

## Braze welding of Dissimilar Materials

**Abstract:** The article presents issues related to the braze welding process, discusses primary methods applied in industry as well as indicates characteristic features of the process, discusses the structure of joints most commonly used in industry and advanced braze welding methods enabling the obtainment of joints satisfying strict quality requirements. In addition, the article assesses the possibility of using the braze welding technology when repairing casts made of various casting alloys, discusses application areas for braze welded joints of materials characterised by different mechanical and physicochemical properties as well as presents metallographic and mechanical test results concerning braze welded joints made using a robotic CMT (Cold Metal Transfer) braze welding station.

**Keywords:** braze welding, dissimilar materials, overlap joints, low-energy methods

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### Introduction

Braze welding is defined as the brazing of non-capillary joints performed using welding methods [1-3]. This means that elements to be joined are prepared as if for welding, i.e. without a capillary gap (characteristic of brazing processes), the width of which is usually restricted within the range of 0.05 to 0.2 mm. The mechanisms responsible for the formation of a joint are the same as those occurring in brazing/soldering processes, i.e. materials to be joined are wetted with a filler metal and the joint is formed as a result of diffusion phenomena (adhesion, cohesion). Filler metals used in braze welding are selected in a manner analogous to that used when selecting filler metals for brazing/soldering, i.e. the melting point of a filler metal must be lower than that of the base

material. In addition, the filler metal must provide the appropriate wetting of the base material surface [3]. Braze welding usually involves the making of overlap joints rather than butt ones (used in cases of thicker elements), which is determined by the possibility of transmitting higher service loads. Typical design solutions related to braze welded joints used in, e.g. the automotive industry, are presented in Figure 1.

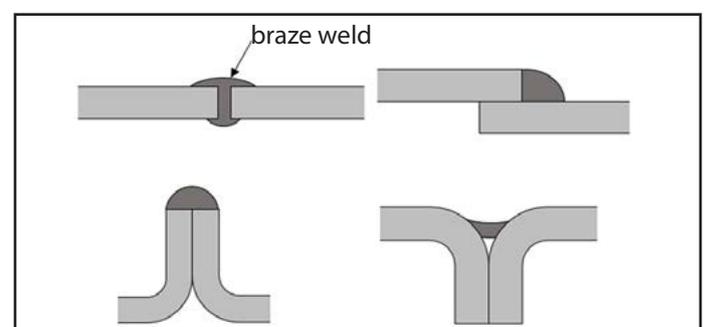


Fig. 1. Exemplary designs of braze welded

prof. dr hab. inż. Zbigniew Mirski (Professor PhD (DSc) Habilitated Eng.); dr inż. Tomasz Wojdat (PhD (DSc) Eng.); inż. Alicja Margielewska (Eng.) – Wrocław University of Technology; Faculty of Mechanical Engineering; Division of Materials Science; Welding and Strength of Materials

Over the past several years the braze welding process has become popular and commonly used particularly in the automotive, shipbuilding, electromechanical, food and installation industries as well as in building engineering and household equipment production. The popularity of braze welding processes in the above-named industrial sectors results from the growing number of structural elements used in the above-named industrial sectors. The aforesaid elements include sheets/plates, sections, shapes etc. provided with protective (zinc, aluminium etc.) coatings and elements made of corrosion resistant steels [3]. In addition, developmental trends also involve the minimisation of weight, which, in addition to the use of light metals, is often connected with the reduction of thicknesses of structural materials. The objective is to join elements of thicknesses restricted within the range of 0.7 mm to 3.0 mm, which when using conventional welding methods, e.g. MIG/MAG welding, is very difficult because of significant deformation of thin elements or damage to protective coatings resulting from an excessive heat input to a joint. Another issue is connected with increasingly high quality and aesthetics-related requirements difficult to satisfy in MIG/MAG welding because of process-related spattering. Spatters formed during MIG/MAG welding are not only expensive and laborious, but sometimes even

impossible to remove completely [3, 4]. The division of braze welding methods in relation to the heat source is presented in Figure 2.

Increasingly high functional properties required for various products have created demand for joints made of materials significantly varying in physico-chemical and mechanical properties, also referred to as dissimilar materials. Developmental trends vary in relation to industry and required operational properties. As a result, the number of material combinations enabling the obtainment of stable and functional joints is on the increase. For instance, in the automotive industry, seeking to reduce the weight of vehicles and, consequently, to decrease fuel consumption and emission of exhaust gases, steel, usually galvanised, is joined with lightweight materials, such as aluminium and its alloys. In turn, in industrial sectors using HVACR (i.e. Heating, Ventilation, Air Conditioning and Refrigeration), the making of heat exchangers often involves the joining of aluminium with copper or copper with acid-resistant steels. The aerospace industry requires joints made of titanium and alloys of aluminium and copper. Because of its low density, magnesium and its alloys are becoming more popular in various industries as well.

The obtainment of stable and functional joints of the above-named dissimilar materials entails numerous difficulties of technological-metallurgical nature. One of the methods providing the most favourable results is braze welding. The fact that braze welding does not require the melting of edges of elements to be joined makes it possible to avoid metallurgical difficulties related to the mixing of the base material and the filler metal during welding. The greatest issue faced when making dissimilar joints is connected with the selection of a filler metal to be used in the process.

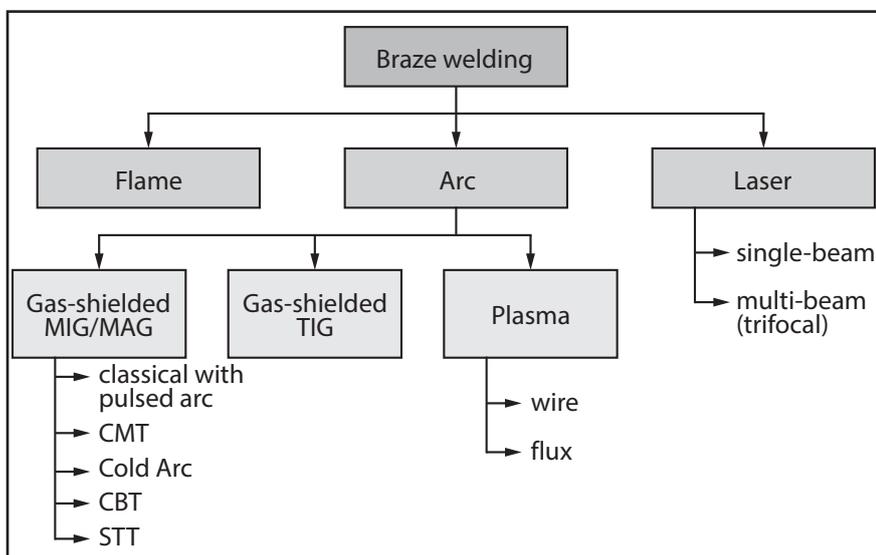


Fig. 2. Methods of braze welding in relation to the heat source

Usually, the filler metal is selected in relation to the less fusible base material. For instance, the braze welding of aluminium with galvanised steel is usually performed using silumin (Al-Si) filler metals and zinc (Zn-Al) filler metals [4,6,7], whereas the braze welding of copper with acid-resistant steel is usually performed using copper-based alloys such as silicon bronzes (Cu-Si) [8]. However, it is not always possible to perform the process without partially melting the edges nearer the lower fusible material, particular in terms of a low gradient between the melting point of the material and the melting point of the filler metal. Joints which are formed in such cases are characterised by specific morphology, i.e. the morphology of the joint near the lower fusible material is typical of welding processes, whereas that near the higher fusible material characteristic of brazing processes. In the above-named situations it is difficult to assess the quality of joints as the partial melting of the base material in the braze welding process is regarded as an imperfection, particularly in cases of systems of the same materials, whereas, in cases of materials significantly varying in melting points, the partial melting of the lower fusible material is acceptable.

Braze welding is also commonly used when surfacing elements made of unweldable steels or steels of limited weldability as it enables the obtainment of sufficiently low sliding friction coefficient. In addition, braze welding is useful when repairing cast elements, primarily those made of hard-to-weld or unweldable materials [1]. Casts are usually repaired using gas-shielded metal arc braze welding or flame braze welding [3]. Apart from traditional arc braze welding methods (GMA), braze welding is performed using increasingly popular low-energy methods, e.g. CMT or ColdArc. The low-energy braze welding processes provide a significantly lower heat input to casts and prevent the formation of spatters, the removal of which proves problematic.

## Characteristics of braze welding methods

Flame braze welding is performed in a manner similar to flame welding, only the edges of materials being joined are not melted. The heating of a material to a temperature enabling the melting of a filler metal is performed using an oxy-acetylene, sometimes oxy-propane, flame [5], depending on physicochemical properties and thicknesses of materials to be joined.

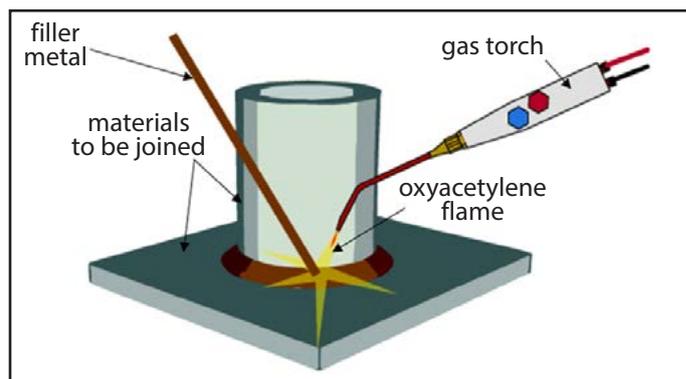


Fig. 3. Scheme of flame braze welding

The above-named technology is used primarily in the sanitary industry when making heating systems, drinking water supply systems, cooling water systems, sewage systems and compressed air systems made of galvanised steel pipes or aluminium tubes. The above-presented method can be used for the joining of elements made of galvanised steel provided with a coating having a thickness of up to 100  $\mu\text{m}$ . Edges of tubes (butting faces) are prepared as for the welding process, where the filler metal (usually brazing brass) is fed between the edges to obtain a diffusion joint. The process is performed using the vertical up position, where the flame heats up edges before the weld as in leftward welding. Other welding positions, e.g. the flat position, require the use of the method performed leftwards, so that the filler metal precedes the torch flame moving from right to left. The major issue accompanying the braze welding of galvanised tubes is the evaporation of zinc, in the form of white zinc oxide (ZnO) vapours. The intense evaporation of zinc leads not only to the deterioration of health and safety

conditions but also to the significant porosity of the braze weld and to the damage to anti-corrosive coating in the joint area. To limit the above-named phenomenon, the oxy-acetylene flame should feature oxidising properties. The aforesaid properties are obtained by adjusting a slight excess of oxygen in relation acetylene. The process can also be facilitated by using filler metals provided with a flux cover to avoid difficulty feeding the flux or applying the flux paste on the surfaces of materials to be joined before the braze welding process [5]. The use of the above-named technology in the making of water supply systems has been known since the beginning of the 20th century. Figure 4 presents a fragment of a braze welded water supply system made of copper, used in the years 1920-1997 in the building belonging to the Congregation of the Sisters of St. Elisabeth, near the Wrocław cathedral.



Fig. 4. Braze welded joint of copper tubes made using brazing brass LM63 (of the year 1920) [17]

### ***Gas-shielded MIG/MAG braze welding***

MIG/MAG welding is one of the most popular methods used when joining elements having thicknesses restricted within the range of 0.2 mm to 3.0 mm, made of unalloyed, low-alloy and alloy steels as well as steels provided with protective aluminium and zinc coatings

having thicknesses reaching 30  $\mu\text{m}$  [3]. The conventional MIG/MAG braze welding method involving the use of pulsed arc is still commonly applied, e.g. when joining dissimilar materials, primarily aluminium with galvanised or aluminised steel in the automotive industry, alloy steels with copper and steels with cast irons [3, 4, 8]. The significant popularity of the above-named method results from the development of innovative braze welding power sources enabling highly advanced control of current and arc voltage parameters and minimising a heat input to joints [3]. The aforesaid so-called low-energy MIG/MAG braze welding variants, the names of which are connected with producers, require the use of special synergic lines enabling the performance of braze welding processes involving various types of filler metals, shielding gases and material thicknesses.

During conventional MIG/MAG short-circuit arc braze welding, stable arc burning combined with low welding energy require that current waveform should maintain voltage at a constant preset level. Short-circuit arc welding entails significant spattering generated when the electrode comes into contact with the liquid metal pool. Because of high short-circuit current, metal drops tearing off the wire are highly overheated. As a result, the spattering of the liquid metal is explosive in nature. The short circuits occur with high frequency (up to 100 Hz) and in an uncontrolled manner, where sizes and numbers of liquid metal drops are accidental [6].

To solve the aforesaid problem and to address market needs, leading manufacturers of welding equipment developed the above-presented braze welding methods. The most popular gas-shielded low-energy arc welding and braze welding methods include ColdArc, CMT (Cold Metal Transfer), CBT (Controlled Bridge Transfer) and STT (Surface Tension Transfer). The use of these methods enables the obtainment of highly aesthetic joints, the minimisation of spatters and the significant reduction of

deformations, particularly in relation to thin elements [6, 8-10]. The above-named methods differ from conventional ones in the manner of intervention in current and arc voltage waveforms during short-circuit arc welding [7]. For this reason, this study discusses and compares the two most popular processes, i.e. ColdArc and CMT.

The ColdArc method was developed by a German company EWM. Because of minimised spattering, the process enables the welding of thin materials and the obtainment of joints characterised by high quality and aesthetics. The only difference between conventional short-circuit arc welding and the ColdArc method involves the current waveform. The waveform of arc voltage remains unchanged (Fig. 5a) [11]. The high value of arc voltage during the interruption of short circuit “informs” the digital control system about the necessity of the immediate reduction of current from the value of short-circuit to that of arc. The foregoing enables the reduction of power in the arc striking circuit, leading to the significantly gentler striking of arc. As a result, for a short time, current rises “smoothly” to reach the impulse level enabling the melting of the wire tip. Afterwards, current decreases to its low basic value to minimise further melting. Once short circuit has taken place, the entire cycle starts again. After each short circuit, the current impulse makes the wire melt. A molten metal drop adopts the shape of a cone having constant dimensions. As a result, the process is stable and the total welding energy is by approximately one third lower than that used in the short-circuit arc welding [10,11].

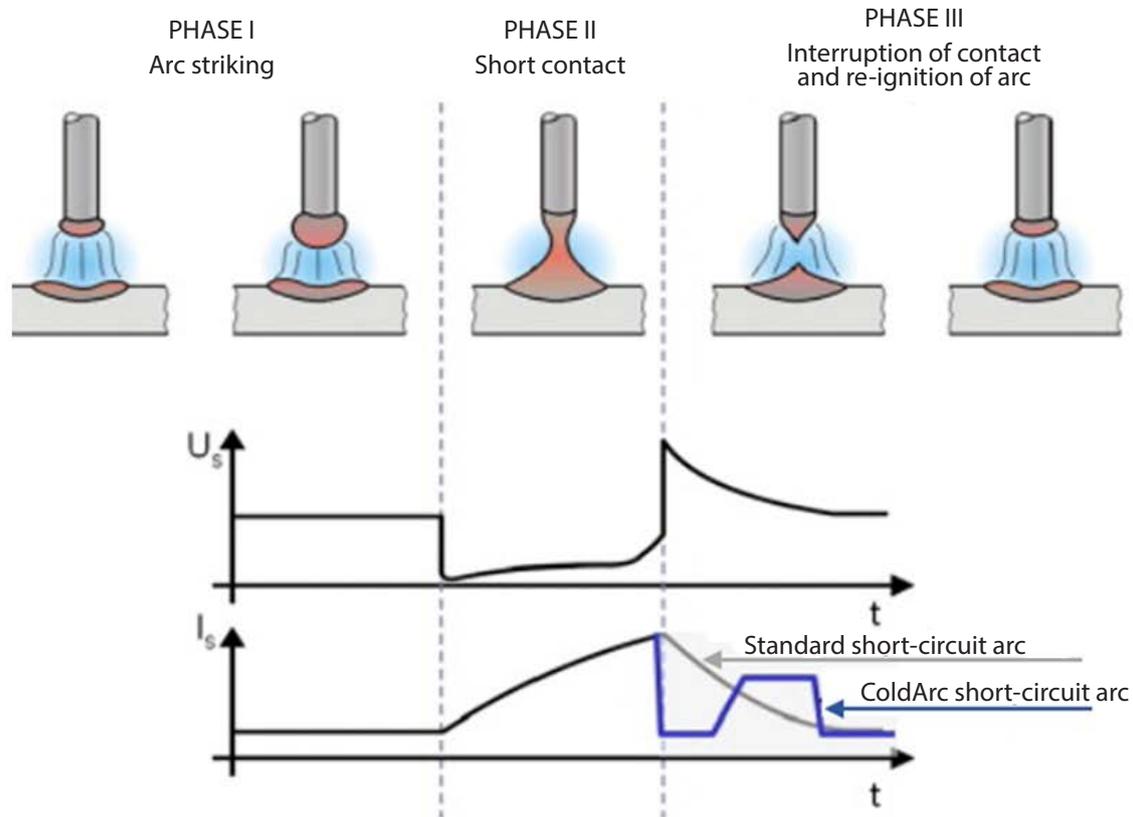
A popular variant of the MIG/MAG welding process, used in the experimental part of this research work, is the CMT (Cold Metal Transfer) method developed by an Austrian company Fronius. The above-named method is characterised by an innovative manner in which a molten metal drop is detached from the electrode wire. A characteristic feature of the process is the

fact that the wire is not only fed in the direction of the weld pool but is also periodically withdrawn at a frequency of approximately 70 Hz, which is used in the control of the process. The wire is fed towards the weld pool until the initiation of short-circuit. Afterwards, the wire feeding direction is reversed, i.e. the wire is withdrawn. When the contact is interrupted, the movement of the electrode wire is reversed again and the wire is fed in the direction of the weld pool. A significant difference is the manner of metal transfer from the electrode tip to the weld pool. Unlike in MIG/MAG short-circuit arc, where, in the above-named moment, the value of current is the highest, in the CMT process the value of current is at its minimum. In the CMT process the interruption of short circuit takes place without the interruption of the current flow, where the backward movement of the wire initiates the transfer of a metal drop to the weld pool induced by forces of surface tension and by gravity. As a result, short-circuit current can adopt very low values, translating into a very low heat input to the element subjected to welding [8,10]. The schematic transfer of metal in electric arc during the CMT process is presented in Figure 5 [11].

The backward movement of the electrode wire during welding or braze welding is possible because of the special welding torch design. In contrast to traditional torches used in the GMA process, the torch used in the CMT method is provided with a high-speed filler metal wire feeder enabling the precise withdrawal of the wire performed at a high frequency once the contact has been detected. The withdrawing wire does not return to the reel mounted on the primary feeder but is compensated in a special wire buffer [12].

One of the most important advantages of the CMT process is the (nearly complete) elimination of spatters achieved by the minimisation of current during the contact and the controlled interruption of the contact by the controlled backward movement of the wire.

a)



b)

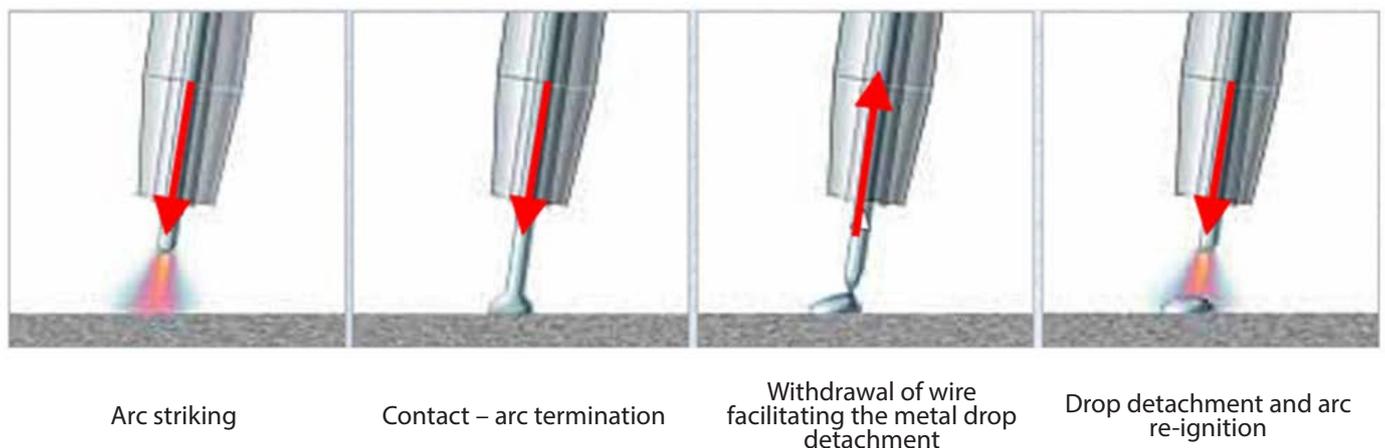


Fig. 5. Liquid metal drop transfer in: a) ColdArc [11] and b) CMT [12]

Another important aspect is the precise control of the arc length. In the MIG/MAG process the arc length is determined on the basis of arc voltage measurements. However, surface impurities may lead to misrepresentations of measurement results and, consequently, result in the deviation of the arc length from the optimum value. In the CMT process, during the contact, when the length of arc amounts to zero, arc is withdrawn at a specific rate based on an electronically preset time. The backward movement rate-time ratio provides the constant length of arc, independent of the welding rate and

electrode extension. As a result, the CMT braze welding process is characterised by very high stability [10].

Both the ColdArc and the CMT were improved by applying variable polarity pulsed current and gained new synergic line names of Cold Process and CMT Advanced respectively. New devices enable the obtainment of alternating current characterised by the variable content of reverse polarity, which in turn makes it possible to shape current and voltage waveforms and, consequently, to reduce a heat input even lower [3, 13].

Arc braze welding methods also include plasma braze welding, involving the use of conventional plasma welding devices. Unlike in traditional arc braze welding methods, during plasma braze welding electric arc is concentrated on a significantly smaller area, leading to a lower heat input to the material and reducing base material strains. In relation to types of filler metals melted in plasma arc, the plasma braze welding process is divided into plasma braze welding performed using a wire and the one performed using flux [14]. In both cases, the process is usually mechanised or robotic. Similar to the above-named methods, the filler metal (wire or powder) has a melting point lower than that of materials being joined and is melted by the heat of plasma arc, additionally activating the process of wetting and the spreading of the filler metal, and, consequently leading to diffusion between the weld deposit and the base material [3]. Research discussed in work [14] revealed that the plasma braze welding of thin galvanised steel sheets (having a thickness of 0.9 mm) requires the very precise adjustment of process parameters (very narrow range of parameters) to prevent damage to protective coatings.

**Laser braze welding** involves the melting of a (brazing) filler metal fed by a defocused laser beam (Fig. 6a). At the same time, the laser beam heats up the base material, enabling the activation of surface phenomena (wettability, spreadability) and diffusion processes. The process is widely used by leading automotive companies.

The thickness of the coating of weldbrazed galvanised steel sheets reaches 30  $\mu\text{m}$ . In most cases, the high aesthetics of joints combined with the smooth weldbraze face enable the application of a varnish coat directly after the braze welding process [3]. Laser braze welding is usually performed using solid-state lasers (disc or fibre lasers) as well as diode lasers mounted on robotic stations. One of laser braze welding variants is the multi-beam (so-called trifocal) braze welding system. The process involves the use of three laser beams generated independently in the laser resonator and transported via special optical fibres to the working head. Two auxiliary beams, characterised by lower power, are used to initially clean and heat up the surfaces of elements to be joined. The aforesaid operation enables the spreading of the brazing filler metal only within the heated material area. The principal beam characterised by greater power and the wider area of effect is used primarily for the melting of the filler metal (Fig. 6b) [15].

### Tests of selected dissimilar joints

Braze welding-related tests involved the making of overlap joints using a robotic station (Fig. 7). The joints were made using the CMT method. One of the most important elements of the welding station was a TransPuls Synergic 3200 CMT pulse welding machine (1). The welding power source was a computer-controlled digitalised inverter machine. The welding station was provided with a filler metal wire feeder located directly above the welding power

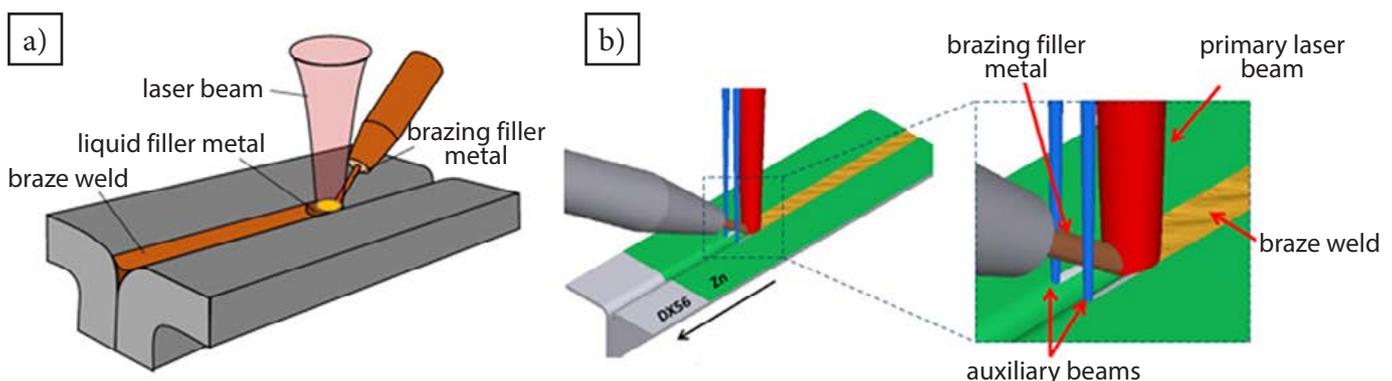


Fig. 6. Laser beam braze welding: a) one- and b) multi-beam [16]

source. The digitally controlled VR 7000-CMT 4R/G/W/F++ filler metal feeder (2) provided high process accuracy and the possibility of using many various filler metal wires. The filler metal feeder was connected to a Kawasaki BA series robot (3) by means of flexible conduits. The robot was equipped with a Robacta Drive CMT PAP W welding torch (4) equipped with a digitally controlled built-in AC asynchronous motor.

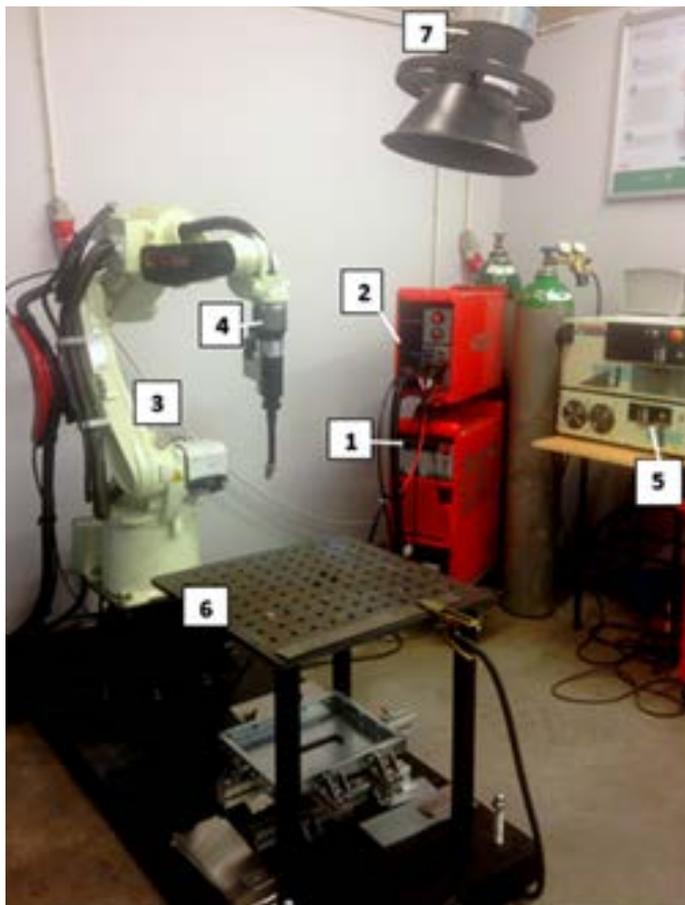


Fig. 7. Robotic CMT braze welding station: 1 - pulse welding machine; 2 - filler metal wire feeder; 3 - Kawasaki robot; 4 - welding torch; 5 - robot interface; 6 - welding table; 7 - exhaust of welding fumes

The CMT robotic braze welding involved the making of two types of dissimilar joints, i.e. aluminium with hot galvanised steel and copper with acid-resistant steel. All of the materials were 1.0 mm thick, apart from copper, which was 2.0 mm thick. The overlap joints were made so that the base materials having lower melting points (aluminium and copper) were placed on the galvanised and acid-resistant steel respectively.

Aluminium alloy grade 5754 was joined with galvanised steel DX51D (coating thickness being 14  $\mu\text{m}$ ) which was performed using silumin wire AlSi5 having a melting point restricted within the range of 573°C to 625°C. In turn, copper Cu-ETP was joined with acid-resistant austenitic steel X5CrNi18-10 using silicon bronze CuSi3 having a melting point restricted within the range of 910°C to 1025°C. In both cases, the braze welding processes were shielded using argon having a purity of 99.995% (ARGON 4.5). Initial braze welding tests confirmed that the process required very precisely adjusted technological parameters (within a very narrow range). However, the appropriate adjustment of parameters enabled the performance of a very stable process and the obtainment of joints characterised by high quality and aesthetics.

The significant flowing power of both filler metals and the small gradient between the melting point of the filler metal (AlSi5) and that of aluminium alloy 5754 as well as between the melting point of CuSi3 and that of copper Cu-ETP were responsible for the fact that even the slightest deviations from the optimum (experimentally determined) parameters led to the formation of numerous welding imperfections. Slight changes in the parameters led to, among other things, the lack of process stability, the greater number of spatters, excess weld face penetration, the burn-through of the sheets, the partial melting of the edges of the lower fusible material, the lack of wettability and incomplete fusions.

Visual tests were performed following the guidelines of the PN-EN ISO 17637:2017-02 standard. To provide appropriate contrast, the illuminance adjusted on the basis of the above-named guidelines amounted to 500 lx and struck the surface of the test joints at an angle of 45°.

The test object was observed from a distance restricted within the range of 450 mm to 500 mm. The angle of observation amounted to 30°. The assessment of the braze welded joints was based on the PN-EN 12799:2003/

A1:2005 standard. The evaluation revealed that the joints were made properly. In both cases the obtained braze weld face was smooth, aesthetic, uniform and spatter-free. In addition, the joints of aluminium 5754 with the galvanised steel did not reveal damage to the protective coating on the other side of the joint.

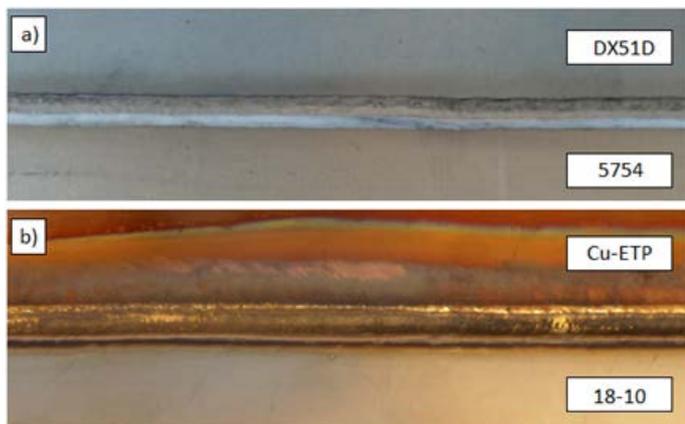


Fig. 8. Braze welded overlap joints made of aluminium alloy 5754 with the galvanised steel (a) and copper with the acid-resistant steel (b)

Macroscopic metallographic tests were performed using an Olympus SZX7 stereoscopic microscope. The assessment of the braze welded joints conducted in accordance with the requirements of the PN-EN 12797:2002/A1:2005 standard revealed that, in spite of appropriate appearance, the joints contained welding imperfections. The braze weld of the joint of aluminium alloy 5754 with galvanised steel DX51D contained numerous gas pores arranged uniformly across the entire cross-section of the joint (Fig. 9a). The number of gas pores could be reduced by the use of shielding gas characterised by higher purity, e.g. ARGON 5.0. The slight partial melting of the aluminium sheet edge (marked white in Fig. 9a, b) could be ascribed to the low gradient of the melting point of the filler metal and that of the base material. The above-named imperfection could be avoided without changing process parameters, i.e. by changing the position (angle or distance) of the welding torch in relation to the aluminium sheet. The joining of copper Cu-ETP with acid-resistant steel X5CrNi18-10 performed using brazing filler metal CuSi3 (Fig. 9b) was not

accompanied by the formation of porosity. The lack of the above-named welding imperfection could be attributed to the lower affinity of the copper-based filler metal for oxygen than that of the aluminium-based filler metal. The visible partial melting of the copper sheet edge might be avoided by optimising the process involving the modification of welding torch settings in relation to the copper sheet.

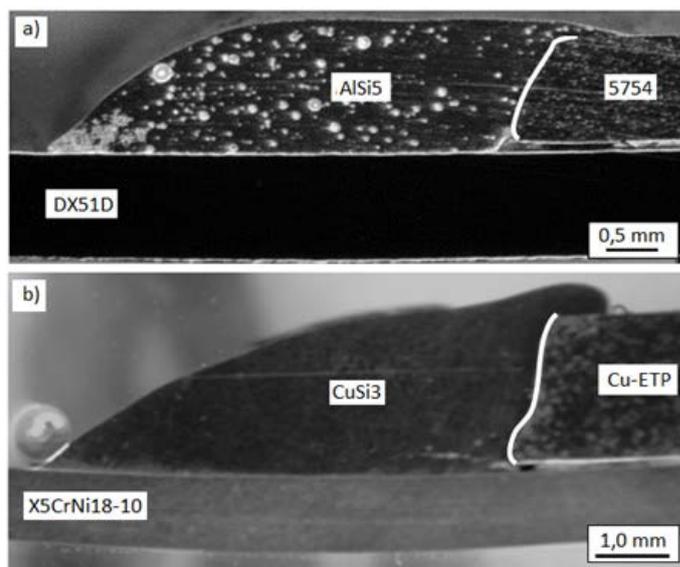


Fig. 9. Macrostructure of the braze welded joints of aluminium alloy 5754 with the galvanised steel (a) and of copper with the acid-resistant steel (b)

The research also involved microscopic tests of the dissimilar joints performed using an Olympus CK40M light microscope (Fig. 10). Observations were performed in the bright field. The joint of aluminium with the galvanised steel did not reveal damage to the protective coating within the joint area. Along the length of the joint, the zone where the galvanised sheet was wetted by the filler metal revealed the partial dissolution of the protective coating zinc in the weld deposit. As a result, the protective coating became thinner and its thickness was restricted within the approximate range of 3  $\mu\text{m}$  to 5  $\mu\text{m}$  (Fig. 10a). The joints of copper with the acid-resistant steel revealed the slight partial melting of the steel surface within a narrow zone having a width restricted within the range of 5  $\mu\text{m}$  to 8  $\mu\text{m}$ . Molten particles of the steel are visible in the braze weld presented in Fig. 10 c, d.

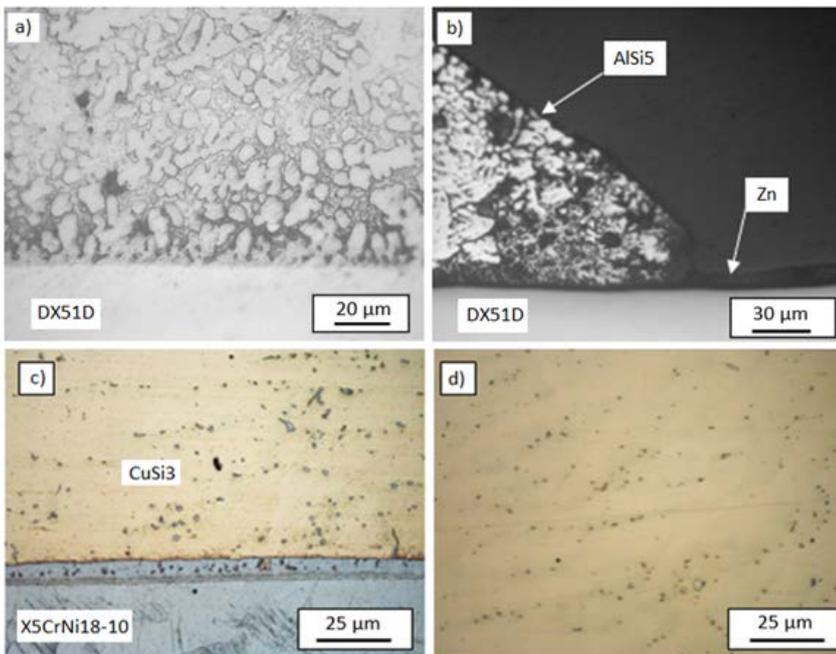


Fig. 10. Microstructure of braze welded joints of aluminium alloy 5754 with the galvanized steel (a,b) and of copper with the acid-resistant steel (c,d)

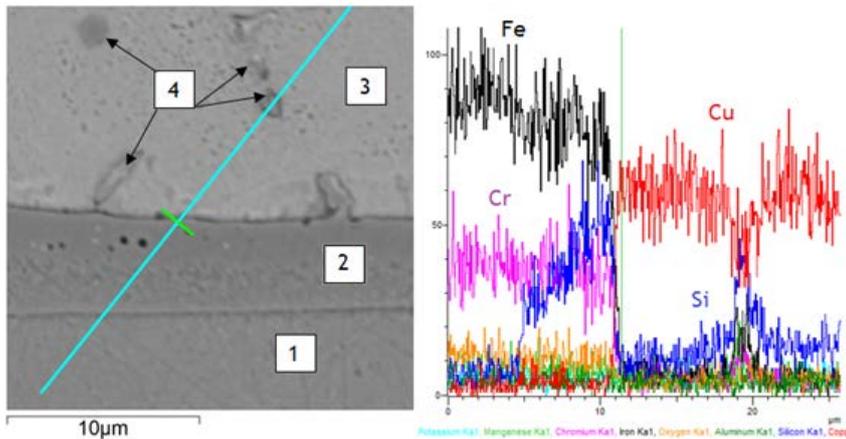


Fig. 11. SEM image presenting the linear distribution of the EDS elements at the boundary between the steel and the braze weld: 1- acid-resistant steel X5CrNi18-10, 2- partially melted steel area, 3- weldbraze, 4- steel precipitates

The linear distribution of chemical elements in the braze welded joint did not reveal the presence of copper in the partially melted zone of the steel (Fig. 11). The fact that copper did not get mixed with the acid-resistant steel was favourable as the mixture of copper and the acid-resistant steel could easily trigger hot cracking.

In a static shear tensile test, the overlap joints ruptured outside the overlap (having the dimensions of 10 × 12 mm). The mechanical strength of the joints of aluminium with the galvanized steel and of copper with the acid-resistant steel corresponded to the tensile strength of the material characterised by the lower strength. The

mean tensile strength of the joints of aluminium with the galvanized steel amounted to 105 MPa, where the rupture took place in aluminium in the HAZ near the joint. The mean tensile strength of the joints of copper with the acid-resistant steel amounted to 215 MPa, with the rupture taking place in copper.

## Conclusions

Braze welding makes it possible to join a wide variety of materials characterised by different physico-chemical and mechanical properties, e.g. elements made of unalloyed steels provided with protective coatings (zinc, aluminium) with aluminium, copper with alloy steels, aluminium with titanium etc. In addition, braze welding can be used for repairing casts, particularly those made of hard-to-weld or unweldable materials. The joints obtained in the research-related tests were characterised by aesthetic appearance, high quality and good mechanical properties. The lower heat input to the joints made it possible to join ma-

terials provided with protective coatings without damaging the latter. The braze welded joints were also characterised by the significantly narrower HAZ (not affecting or negligibly affecting the properties of the joints). The low-energy arc braze welding variants, e.g. CMT, enabled the limitation or even the elimination of spatters as well as the significant reduction of strains without compromising high mechanical properties. Most of the braze welding methods combined with automated and robotic applications can be successfully used in various industries enabling the obtainment of joints characterised by high quality and repeatability.

## References

- [1] Gawrysiuk W.: *Technologia lutowania łukowego. Zalecenia technologiczne i przemysłowe przykłady zastosowań*. Biuletyn Instytutu Spawalnictwa, 2005, vol. 49, no. 3, pp. 35-40.
- [2] Pilarczyk J. (red.): *Poradnik inżyniera. Spawalnictwo*. 2014, vol. 2, WNT, Warszawa.
- [3] Pfeifer T., Stano S.: *Nowoczesne metody lutowania w aspekcie jakości i właściwości połączeń*. Przegląd Spawalnictwa, 2016, no. 9, pp. 95-102.  
<http://dx.doi.org/10.26628/ps.v88i9.665>
- [4] Wojdat T., Kustroń P., Lange A., Łącka I.: *Badanie właściwości złączy lutowanych aluminium ze stalą wykonanych przy użyciu spoiw na bazie Al i Zn*. Przegląd Spawalnictwa, 2017, no. 7, pp. 22-25.  
<http://dx.doi.org/10.26628/ps.v89i7.794>
- [5] Mirski Z., Granat K.: *Lutowanie gazowe ocynkowanych rur stalowych*. Przegląd Spawalnictwa, 2013, no. 2-3, pp. 19-21.
- [6] Białycki P., Ambroziak A., Derlukiewicz W., Lange A., Glezman M.: *Właściwości złączy lutowanych aluminium ze stalą*. Przegląd Spawalnictwa, 2013, no. 9, pp. 40-44.  
<http://dx.doi.org/10.26628/ps.v85i9.197>
- [7] Klimpel A., Czupryński A., Górka J.: *Lutowanie metodą GMA cienkich blach ocynkowanych*. Przegląd Spawalnictwa, 2004, no. 8-9, pp.81-85.
- [8] Wojdat T., Kustroń P., Skuratowicz F., Michalak P., Piotrowska P.: *Zastosowanie niskoenergetycznego procesu CMT do lutowania złączy miedź – stal kwasoodporna w różnych osłonach gazowych*. Przegląd Spawalnictwa, 2018, no. 1.  
<http://dx.doi.org/10.26628/ps.v90i1.848>
- [9] Kiszka A., Pfeifer T.: *Spawanie cienkich blach stalowych z powłokami ochronnymi metodą MAG prądem o zmiennej biegunowości*. Biuletyn Instytutu Spawalnictwa, 2012, no. 2, pp. 39-43.
- [10] Matusiak J., Czwońnóg B.: *Niskoenergetyczne procesy spawania łukowego w osłonie gazów do łączenia cienkich blach stalowych*. Hutnik – Wiadomości Hutnicze, 2008, no. 1, pp. 10-16.
- [11] Goecke S.F.: *Low Energy Arc Joining Process for Materials Sensitive to Heat*. Materiały firmy EWM Hightec Welding.
- [12] Himmelbauer K.: *The CMT process – a revolution in welding technology*. Materials by Fronius International GmbH.
- [13] Piłkuła J., Mendakiewicz J., Pfeifer T.: *Influence of the shielding gas on the properties of VP-GMA braze-welded joints in zinc coated steel sheets*. Biuletyn Instytutu Spawalnictwa, 2014, vol. 58 no. 1, pp. 54-59.  
<http://bulletin.is.gliwice.pl/article/influence-shielding-gas-properties-vp-gma-braze-welded-joints-zinc-coated-steel-sheets>
- [14] Klimpel A., Czupryński A., Górka J.: *Lutowanie plazmowe proszkowe PTA złączy blach karoseryjnych galwanizowanych cynkiem*. Przegląd Spawalnictwa, 2007, no. 9, pp. 26-31.
- [15] Strite T., Gusenko A., Grupp M., Hoult T.: *Multiple Beam Fibre Lasers Used for Material Processing*. Biuletyn Instytutu Spawalnictwa, 2016, no. 3, pp. 46-48  
<http://dx.doi.org/10.17729/ebis.2016.3/4>
- [16] Majeran E.: *Lutowanie laserowe w przemyśle motoryzacyjnym metodą Trifocal na przykładzie tylnej klapy Volkswagena Caddy*. Przegląd Spawalnictwa, 2016, no. 9, pp. 14-17.  
<http://dx.doi.org/10.26628/ps.v88i9.650>
- [17] Mirski Z.: *Spajanie termiczne instalacji miedzianych*. Polski Instalator, 2001, no. 4, pp. 14-20.