which zinc evaporation can reduce or deteriorate joint mechanical properties. Due to a high hydrogen content, welding aluminium casting alloys can be accompanied by porosity formation. Should this be the case, it is necessary to apply the “multi-beam” welding technology [11].

Copper and Copper Alloys

Electron beam welding of copper and its alloys, in comparison with arc welding processes, does not generate major problems, except for brasses (due to zinc evaporation). High beam power density is responsible for the fact that without preheating it is possible to weld elements having a thickness of over 50 mm in a single run. It is known that even pure copper can contain significant amounts of impurities such as oxygen, sulphur, phosphorus and carbon. Because of this it is recommended to use deoxidised copper with a low phosphorus content. It should be mentioned that particularly in the case of materials having high thermal conductance, such as aluminium and copper, welding with incomplete fusion can be accompanied by the formation of so-called spikings – imperfections characteristic only of high-power methods, resulting from the cyclically changing penetration depth caused by unstable evaporation and pressure distribution in the gasodynamic channel. Eliminating such imperfections is possible by changing the joint structure and making a weld with thorough material penetration [11].

Reactive Materials

High beam power density and conducting a welding process in vacuum enables electron beam welding not only of poorly weldable materials but also reactive materials, e.g. titanium and its alloys, sensitive to even small amounts of gases. Such reactive materials can be electron beam welded without risking oxidation, carbide formation, generation of hydrogen-induced brittleness or poorly detectable reduced impact strength. For this reason titanium elements responsible for safety in aviation are electron beam welded. Electron beam welding of titanium and its alloys is widely used also in the medical industry, particularly in the production of implants and surgical instruments. This is due to the fact that the active life of implants is counted in many years, which necessitates their highest workmanship and, as a result, failure-free operation [11].

Zirconium and niobium alloys, used mainly in the construction of nuclear reactors, also react with gases during welding. Taking this into account as well as their very high price and restrictive requirements concerning the quality of joints, the only possible method for joining elements made of such alloys is electron beam welding. Similar requirements also refer to tantalum, iridium, vanadium and their alloys. It is possible to weld tungsten, molybdenum and their alloys, yet the possibility of lower impact strength should be taken into account. The reduction of impact strength is due to quick evaporation of nickel taking place, e.g. in tungsten. It should also be emphasized that electron beam welding is the only method applicable for welding tungsten [11].

Steels

Most steels welded using arc methods can also be electron beam welded. A narrow HAZ and the absence of hydrogen in the atmosphere make it possible for fine-grained steels, susceptible to the reduction of mechanical properties, to be readily weldable with an electron beam. In this case no additional procedures are required. The method is also used for welding transformer sheets made of steels having a high silicon content [11].

In alloy steels, including those austenitic and duplex, nitrogen often plays the role of an alloying addition. For this reason, during welding it necessary to use parameters limiting the risk of porosity generation caused by nitrogen degassing and, particularly in duplex steels, compensating nitrogen loss and preventing the loss of phase equilibrium. During welding duplex steels nitrogen degassing shifts the phase diagram towards ferrite, reducing corrosion resistance. However, it should be emphasized that using appropriate welding parameters and filler metals can compensate for the reduction of nitrogen content and thus maintain proper corrosion resistance. In cases when precipitation hardening takes place, electron beam welding can cause joint strength reduction, the prevention of which requires additional technological procedures. In many applications alloy steels are electron beam welded without additional procedures even if elements made of such steels constitute responsible elements in airplane or car turbines. Aging-resistant NiCrMo steels can be welded without preheating, also while making joints of considerable thicknesses [11].

Alloy ferritic steels are usually readily weldable if their carbon content does not exceed 0.2%. In such a situation, additional technological procedures are not required. Steels having a higher carbon content can be susceptible to the formation of martensitic phase necessitating preheating. This procedure can be carried out by using "multi-beam" welding or pre-heating in the furnace. Electron beam preheating is used while making joints of 42CrMo4 steel up to 20 mm thick. Above this thickness it is necessary to use additional preheating. Some greater problems can be encountered while welding 17CrNiMo5 or 16MnCr5 (carbonised and hardened) steels, used for instance in the production of gear wheels in the automotive industry. High carbon content in the outer layer has to be removed from the joint area. Additionally, in order to reduce cold crack risk, it is usually necessary to use preheating up to the range 150÷ 80°C [11].

Cast iron

Although from the metallurgical point of view cast iron is a poorly weldable material, maintaining appropriate process conditions can result in obtaining a proper joint. However, it is necessary to make allowances for possible porosity formation. The maximum penetration depth is approximately 20 mm. Thicker elements require double-sided welding. Better weldable is spheroidal cast iron. Making dissimilar joints, e.g. of GJS440 cast iron and S235 steel, requires the use of a filler metal. Such a solution enables significant hardness reduction in the weld (from 1000 HV1 to 300 HV1), Fig. 10. In the case of this joint mere preheating reduced hardness to 600 HV1 [11].

Nickel and Nickel Alloys

Pure nickel, nickel-copper alloy and many nickel-iron alloy grades can be electron beam welded without major problems. However, superalloys of more complicated chemical composition require additional procedures in order to reduce the risk of cracking during post-weld heat treatment. In this case, in order to prevent the generation of hot cracks, the use of "multi-beam" welding should be used [11].

Dissimilar Joints

One of the main advantages of electron beam welding is the possibility of welding materials having various melting points and thermal conductance. However, due to significantly different chemical compositions and possible formation of disadvantageous phases not all material combinations are weldable. As a result of thermoelectric phenomenon, joining different materials can cause the generation of a magnetic field strong enough to deflect the electron beam and make the welding process unstable. The phenomenon determines possible combinations of materials to be joined with reference to their chemical composition and shape. If two materials cannot be joined directly, it is possible to join them indirectly using electron beam weldable materials in-between. Figures 11 and 12 present possible electron beam weldable material combinations [11].

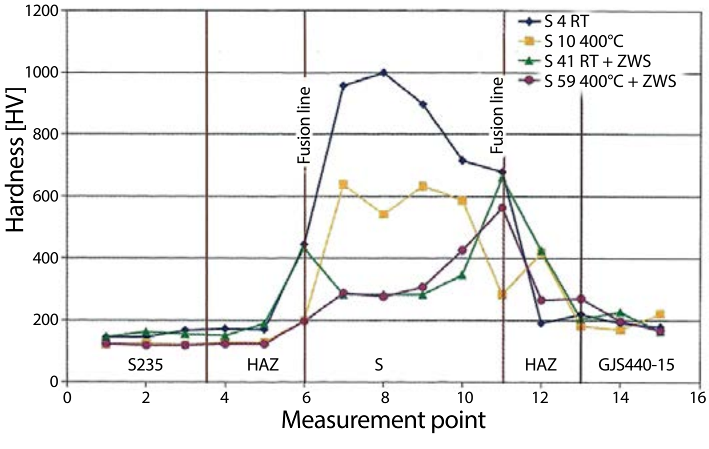

Fig. 10. Hardness distribution in a beam welded joint: GJS440 cast iron + S235 steel, RT – without a filler metal and preheating, ZWS – filler metal [11]

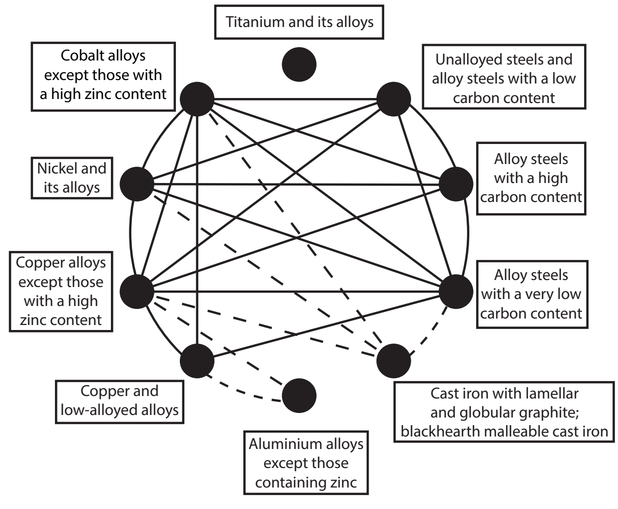

Fig. 11. Possible combinations of electron beam weldable materials;
——— good weldability, - - - restricted weldability [11]

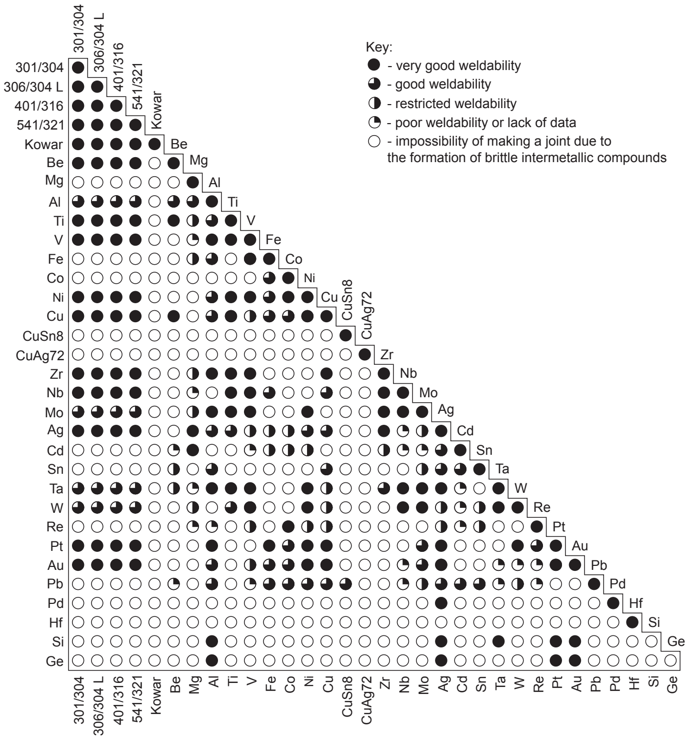

Fig. 12. Weldability of structural materials as regards electron beam welding [12]

Advantages and Applications of Electron Beam Welding

Electron technologies are particularly useful in the following industries:

- automotive; welding elements of gear transmissions, engine housings, detectors, radiators, crankshafts, piston rods, valve heads, filters, catalysts, turbocompressors, wheel rims, airbags and many others;
- aviation; welding of titanium tanks for propylene used in satellites and rockets, aluminium containers, thrust jets, fuel injections, fuselage elements made of titanium, armrests, stators, turbine blades and housings, discs in drum rotors of axial-flow compressors, perforated bottoms in rockets;
- power engineering and electrical power engineering; welding of turbine elements, blades, high-current flexible connectors, containers for nuclear waste;
- mechanical engineering; welding of transport hook elements in marine engines, furnaces for destroying used ammunition, wheels and gear transmissions, hydraulic cylinders, sensors of temperature and deformations, microscope frames made of aluminium alloys, commutators, band-sawing machines, drilling tools, catalysts for continuous steel casting, high-pressure valves;
- medical; welding of toothed gear elements in artificial limbs, quick prototyping of endoprosthesis elements, implant surface processing;
- railway; welding of carriage elements, e.g. cross-beams made of aluminium alloys, tow hooks, bearing sleeves, points elements, universal couplings.

Electron beam welding iss used in both mass-scale production and in the manufacturing of single elements. The welding process is carried out in a vacuum chambers having a volume ranging from several to several hundred thousand litres. Modern electron devices for welding and surface processing ensure the stability of technological process parameters, full repeatability of results and freedom of programming. Universal made-to-stock devices with accelerating voltage of 150 kV enable the production of welded joints of steels whose thicknesses exceed 100 mm (as against the maximum thickness of elements welded with commercially available lasers amounting to approximately 20 mm). For instance, in submerged arc welding making a 150 mm thick steel joint requires 157 runs with the welding time of 1 running metre being 314 min (without taking into account necessary pauses) and the amount of necessary welding consumables being 32 kg. In electron beam welding a joint is made with a single run, without a filler metal, without bevelling and with the welding time of 1 running metre being 8 min [11].

It should be emphasized that electron beam welding devices also enable carrying out other technological processes such as brazing, overlay welding, alloying, quick prototyping, surface texturing, engraving, testing physical phenomena during the interaction of electrons with the matter and monitoring electron beam welding processes.

Electron beam welding is one of the most power and material saving technologies. The use of an electron beam in welding processes enables [13]:

- welding metals having various physicochemical properties;
- making welds in poorly accessible places, e.g. at the bottom of deep and narrow gaps (width of approximately 2-3 mm, depth of several hundred mm), within a wide range of focus position (over 1000 mm from the electron gun outlet);
- obtaining narrow welds due to high power density and high welding rate (weld width/depth ratio from 1:10 to 1:50) with limited HAZ in a welded joint and minimum (practically negligible) deformations of workpieces;
- using butt joints with square preparation without bevelling edges within the complete range of workpiece thicknesses and without the necessity of using filler metals,
- automation of technological processes;
- easy integration with other technological systems.

Rationally used electron beam welding allows obtaining significant economic results and quick return on investment as a result of the following [13]:

- increased rate, efficiency and possibility of welding process automation,
- elimination of welding consumables (filler metals, fluxes and gases),
- technological simplification by changing product structural solutions, i.e. the replacement of complicated machining by dividing a given structural system into geometrically simpler elements and by welding such elements without additional post-weld heat treatment or machining,
- improving product quality,
- elimination of welding deformations,
- possibility of welding elements following after-machining or heat treatment.

Summary

Electron technologies, in spite of continually developed welding methods based on a concentrated photon beam, are still used and developed in many industries. Joining materials significantly differing in physical properties or having considerable thicknesses can be successful only by means of electron welding. Equally important is the use of electron beam welding for making joints of shapes or in places eliminating the use of other technologies. Electron beam welding provides very good joint quality and very high process efficiency.

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