

# Advanced Applications of Microplasma Welding

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**Abstract:** The article discusses microplasma arc applications in welding, surfacing and remelting processes, describes the effect of microplasma arc and its burning conditions as well as presents the properties and the application range of plasma welding. In addition, the article presents examples of microplasma welded joints of thin elements and discusses the application of microplasma arc in surfacing and remelting as well as indicates advantageous features of plasma arc and its application potential as an alternative to other welding power sources.

**Keywords:** microplasma, welding, surfacing, remelting, application

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## Introduction

Significant progress in materials engineering, electrical engineering and control systems impose the continuous development of welding processes to satisfy increasingly new and difficult requirements set by various industries. Welding processes enable the obtainment of joints both in miniature electric circuits and large-sized structures. Presently, welding processes can be very precise and closely related to automation or robotisation, reducing manufacturing costs and improving the quality and repeatability of joints. Recent years have seen an increase in the number of joining applications utilising the heat of plasma arc, the energy of electrons or the radiation of laser. One of the methods which has established itself among welding technologies is plasma welding (method 15 – plasma welding in accordance with PN-EN ISO 4063). Plasma welding enables the joining of nearly all metals and alloys and is used in the automotive, aviation,

aerospace and food industry as well as in the welding of pipelines, pressure vessels, precision engineering, medical technique, electronics etc. [1-3]. Thicknesses of plasma (microplasma) welded elements are restricted within the range of 0.01 mm to between ten and twenty millimetres. The method consists in the obtainment of an inseparable joint by the high-temperature melting of sheet edges using concentrated plasma arc. The process can be performed with or without the filler metal fed to the arc-affected area. Microplasma welding is one of the dominant methods as regards the welding of sheets having thicknesses below 1 mm. The article discusses selected examples of microplasma welding in joining processes and surface processing applications.

## Essence of microplasma welding

Similar to other welding methods, plasma welding consists in the permanent joining of

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metals and their alloys through the melting of edges of elements and, if need be, of the filler metal, by the heat of plasma arc. Welding plasma arc is a stream of strongly ionised gas narrowed mechanically by a plasma nozzle. The start-up involves the initiation of pilot arc between a tungsten non-consumable electrode (cathode) and a narrowing nozzle (anode) by a system generating high-voltage and high-frequency impulse. Pilot arc partly ionises plasma gas (argon) flowing out of the narrowing nozzle and facilitates the initiation of primary plasma arc. Afterwards, the current of plasma arc is switched off. Narrowed electric arc burns between the electrode (cathode) and a material being welded (anode) (Fig. 1).

Plasma devices generating low-temperature plasma arc as the source of thermal energy are used in the welding, surfacing and thermal cutting of metals. The application of a given machine is primarily determined by the design of individual units, mainly that of the torch and the arc power source. Plasma gases usually include argon-hydrogen mixtures, air and pure oxygen. Low-temperature plasma is formed through an imposed increase in the density of ionised molecules in the arc column resulting from a decrease in the arc column diameter. Welding arc burning in the shielding gas atmosphere between the non-consumable electrode and the material being welded has the shape of a cone, the dimensions of which depend on supply parameters and the distance between electrodes. As a result of a decrease in the transverse dimensions of arc (i.e. arc narrowing), the temperature of arc will grow up to tens of thousands of degrees. The narrowing of burning electric arc in the plasma gas stream increases the density of conductive current and the intensity of the electromagnetic field around arc, which in turn, increases Lorentz force directed axially onto the plasma beam, causing its

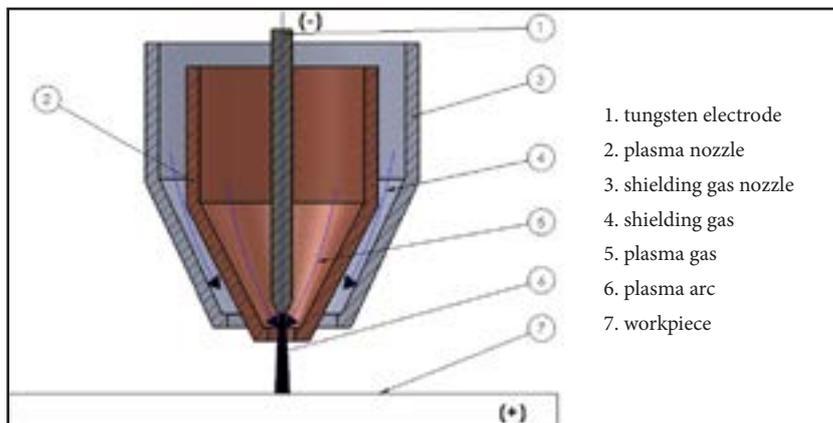


Fig. 1 Schematic diagram of a plasma welding torch (method 153 – plasma arc welding in accordance with PN-EN ISO 4063)

further narrowing. The foregoing results in an increase in the electric and core conductance of arc (part of it), an increase in the degree of arc plasma ionisation and a further decrease in the arc cross-sectional area [1]. The above-presented phenomena lead to the state of equilibrium characterised by very high temperature, an increase in voltage and a significant reduction of the cross-sectional area of (columnar) arc.

Plasma itself is composed of gas heated to its, at least partly, ionised state, enabling the conduction of electric current. If electric current burns between two electrodes, a certain number of gas stream molecules located between the electrodes becomes ionised. The electric conductance of such gas plasma (having a temperature of approximately 20 000 K) depends on the degree of its ionisation and, for instance, in relation to argon amounts to approximately 0.05% of pure copper conductivity [1,3].

### Technological characteristics and applications

Initially, plasma welding and microplasma welding processes were performed using current restricted within the range of 25 A to 30 A. Afterwards, the development of TIG plasma welding enabled the performance of joining processes using current restricted within the range of 400 A to 600 A. A subsequently developed plasma welding method was based on MIG welding and involved the use of a consumable electrode. Presently, plasma and

microplasma welding involving the use of a non-consumable electrode is referred to as TIG plasma welding, whereas the process involving the use of a consumable electrode is classified as MIG plasma welding (Fig. 2).

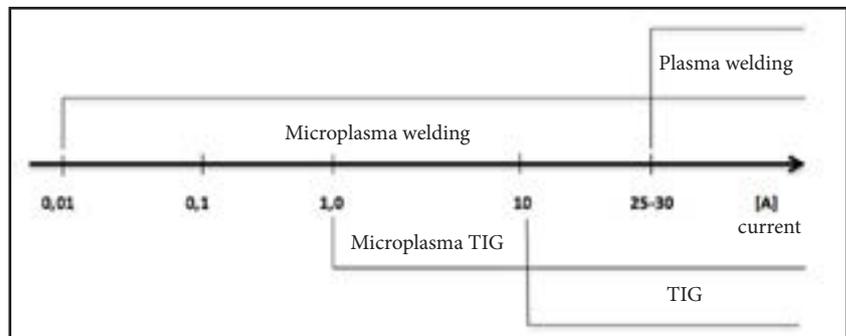


Fig. 2. Current range in relation to plasma welding and TIG welding [1]

TIG welding limitations include the excessively high thermal power of arc, precluding the welding of thin elements (below 1 mm in thickness). In relation to low welding current (below 10 A), used when welding sheets of the above-named thickness, electric arc tends to be very unstable. The foregoing is related to the steeply declining characteristics of low-current arc. Slight changes in length can result in arc wander, precluding the welding of thin materials and leading to the formation of welds characterised by very non-uniform cross-sections, burn-throughs or even the lack of penetration. However, the aforesaid problems can be overcome by the use of microplasma welding [1,3].

Such arc can be stabilised by providing the nozzle (inside) with a well-cooled reducer directing arc and by the leading of arc by means of a special “blanket” made of the shielding gas. The composition of the gas mixture differs from arc column plasma (containing pure argon) and may contain, e.g. 95% of argon and 5% of hydrogen. The thermal properties of hydrogen, i.e. high enthalpy, high heat conductivity and relatively low dissociation temperature, are used to prevent the excessive expansion of arc. At a temperature of 5000 K, the high kinetic energy of most of the hydrogen molecules combined with ongoing collisions results in the decomposition of molecules into atoms. A hydrogen addition (restricted within the range of 1 % to 5%) to the shielding gas (argon) makes it possible to provide arc with a thin gas blanket characterised by high thermal conductivity and being the space of intense dissociation and association processes. The complex interaction of the above-named properties of the

gas blanket enables the obtainment of stable arc even in milliamper conditions [1].

Similar to all plasma-based methods, microplasma welding requires the use of the so-called pilot arc burning between the copper nozzle and the tungsten electrode, providing the blast of plasma gas enabling the transfer of primary arc onto the material being welded. Pilot arc also burns during the welding process itself and is indispensable for the transfer of primary arc in low current conditions. The process entails the formation of magnetic field characterised by high-frequency current (1 MHz, 2000 V). The effect of the high temperature of arc ionises argon atoms forming the mixture of free electrons, positive ions and atoms, referred to as plasma. Energy needed to start the formation of plasma is obtained through collisions of atoms and ions as well as through their heating by arc. The plasma beam leaving the internal nozzle triggers the formation of primary arc between a tungsten electrode and a sheet subjected to welding. The direction of flow is induced by the positive of primary arc power source. During welding, internal arc is burning at all times, enabling the fast re-initiation of primary arc the moment the latter goes out. Microplasma welding is also characterised by the fact that, in certain applications, the current of internal arc (usually approximately 2 A) can exceed the current of primary arc (0.2 A – 30 A). In the latter case, the primary source of heat is the kinetic energy of plasma and not the energy of electric arc. The thermal energy of the plasma beam increases along with the

growing current of primary arc, which, in turn, entails the necessity of increasing the flow of plasma-forming gas [2,4].

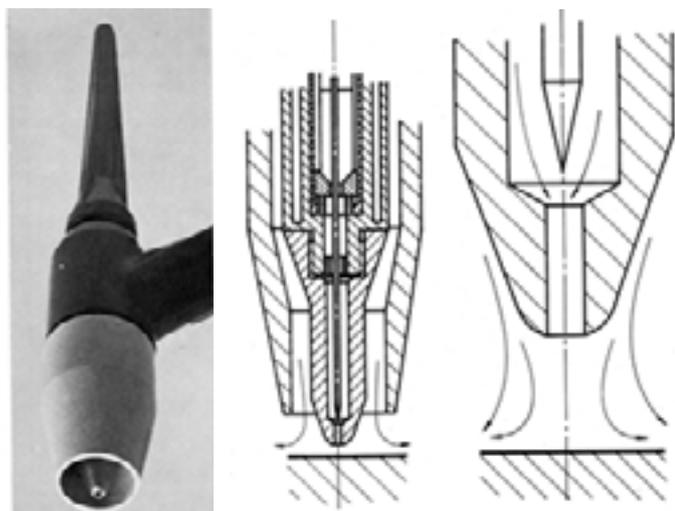


Fig. 3. Microplasma torch model MP-10 in cross-section [4]

Figure 3 presents the cross-sectional view of the MP-10 microplasma welding torch, including the nozzle with the outlet of plasma gas and the ceramic nozzle forming the gas blanket. On the right, the figure presents the cross-section of the long cylindrical opening in the copper nozzle. The initiation of arc between the tungsten electrode and the nozzle is accompanied by the initiation of pilot arc (by high-frequency current). Because of its

properties, i.e. the reversible dissociation and association of atoms into molecules (H<sub>2</sub>) occurring not only in the arc area, but also in the direct vicinity of the material being welded, hydrogen present in the gas shield advantageously affects the welding of thin elements. As a result of the foregoing, heat entering the weld pool is exceptionally concentrated. In addition, hydrogen reduces surface tension, which is of significant importance when welding thin elements.

The microplasma welding method enables the making of joints in sheets having thicknesses restricted within the range of 0.01 mm to 0.8 mm (using the above-presented MP-10 torch). A small amount of hydrogen in the shielding gas does not adversely affect structural and mechanical properties when joining austenitic stainless steels, nickel and nickel alloys. In addition, if the content of hydrogen in the shielding gas is restricted within the range of 2 % to 4%, microplasma welding can be used to joint titanium and its alloys. Microplasma welding can be successfully used to joint most noble metals. Table 1 presents microplasma welding parameters in relation to selected materials and thicknesses.

Table 1. Exemplary materials and welding parameters in relation to microplasma welding [5]

Material	Thickness (mm)	Torch		Gas (l/min)					Current A	Welding rate cm/min
		Electrode $\varphi$ (mm)	Nozzle $\varphi$ (mm)	Plasma argon	Shielding Ar (%)	Shielding H <sub>2</sub> (%)	Shielding He (%)	l/min		
steel	0.06	1	0.8	0.15	95	5	0	4/6	2	65
constantan	0.10	1	0.8	0.15	95	5	0	4/6	5	50
iron/nickel	0.80	1.6	1.5	0.20	95	5	0	517	15	45
cupronickel	0.50	1.6	1.2	0.20	95	5	0	517	10	60
silver/nickel	0.30	1.6	1.8	0.20	0	0	100	7	45	60
titanium, tantalum, zirconium	0.50	1.6	1.2	0.20	0	0	100	7	25	70
gold	0.20	1	1	0.15	95	5	0	4/6	5	40

In terms of investment and running costs as well as the quality of joints and process efficiency, plasma welding is an intermediate method between TIG and laser welding. In comparison with the TIG welding process, plasma welding is characterised by higher precision, more stable and concentrated arc, a narrow and clean weld, a smaller heat affected zone and a longer electrode life [1, 5].

Plasma welding requires meticulous surface preparation and, in mechanised processes, the uniform and precise control of the welding torch. In terms of plasma welding, surface preparation-related requirements are by approximately 50% more strict than those concerning surface preparation in TIG welding. However, the aforesaid requirements are fully compensated by the obtainment of significantly higher welding rates (several times) and higher efficiency (Fig. 4 and 5).

A significant advantage of manual, automated and robotic plasma welding is the low sensitivity of arc to its length changes, enabling the welding of elements characterised by complicated shapes and/or located in poorly accessible areas/spaces. Plasma welding is characterised by easy

arc initiation resulting from the use of pilot arc burning between the welding torch cathode and the plasma nozzle as well as due to high power density (approximately 3 times higher than that in the TIG method), enabling the obtainment of deeper penetration, narrower welds and heat affected zones (translating into smaller thermal strains of welded elements), high quality, aesthetics and metallurgical purity of welds.

### Microplasma welding applications

The development of plasma-based methods has extended the range of microplasma welding applications by successive material groups including aluminium alloys or unalloyed steels. To a certain extent, microplasma welding can be perceived as a method competitive in relation to TIG welding, outstripping the latter in terms of arc efficiency, penetration depth and welding process efficiency. However, plasma welding machines are more expensive than TIG welding equipment. In many cases, microplasma welding can be treated as a cheaper alternative to significantly more expensive electron beam and laser beam welding methods.

Microplasma welding is commonly used in

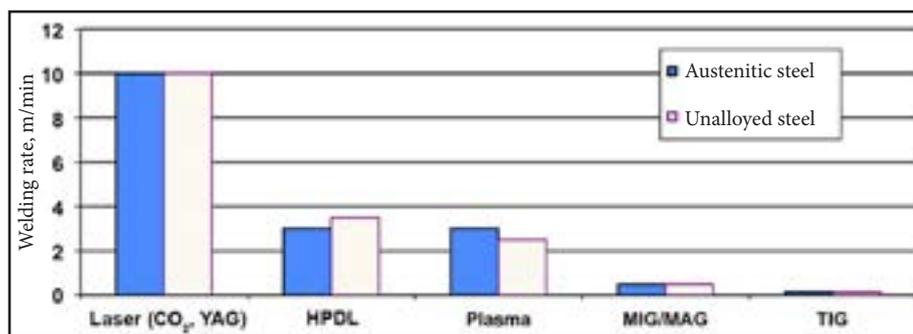


Fig. 4. Comparison of welding rates in relation to various welding methods when joining 1 mm thick sheets [5]

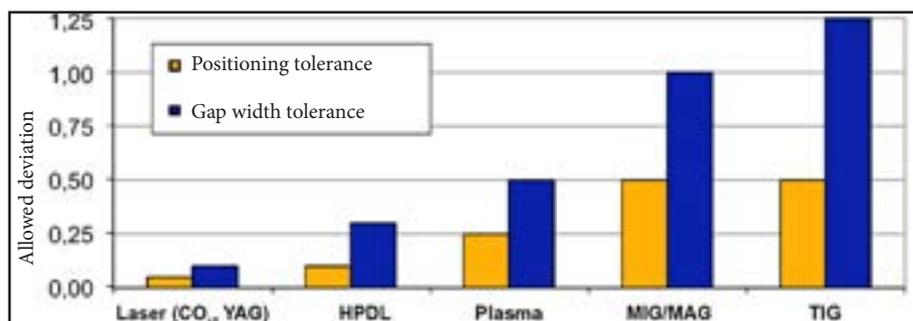


Fig. 5. Comparison of positioning tolerance and gap width tolerance in relation to various welding methods [5]

the electronic industry, medical technique, food industry and precision engineering. The process can also be used in single repair processes involving precise machinery elements. In general, it can be stated that microplasma welding can be widely used in the precise manufacturing of very small elements. Exemplary applications of microplasma welding include the making of measurement instruments, metal capsules, metal fabrics, welded capillary tubes used in measurement equipment, thermal capacitors, joints bonding membranes and thermocouples, miniature heat exchangers

as well as the welding of tubes made of stainless steel and the joining of filter sieves [6]. Because of its numerous advantages, microplasma welding is commonly used when joining sheets/plates, wires, foils, nets made of high-alloy steels, nickel, copper, gold, titanium alloys and special alloys. In addition, microplasma welding sometimes replaces expensive electron beam or laser welding processes, where obtained results are often comparable while equipment-related costs are significantly lower. Microplasma welding can also replace some brazing/soldering processes and, last but not least, microplasma arc can be successfully used in surfacing and remelting processes.

### Microplasma welding of thin sheets

A special advantage of microplasma welding is the possibility of joining thin sheets (less than 1 mm thick). Typical joints made using the above-named method include butt, edge and overlap joints. Microplasma method-based technological processes can involve the manual or mechanised control of the welding torch. Usually, materials to be joined are placed in special fixtures whereas the torch moves forward at an appropriate welding rate. The welding process is usually performed without the use of the filler metal and the weld itself is composed of

materials being joined. In some cases, the filler metal can be fed (in a manual or mechanised/automated manner) in the form of a wire.

The microplasma welding technique has found its special application in the two-sided welding of metal capsules composed of many single membranes (Fig. 6). The method enables the obtainment of membrane capsules of any shape, dimensions and characterised by significant elasticity and wide application potential.

Exemplary photographs of surfaces of microplasma welded joints made of thin sheets are presented in Figure 7.

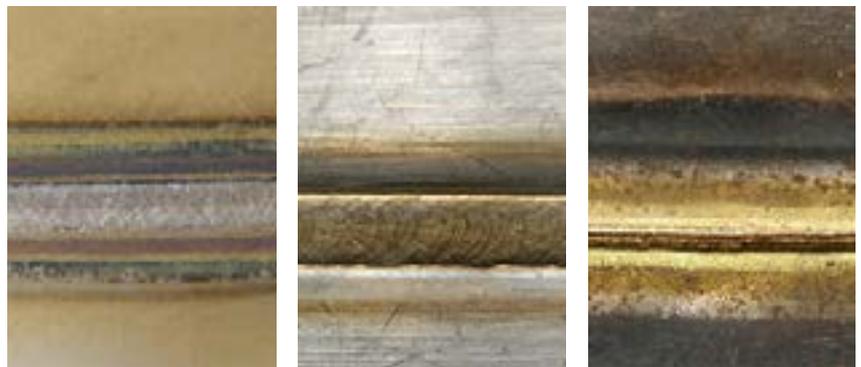


Fig. 7. Frontal photographs of welded joints: a) steel X6Cr17;  $g = 0.4$  mm,  $I = 5$  A,  $v_{weld} = 5$  cm/min, b) steel X6CrNiTi18-10;  $g = 0.8$  mm,  $I = 7.7$  A,  $v_{weld} = 20$  cm/min and c) brass M80;  $g = 0.5$  mm,  $I = 8.5$  A,  $v_{weld} = 20$  cm/min

Microplasma welding can also be successfully used when joining dissimilar materials (Fig. 8). The primary condition, the fulfilment of which leads to the obtainment of a proper weld, is the proper preparation of the edges of elements to be joined. The preparation involves the accurate matching of specimens in the welding area so that the gap between the edges and the displacement of the edges in relation to the plane should not exceed 10% of the thickness of workpieces. As a result, it is not necessary to apply a filler metal.

Microplasma welding is commonly used in the electronic industry (semiconductor elements, capacitors) and food industry as well as in medical technique (heart prosthesis elements, surgical instruments, dentures) and precision engineering (thermocouples, pressure transducers, vacuum elements).



Fig. 6. Butt welded metal capsule welded along a corrugated tube made of austenitic steel having an external diameter of 60 mm and a sheet thickness of 0.12 mm,  $I = 2$  A [6]

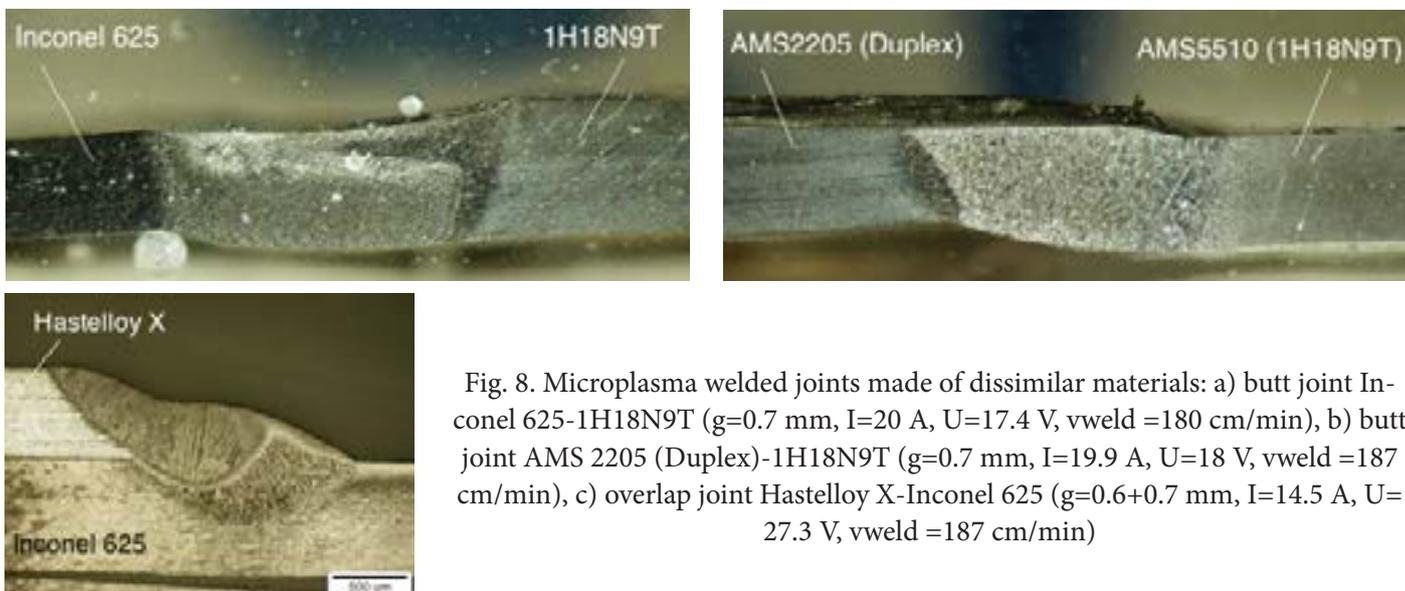


Fig. 8. Microplasma welded joints made of dissimilar materials: a) butt joint Inconel 625-1H18N9T ( $g=0.7$  mm,  $I=20$  A,  $U=17.4$  V,  $v_{weld}=180$  cm/min), b) butt joint AMS 2205 (Duplex)-1H18N9T ( $g=0.7$  mm,  $I=19.9$  A,  $U=18$  V,  $v_{weld}=187$  cm/min), c) overlap joint Hastelloy X-Inconel 625 ( $g=0.6+0.7$  mm,  $I=14.5$  A,  $U=27.3$  V,  $v_{weld}=187$  cm/min)

Microplasma is also used in the precise repair of machinery elements, often on a single basis, or in the welding of small-sized elements and elements where the workmanship accuracy is a very important aspect. Exemplary applications of microplasma welding include the making of measurement instruments, metal capsules, metal fabrics (e.g. net up to 8 metres long, composed of single wires having a diameter of 0.1 mm, containing approximately 30 meshes of 1 cm in length), welded capillary tubes used in measurement equipment, thermal capacitors, joints bonding membranes and thermocouples, miniature heat exchangers as well as the welding of tubes made of stainless steel and the joining of filter sieves [6-9]. An important aspect of the above-named welding method is the fact that, in some cases, it can replace expensive methods, e.g. electron beam welding or laser welding, and reduce the cost related to the making of joints without compromising their quality.

### Microplasma surfacing

Plasma (microplasma) surfacing is a process combining the simultaneous melting of the base material with that of the filler metal (in the form of wire, bar or flux) to make a surface layer (overlay weld) characterised by specific functional properties. When

surfacing, the degree of the stirring of materials being melted should be as low as possible so that the surface layer could maintain the properties of a deposited material. Plasma surfacing can be used to repair or process worn-out surfaces enabling the obtainment of new more favourable functional properties. In microplasma surfacing the area affected by plasma arc is restricted to products characterised by significantly smaller dimensions and scale than in cases of other surfacing techniques.

Figure 9 presents exemplary overlay welds made on austenitic steel X6CrNiTi18-10 using the microplasma surfacing method and filler metal OK Autrod 16.95 (307Si) in the form of a wire having a diameter of 1.2 mm (Fig. 9a) and filler metal Castolin DO\*04 having the form of flux-cored wire characterised by high hardness and corrosion resistance. In both cases, the same plasma gas (100%Ar) and shielding gas (Ar+3% $H_2$ ) were used.

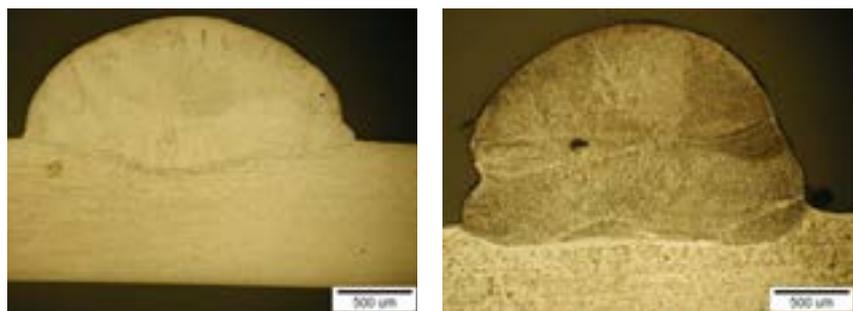


Fig.9. Structure of the overlay weld on steel X6CrNiTi18-10 made using: a) filler metal W18\_8Mn (OK Autrod 16.95 (307Si),  $I=15$  A,  $U=18.4$  V), b) filler metal Castolin DO\*04 ( $I=16.5$  A,  $U=17.8$  V)



Fig. 10. Multi-run overlay weld made on the edge of the guide bar using the microplasma-based method



Fig. 11. Repair surfacing of the crankshaft main bearing journal performed using the microplasma-based method



The overlay weld made on steel X6CrNi-Ti18-10 (Fig. 9a) using the chromium-nickel-manganese wire (providing corrosion resistance) was characterised by a very symmetric shape and an overlay weld stirring degree of 14.8 %. The austenitic structure of the overlay weld was crystallised in the cellular form. The fusion line was characterised by high homogeneity. The width of the heat affected zone was narrow and amounted to approximately 100  $\mu\text{m}$ . The second multilayer overlay weld (Fig. 9b), made using the flux-cored wire characterised by high hardness and corrosion resistance, had a regular shape and the homogenous fusion line. It was possible to notice boundaries of deposited runs and significant precipitates in the overlay weld material. The depth of the remelted area was relatively shallow and smooth across the entire width of the fusion area. The heat affected zone was very limited. In terms of the overlay weld, the stirring degree amounted to 13.1 %.

Microplasma surfacing can successfully be used to repair surfaces of small-sized machinery parts. Exemplary applications of repair microplasma surfacing on work surfaces of structural elements are presented in Figure 10 and 11.

### Microplasma remelting

Microplasma remelting is a welding process used to join metals and/or their alloys, where a stable bonding (joint) is obtained through the melting of a layer to be deposited (to the liquid

state) and the simultaneous partial melting of the base material using the heat of plasma arc, the current intensity of which is restricted within the range of 0.01 A to 50 A. In many cases, the process of remelting makes up part two-stage material surface processing. The aforesaid process includes the thermal spraying of a metal or composite coating on a previously selected substrate followed by the remelting involving the use of plasma arc. The process of remelting results in the obtainment of a surface layer free from porosity as well as in the enhanced adhesion of the coating to the substrate. Figure 12 presents the remelting of a previously sprayed coating performed using an FP1-15 microplasma torch and a single remelted run.



Fig. 12. Microplasma remelting of a sprayed coating: a) Al coating during remelting, b) single run after remelting

The exemplary remelting of a composite coating based on stellite PMNiCr50P with a titanium carbide content of 70% is presented in Figure 13. The primary issue concerned with the above-presented technology was the obtaining of the appropriate composite remelting temperature cycle ensuring the appropriate metallurgical bonding of stellite with the substrate, i.e. without the significant stirring of the composite material with the substrate, characteristic of other plasma methods. Because of varying melting points of the substrate and of the composite, in the case under consideration the process of microplasma remelting could be compared to the wetting of the substrate with the brazing material. In relation to the scanned layers, the optimum remelting parameters were the following: torch oscillation frequency  $f = 30 \div 32$  osc./min, torch travel rate  $v = 33.4$  mm/min., distance between the torch and the workpiece  $l = 3 \div 4$  mm and primary arc current  $I = 21 \div 25$  A. The presence of carbides in the titanium layer were confirmed by the layer cross-sectional microhardness tests and surface phase analysis.

the above-presented approach is the fact that the formation of the layer containing the intermetallic alloy requires individual ingredients contained in the coating being remelted (Al) and the substrate (Fe), which significantly reduces the cost related to the making of the coating in comparison with the cost of ready-made commercially available powders of intermetallic alloys. The schematic remelting of the Al coating sprayed on steel (in relation to the above-presented method) is shown in Figure 14.

The microplasma remelting parameters were the following: pulsed arc  $I = 25$  A,  $U = 11.7$  V, shielding gas - Ar (12 l/min), plasma gas - Ar (0.6 l/min), distance between the nozzle and the remelted layer: 3 mm and remelting rate

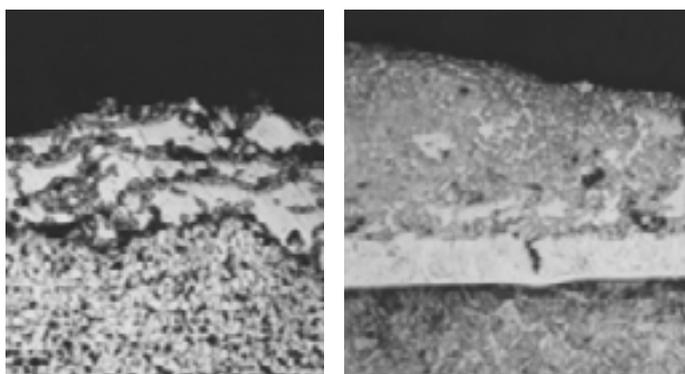


Fig. 13. Microstructure of the composite layer TiC (70% by volume)+PMNiCr50P: a) plasma-sprayed on the substrate of steel 18G2A b) after remelting performed using the microplasma torch (mag. 200x) [10]

Another possible application of microplasma remelting is a process where surface layers are formed out of intermetallic phases (e.g. Fe-Al, Ti-Al or Ni-Al) through the spontaneous synthesis (in-situ) of the coating material ingredients and the substrate material ingredients (during remelting). A significant advantage of

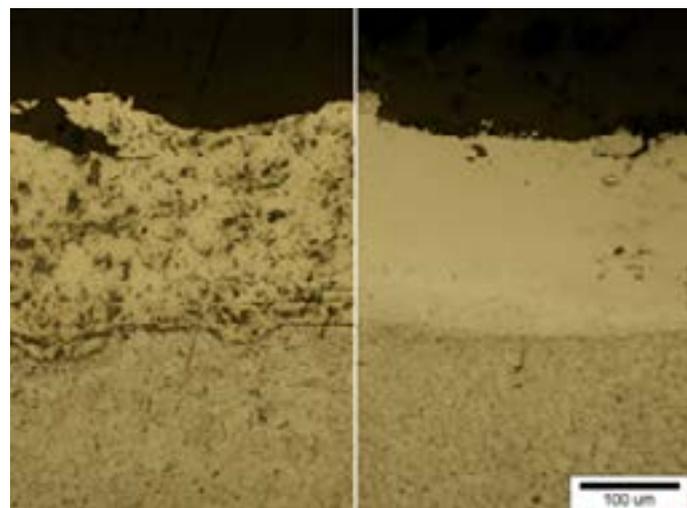
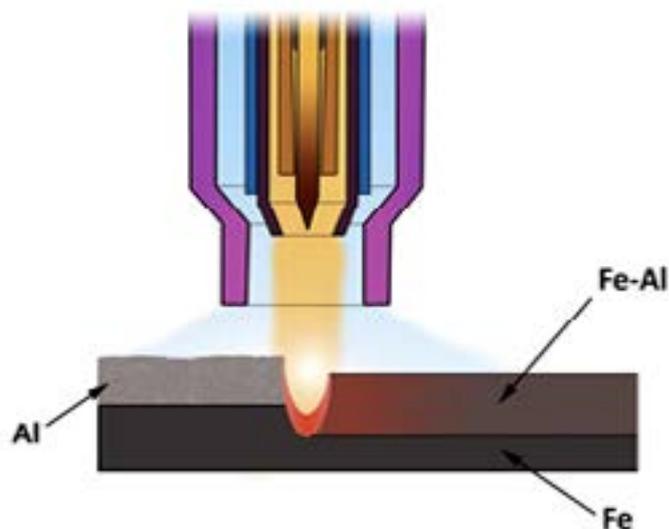


Fig. 14. Making layers out of Fe-Al intermetallic phase-based alloys: a) schematic microplasma remelting of the Al coating sprayed on steel, b) microstructure of the Al layer on steel S235JR after arc spraying, c) microstructure of the layer after microplasma remelting, x200 [11]

$v=15$  mm/min. The presence of the Fe-Al intermetallic phase in the remelted coating was confirmed by X-ray phase analysis and measurements of coating microhardness, the value of which was restricted within the range of 600 HV<sub>0.1</sub> to 700 HV<sub>0.1</sub>. In addition to the relatively low cost spent on the obtainment of the alloy based on the ordered FeAl intermetallic phase, the above-presented manufacturing method makes it possible to obtain the high adhesion of the coating to the substrate, i.e. higher by an order of magnitude than thermally sprayed coatings (characteristic of surfacing methods). In addition, when remelting, the applied heat source (having the form of a concentrated microplasma beam) makes it possible to perform the remelting process selectively over isolated areas of machinery parts.

## Summary

The above-presented examples of applications of microplasma arc in the welding, surfacing and remelting of various materials, coatings and layers proved the significant application potential of the aforesaid heat source. Microplasma enables the making of welded joints in thin sheets of similar and dissimilar materials as well as makes it possible to precisely and selectively process surfaces of small-sized machinery parts. The above-presented examples of microplasma surfacing and remelting indicate the considerable extendibility of the application range of microplasma arc in surface processing tasks. The foregoing refers to the making of metallic or composite layers as well as surface layers using increasingly popular intermetallic phase-based alloys made in-situ (out of cheap ingredient) during the process of microplasma remelting. Microplasma-based methods can be regarded as favourable alternatives to other methods of welding and surface processing involving the use of the laser or electron beam.

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