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Induction and Electric Arc-Based Remelting of Thermally Sprayed Layers – Overview

Abstract: In many cases, the technology enabling the melting of thermally sprayed layers has no alternative. High-performance thermal spraying processes make it possible to obtain densely sprayed layers. However, previous research revealed that sprayed layers are characterised by porosity and numerous material imperfections. The above-named situation results from the specific manner of layer application. The article overviews induction and arc-based technologies enabling the melting of sprayed layers as well as discusses possible post-spray imperfections.

Keywords: thermal spraying, induction remelting, TIG remelting, plasma arc remelting

DOI: *10.17729/ebis.2021.1/1*

Introduction

Thermal spraying is one of the surface engineering techniques. In the aforesaid process, the remelted or plasticised and softened material is applied (by spraying) onto the surface of the previously prepared substrate. The surface of the substrate is not subjected to partial remelting. The properties of sprayed layers can be improved through additional mechanical or thermal treatment [1].

Among all available processes enabling the application of layers and coatings, including chemical vapour deposition (CVD), physical vapour deposition, surfacing, chemical processes or ion implantation, the thermal spraying technology provides the widest range of applicable sprayed materials and the widest range of obtainable layer thicknesses [2].

The source of heat indispensable for the remelting of metal to be sprayed (having the form of a wire, powder or strip) can be the gas flame or electric or plasma arc. Various processes

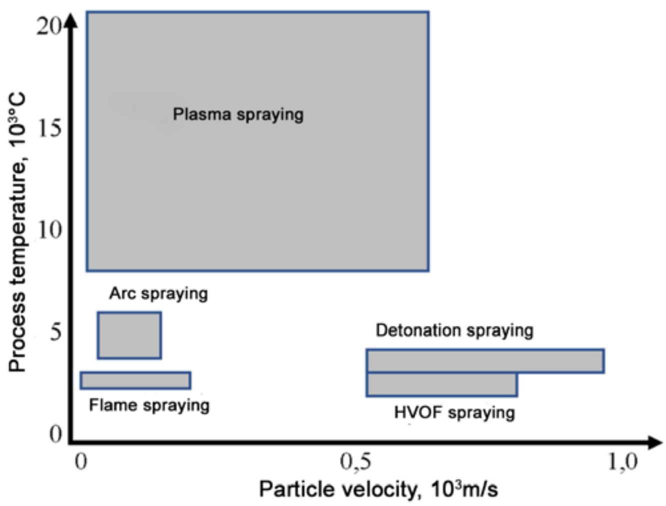

Fig. 1. Comparison of temperature in various spraying processes along with velocity of sprayed materials [3]

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enable the obtainment of various temperatures and velocity of particles striking the substrate subjected to spraying (Fig. 1).

The process of spraying is composed of the following stages:

1. mechanical feeding of the filler metal (in the solid or liquid state) to the remelting area in the spraying device;
2. continuous remelting and spraying of the material. The remelting is accompanied by the spraying of metal particles by means of compressed gas (e.g. air) and, sometimes, combustion gases (in cases of gas equipment). The time of remelting and spraying is very short, amounting to 10^{-3} s;
3. transport of remelted spherical particles ejected from the torch nozzle towards the surface to be coated. During the transport, the particles become oxidised (by oxygen contained in air), which results in the formation of oxide shells on the surface of the particles;
4. formation of the layer, lasting from the moment when the particles come into contact with the surface subjected to spraying to the cooling of the layer to ambient do temperature.

When striking the surface subjected to spraying, the spherical particles become flattened and their area expands. As a result, the brittle film of oxides undergoes cracking and uncovers the surface of pure metal. Fragments in the liquid state sprinkle on the surface subjected to spraying and, after solidification, deform, "jam" in and adjust to the surface irregularities, and next, are combined with other particles striking the surface. When non-oxidised metal fragments come into contact, cohesive-type bonds are formed as a result. The newly-formed layer is bonded to the substrate (and also in terms of its own particles) mechanically, i.e. by means of cohesion and adhesion forces and, in some cases, by means of metallic diffusive bonds, without the partial remelting of the substrate metal. The fraction of individual types of bonds varies depending on the spraying method and conditions, providing layers with various properties, including the strength of the bond with the substrate subjected to spraying.

The use of thermal spraying techniques makes it possible to obtain the properties of layers, which are difficult to achieve using other methods [4–10]:

- protection against corrosion – Zn or Al sprayed on cast irons or steels increase corrosion resistance and, as a result, extend the service life of bridges, buildings and other elements of infrastructure. To increase their heat resistance or corrosion resistance, internal surfaces of boilers can be covered with high-chromium alloys;
- surface hardening – used when it is necessary to obtain smaller thickness than that obtainable through surfacing. Typical applications include the spraying of car engine cylinders, piston rings, elements of textile machinery or elements of pumps and bearings;
- repair of surface defects – surfaces damages as a result of operation or technological faults can be reworked (e.g. elements of aero-engines);
- electric conductance – it is possible to provide surfaces of poor conductors or materials not conducting electric current with electric conductance. Cu, Al or Ag is sprayed onto glass or polymer substrates. In turn, surfaces of electric conductors are provided with insulation layers made of Al_2O_3;
- surface porosity – porous Co or Ti layers and ceramic materials are sprayed onto medical implants to provide the latter with adhesion and enable the growth of bones or tissues;
- coating with precious metals – used when, because of technological or economic factors, conventional cladding is not possible;
- ornamental effects – decorative materials are sprayed onto various products and architectural elements;
- reflection of light – mirrors are obtained by spraying Al onto glass surfaces,

- abrasive wear resistant layers,
- layers constituting heat barriers.

Imperfections in thermally sprayed layers

Thermal spraying technologies enable the obtainment of surface layers characterised by the predefined chemical composition and thickness, yet containing numerous imperfections resulting from the deposition of powder (or remelted wire) on a previously prepared surface. As the substrate is struck by variously sized particles characterised by various energy states, the sudden solidification of layers results in the formation of various microstructures characterised by significant heterogeneity. The microstructures may contain frozen, columnar and equiaxial crystals, metastable and amorphous phases as well as be characterised by the significant concentration of point-like imperfections (defects) [11]. The authors of publications [12, 13] associate the formation of columnar cracks in layers with the thickness of the layer applied in one run. In terms of layers characterised by small thickness (15 m), each layer is cooled to the temperature of the substrate before being struck by the next layer and the entire layer also cools before it is covered with another one. As a result, the columnar structure is formed in the layer. The aforesaid columnar structure may, exceptionally, pass through two or three layers, yet never across the entire layer thickness.

In turn, as regards layers, the thickness of which is restricted within the range of 160 μm to 200 μm, the first layer cools to the temperature of the substrate, whereas columnar structures are only present within one layer. After the application of three layers, temperature increases (depending on the temperature up to which the substrate has been heated and on the temperature of the gas stream). In such a situation, the columnar structure is formed in each layer, passing through the entire layer thickness apart from that of the first layer (Fig. 2). The structure of each thermally sprayed layer has pores (resulting from the course of the process). Table 1 presents the comparison of the quality of layers with reference to thermal spraying processes.

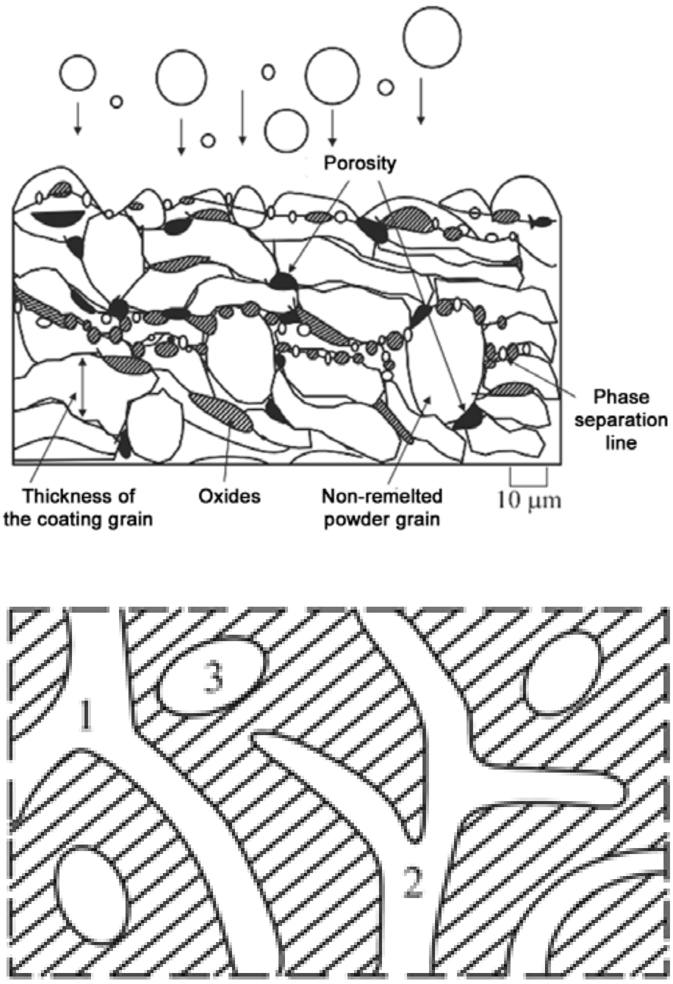

Fig. 2. Structure of thermally sprayed layers (a) and types of porosity (b): 1 – open pass-through pores, 2 – open non-pass-through pores and 3 – closed pores, in accordance with [14, 15]

The adhesion of the layers results from the phenomena of adhesion and cohesion as well as from the presence of imperfections. In addition, sprayed layers are characterised by the anisotropy of mechanical and functional properties resulting from the porosity and heterogeneous partial remelting of particles during their transfer from the torch onto the surface [16, 17, and 18].

Some of these imperfections can be eliminated by appropriately adjusting process parameters. However, previous tests revealed that, in most cases, the elimination of porosity, combined with a simultaneous increase in hardness,

Table 1. Comparison of thermal spraying processes in respect of layer quality [16]

Method	Quality
Plasma spraying	Porosity 3–8% Adhesion >50MPa Output of approximately 50%
Arc spraying	Porosity >10% Adhesion ≈40MPa Output of approximately 80%
Flame spraying	Porosity >10% Adhesion <30MPa Output of approximately 50% Oxygen content 6–12%
HVOF and HVAF flame spraying	Low porosity Adhesion 60–80 MPa Output of approximately 70% Oxygen content 0.5%
Detonation flame spraying	Low porosity < 1% High adhesion Output of approximately 90% Oxygen content: 0.1–0.5%

can only be achieved using the laser beam [18, 19], electron beam [20, 21], electric arc [22] or induction heating-based [23] remelting of the layer.

Induction remelting

Induction heating consists in the generation of heat during the flow of eddy currents generated by the phenomenon of electromagnetic induction. Metals placed in the alternate electromagnetic field are areas where electromotive forces (EMF) are induced, subsequently generating eddy currents. The values of the above-named forces depend on the rate of changes in the magnetic flux. A source necessary in the induction heating of the electromagnetic field is a set of electric current conductors (so-called inductors), usually in the form of a single or multi-turn cylindrical coil. Figure 3 presents the method and the block diagram of an induction heating device [24–26].

The inductor and the element being heated constitute a heating system (inductor-charge). The inductor is powered by an adjusting system (transformer) from the generator (frequency converter). The presence of the transformer enables the obtainment of the optimum adjustment of the power supply source to the load, decreases losses in transmission lines and increases personnel safety. In cases of ferromagnetic materials, a certain part of emitted heat is the result of hysteresis losses [24–26].

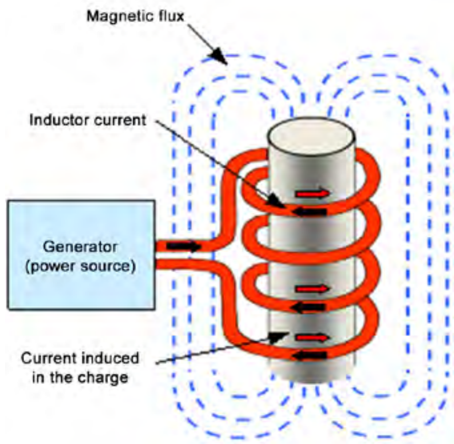

Fig. 3. Induction heating device – principle of operation [26]

Induction heating is widely used in many industrial sectors. In welding engineering, the method is used, among other things, in brazing and soldering. Induction heating is also widely applied in both the pre and post-weld heat treatment of welded joints (e.g. tempering and stress relief annealing). In addition, induction heating is also used to melt thermally

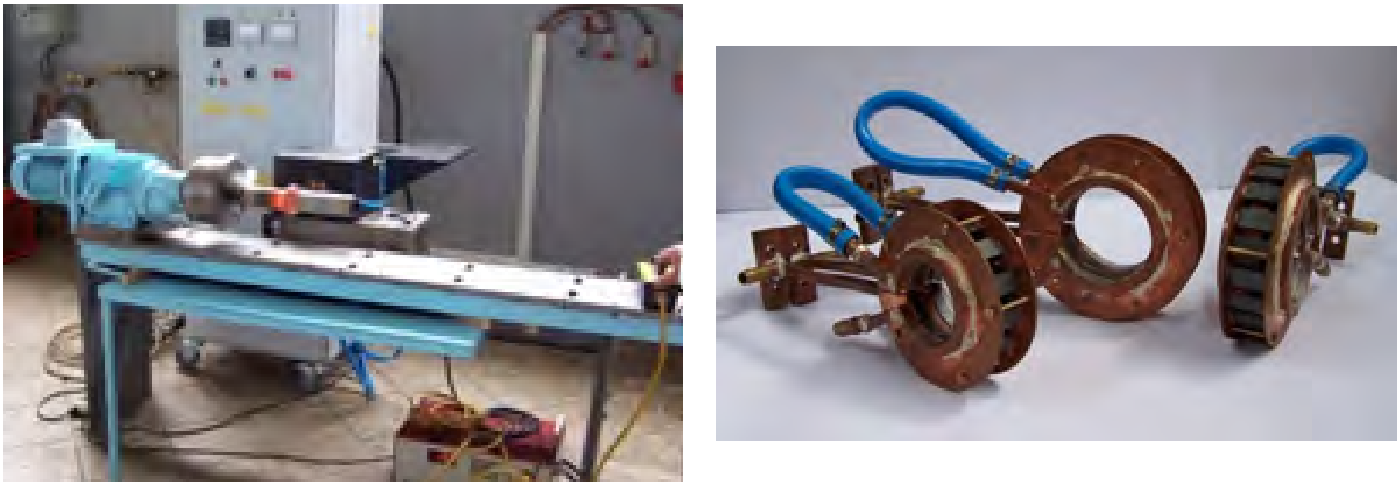

Fig. 4. a) Testing station for the experimental induction remelting of sprayed layers, b) inductors with concentrators and water cooling elements [27]

sprayed layers [23, 27]. The method makes it possible to increase the adhesion between the (sprayed) layer and the substrate material. A targeted project [27] implemented at Łukasiewicz – Instytut Spawalnictwa in Gliwice included the development of a testing station enabling the performance of tests involving the induction remelting of layers thermally (plasma) sprayed on tubes made of boiler steels; the tubes were 500 mm in length, their diameters were restricted within the range of 30 mm to 60 mm, whereas their wall thicknesses were restricted within the range of 3 mm to 6 mm (Fig. 4). The project-related research work involved the inductor-triggered remelting of layers made on tubes having the external diameter of 35 mm and that of 58 mm (Fig. 4).

Metallographic tests confirmed the usability of induction heating for the improvement of the quality (reduction of porosity) of thermally sprayed layers (Fig. 5).

Hardness measurements concerning the layers and the interface revealed that the hardness of the sprayed layer after remelting amounted to 1009 HV0.3. The tests revealed that the induction remelting of layers sprayed thermally on tubular elements could be an alternative to other remelting methods, e.g. involving the use of a gas flame.

It was also noticed that the obtainment of the proper remelting of the sprayed layer required the precise adjustment of technological process parameters within a relatively narrow range (particularly as regards the linear velocity of the inductor). The metallographic tests

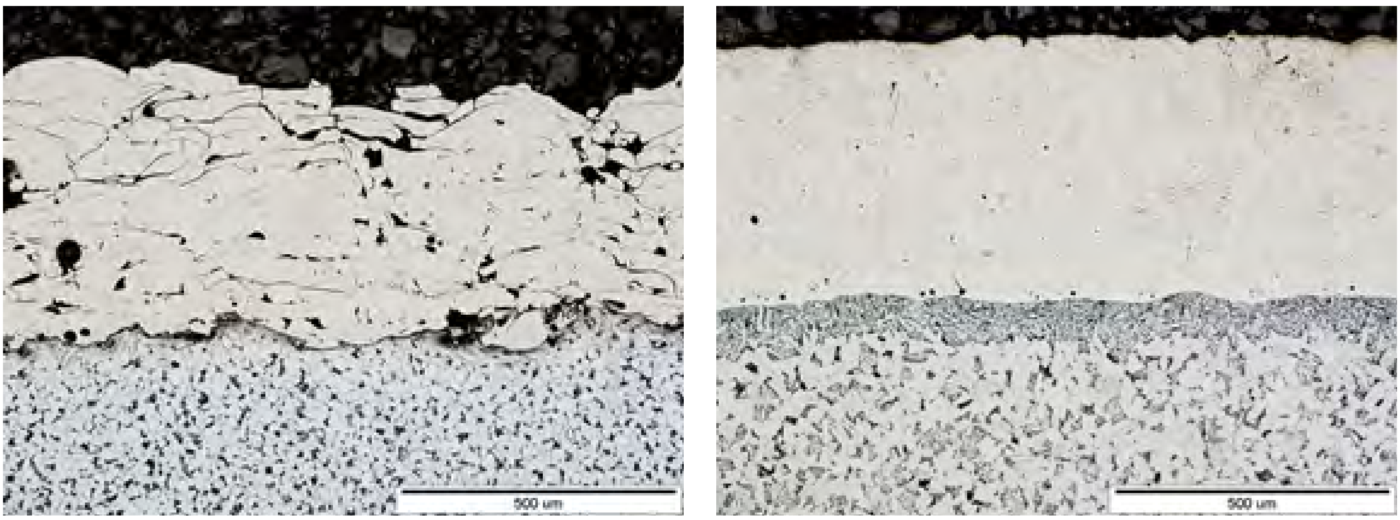

Fig. 5. Microstructure of the layer sprayed on the tube having a diameter of 35 mm: a) after thermal spraying and b) after induction heating [27]

of the layers after induction remelting revealed that the applied parameters of induction remelting resulted in the complete remelting of thermally sprayed layers. The characteristic lamellar microstructure of the layers obtained after thermal spraying was removed and the induction remelting process resulted in the obtainment of the continuous and homogenous microstructure over the entire surface of the test tubes. The microstructural tests also revealed that the width of the interface between the layer and the tube surface varied in relation to individual pipes and did not exceed 60 μm. The foregoing was also confirmed by hardness measurements performed in the layer-tube surface interface [27]. It should also be emphasized that the induction remelting method is safer, less bothersome for the surroundings and easier in automation in comparison with, e.g. gas flame remelting, as well as proves considerably cheaper than technologies based on concentrated sources of energy (e.g. laser or electron beam). The research work-related tests also revealed that the remelting process should be performed using simple multi-turn inductors providing the gradual increase in the temperature of the tube during heating [27].

The induction remelting of layers thermally sprayed on tubes was also the subject of another publication [23], presenting test results concerning induction-remelted NiCrBSi composite layers enriched with titanium nitride (TiN). The use of TiN aimed to increase hardness, high-temperature resistance as well as resistance to corrosion. The layer was obtained by stirring the NiCrBSi alloy with the Ti powder in a proportion of 7 to 3.

In the tests, the authors used a tube made of steel grade 42CrMo (Ø30 mm ×100 mm). The tube surface was subjected to degreasing and sandblasting. The layer was thermally sprayed using plasma. During remelting, the surface was provided with a special coating, the purpose of which was to prevent the oxidation of the surface at a temperature of 1200°C. The specimens were subjected to detailed metallographic tests involving the use of a scanning electron microscope (SEM) and a transmission electron microscope (TEM). The research work also involved the performance of the EDS microanalysis and the identification of individual phases using a diffractometer. The hardness of the remelted layers was measured under a load of 200 g. The research work also included abrasive wear resistance tests and erosive wear tests of the layers both before and after induction remelting. Figure 6 presents the results of the SEM-based metallographic tests [23].

The analysis revealed that the layer not subjected to remelting was characterised by the typical lamellar microstructure (Fig. 6a). The analysis also revealed the presence of

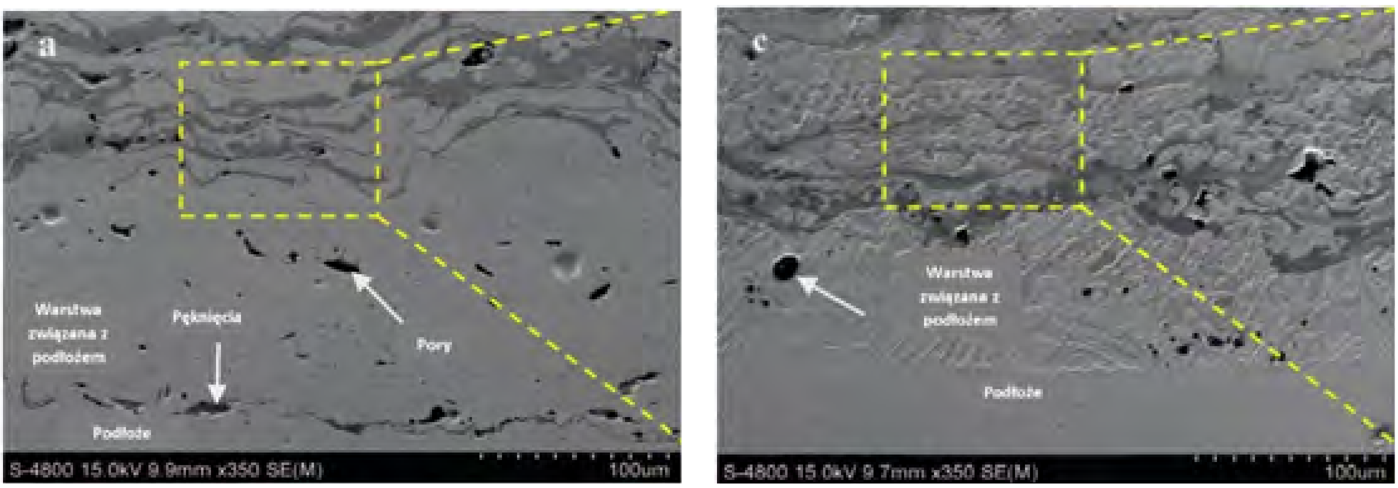

Fig. 5. Microstructure of the layer sprayed on the tube having a diameter of 35 mm:
a) after thermal spraying and b) after induction heating [27]

microcracks and pores in the thermally sprayed layer. The cracks were formed both in the area directly adjacent to the substrate and in the surface layer. The induction-remelted layer (Fig. 6b) was characterised by the significantly lower porosity and the significantly lower number of microcracks [23].

The EDS analysis revealed the presence of phases rich in nickel, chromium and titanium. Hardness measurements revealed that the induction-remelted layer was characterised by higher hardness. The hardness of the plasma sprayed layer was restricted within the range of 867 HV0.2 to 1071 HV0.2, whereas the hardness of the induction-remelted layer was restricted within the range of 867 HV0.2 to 1150 HV0.2 [23].

The tests of abrasive wear resistance revealed that the induction-remelted layer was characterised by higher resistance than the layer not subjected to induction remelting. In terms of the layer not subjected to induction remelting, the decrement of mass was approximately ten times higher than that of the layer subjected to induction heating.

Publication [28] also presents test results concerning the induction remelting of a plasma powder (NiCrBSiNb) sprayed layer deposited on the substrate having the form of a tube segment (20 mm in length; external diameter amounting to 60 mm, internal diameter amounting to 30 mm) made of steel grade AISI 1045. The remelting reduced the presence of porosity, microcracks and the lamellar structure in the microstructure. In addition, the remelting of the sprayed layer along with the substrate enabled the obtainment of metallurgical bonding with the substrate. The hardness of the sprayed layer after remelting increased from 850 HV0.1 to 1170 HV0.1 and so did its abrasive wear resistance. In relation to the sprayed layer, the decrement of mass amounted to 0.1349 mm3. In terms of the remelted layer, the decrement of mass amounted to 0.0573 mm3. The surface wear was reduced by 58%. The fatigue strength of the thermally sprayed layer subjected to remelting also increased [29].

The induction remelting of plasma sprayed layers can also be performed using additional water cooling. In the aforesaid method it is possible to control the directional crystallisation of the layer subjected to remelting. Publication [30] presents test results concerning the remelting of a layer applied on the substrate of steel C45 using the plasma powder (NiCrBSiFeC (60%)+CuAlMnFeCoNi (40%)) spraying method. The use of induction remelting made it possible to reduce the formation of imperfections in the thermally sprayed layer and increased its abrasive wear resistance (Fig. 7).

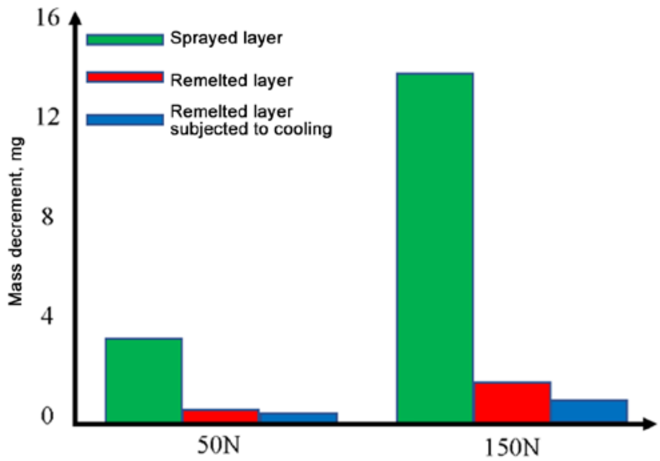

Fig. 7. Effect of the modification of the sprayed layer on its abrasive wear resistance [30]

Work [31] presents tests results concerning layers applied on the substrate of steel AISI 1045 using flame powder (NiCrBSi) spraying and subjected to induction and flame remelting. The abrasive wear resistance tests concerning the layers revealed that the decrement of mass in relation to the thermally sprayed layer amounted to 16.12 mm^3/m, the decrement of mass in relation to layer subjected to flame remelting amounted to 10.15 mm^3/m, whereas that of the layer subjected to induction remelting amounted to 7.39 mm^3/m (Fig. 8a). In addition, the microhardness of the thermally sprayed layer after induction remelting was higher than that of the layer subjected to flame remelting (Fig. 8b). The XRD phase analysis

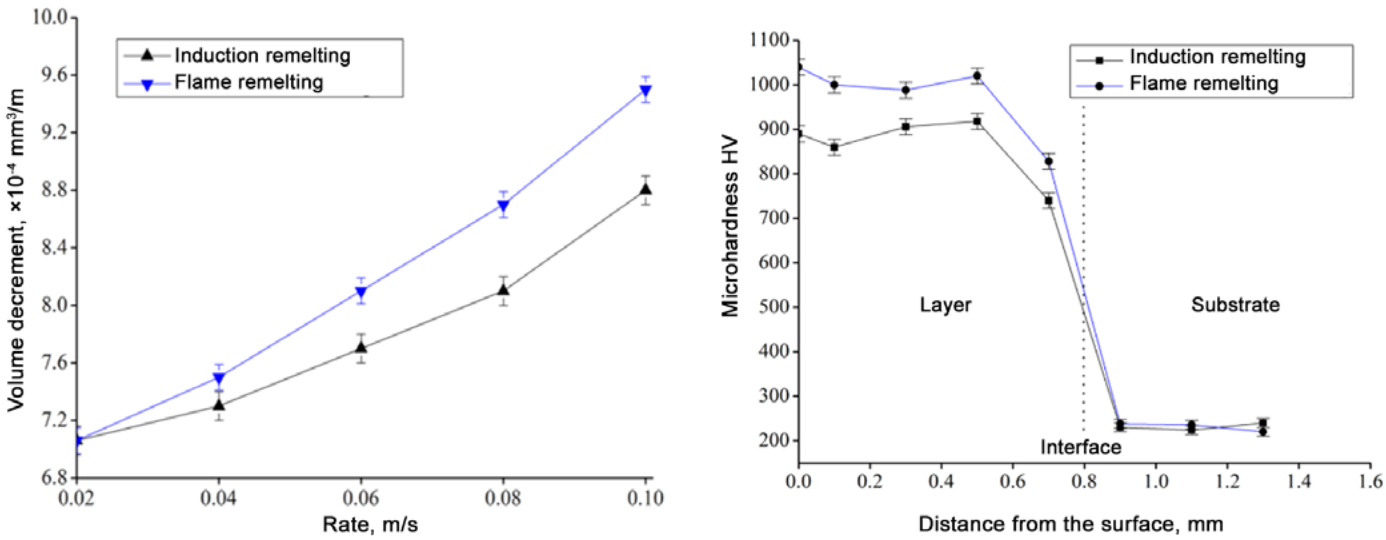

Fig. 8. Effect of the remelting process on a) microhardness and b) abrasive wear resistance [31]

enabled the identification of phases. The phases primarily contained in the structure were CrB and Cr_7C_3 in the α-Ni matrix. The eutectic phase was mainly composed of the α-Ni matrix and Ni_3Si.

The analysis of the above-presented test results justified the conclusion that the induction remelting process significantly improves the properties of thermally sprayed layers.

Plasma arc remelting

One of the solutions enabling the improvement of the quality of thermally sprayed layers is plasma arc remelting. The authors of publication [32] performed tests of oxide (Cr_2O_3, Al_2O_3 and ZrO_2) and carbide (Cr_3C_2) layers subjected to electric plasma arc remelting. As regards the Cr_2O_3 and ZrO_2 layers, the X-ray analysis did not reveal any significant changes in the phase composition. However, in terms of the Cr_3C_2 layers, the X-ray analysis revealed the presence of Cr_7C_3 in the layer both before and after remelting. This fact could indicate the low stability of the Cr_3C_2 carbide at high temperature, accompanying both the spraying and the remelting process [32]. In addition, in most cases, the microstructural tests revealed the presence of two different zones in the layer. The first zone, closer to the surface, was characterised by low porosity, whereas the second zone contained the primary structure and the morphology of the thermally sprayed layer. The monolithic surface layer was an effective barrier to corrosive factors, whereas the internal layer, characterised by porosity, constituted a thermal barrier. The tests revealed that the appropriate adjustment of plasma processing parameters enabled the flexible adjustment of quantitative correlation between the two layers [32]. Both the one-time and multiple remelting resulted in the significant reduction of both open and closed porosity as well as in the increased smoothness of the surface. Therefore, it can be stated that the disadvantages of the plasma spraying process were noticeably eliminated. The authors also stated that plasma spraying led to the homogenisation of the chemical composition and the reduction of the density of lattice imperfections. It was also observed that plasma arc remelting enabled, to a significant extent, the modelling of the "nature" and the properties of ceramic layers as well as provided the substrate with the features of a composite material. The authors demonstrated that the use of the plasma remelting technique could constitute an actual alternative to other remelting methods [32].

The authors of publication [33] performed tests involving the electric plasma arc remelting of the NiCr-Cr_3C_2 layer sprayed thermally onto the substrate of steel C 45. Before spraying, the element was degreased and subjected to shot blasting. The first stage involved the deposition of an intermediate layer having a thickness of 100 μm, whereas the subsequent stage involved the deposition of a ceramic layer having a thickness of 350 μm. The layer made in the aforesaid manner was subjected to remelting. The XRD analysis did not reveal the presence of any metal oxides, yet it revealed the presence of such phases ad Cr_3C_2, Cr_7C_3, $Cr_{23}C_6$ and γ-[Cr,Ni]. Based on the results it was possible to state that the remelting did not affect the presence of individual phases in the layer [33]. The subsequent stage of the research involved the application of scanning electron microscopy (SEM). Figure 9 presents exemplary layer-related results directly after deposition and plasma arc remelting. The analysis of the results revealed the presence of numerous imperfections (cavities, discontinuities and numerous non-remelted particles) in the non-remelted layer.

It was noticed that remelting significantly reduced the porosity of the thermally sprayed layers. The surface porosity after spraying amounted, on average, to 12.3%, whereas that after remelting amounted to 7.1%.

Microhardness measurements revealed that the hardness of the remelted layers exceeded 1300 HV0.2. In addition, after 180 hours of related tests, it was revealed that abrasive wear resistance increased four times [33].

Thermally sprayed layers can also be remelted using the microplasma technology, characterised primarily by significantly lower current. The authors of publication [34, 35] presented the application of a two-stage technological process. The first stage involved the arc spraying of a 0.2 mm thick aluminium layer onto the substrate of steel grade S355JR. The arc spraying process involved the use of an aluminium wire having a diameter of 1.6 mm. During spraying, the temperature of the substrate did not exceed 100°C. The subsequent stage involved the remelting of the sprayed aluminium layer along with the substrate (across the entire depth of approximately 0.4 mm) [34]. The application of the microplasma beam simplified the process of remelting and reduced its cost in comparison with that of laser beam remelting. The method enabling the making of Fe-Al intermetallic phase-based alloy proved primarily cheaper and more flexible. The layer composed of the intermetallic Fe-Al phase was made in-situ [34]. The area of the newly-formed alloy (Fe, Al) contained the microstructure characteristic of intermetallic phases, containing grains having a size of 20 μm and dispersive Fe_2O_3 precipitates having dimensions not exceeding 2 μm. The presence of the above-named uniformly dispersed particles in the volume of the remelted area could positively affect, among other things, the tribological properties of the layer. The lower layer was free from cracks and porosity, characteristic of the thermally sprayed layer. The

Fig. 9. Results of SEM-based metallographic tests: a) layer after spraying and b) laser subjected to plasma remelting [33]

most important advantage in relation to the thermally sprayed layer was the metallurgical bonding with the substrate, providing the adhesion of the layer higher by the order of magnitude than that characteristic of the thermally sprayed layer. The results of the X-ray analysis confirmed the presence of phase Fe-Al of the secondary solid solution as the primary structural constituent and, at the same time confirmed the presence of slight contents of other phases such as Fe_2O_3 (previously not present in the layer) and Fe_2Al_5. The hardness of the layer subjected to remelting was restricted within the range of 530 μHV0.1 to 810 μHV0.1, i.e. the level corresponding to the solid solution of FeAl. The results confirmed that also after remelting the layer was characterised by slight chemical, structural and phase heterogeneity [34].

In the summary the authors stated that the greatest advantages of the method included the low cost of materials used in the process and, during the remelting of the layer and substrate, the obtainment of a new alloy on the surface of the modified element. In addition to the relatively low cost enabling the obtainment of the alloy based on the ordered intermetallic FeAl phase, the above-presented method enabled the obtainment of high adhesion to the substrate, by the order of magnitude higher than that of thermally sprayed layers (and characteristic of surfacing methods). In addition, the heat source used in the remelting process and having the form of microplasma arc enabled the selective performance of the process over the separated area of machinery elements. The above-presented method enables the in-situ making of protective secondary FeAl solution-based layers, whose structure as well as mechanical and functional properties could pave the way for new applications on machinery elements exposed to high mechanical and thermal loads and elements exposed to intense abrasive wear [34, 35].

TIG arc remelting

One of the applicable remelting technologies is the TIG method [36–38]. Publication [36] presents results of tests involving the TIG method-based remelting of the thermally (arc) sprayed layer of FeNiCrAlBRe deposited on the substrate of steel grade AISI 1045. The surface of the substrate was degreased and subjected to sandblasting. Figure 10 presents results of SEM-based metallographic tests [36].

The SEM-based analysis revealed that the layer subjected to the TIG method-based remelting process was characterised by a significantly lower number of microcracks and lower porosity in comparison with that of the layer not subjected to remelting. The porosity of the non-remelted layer amounted to approximately

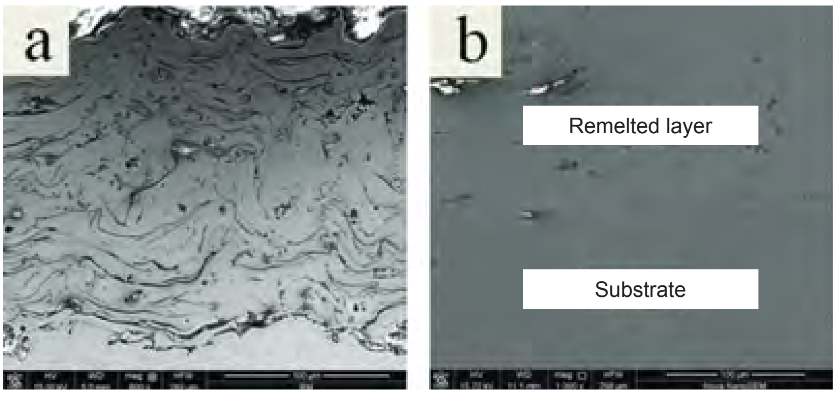

Fig. 10. Results of the SEM-based analysis: a) layer not subjected to remelting and b) layer subjected to TIG method-based electric arc remelting [36]

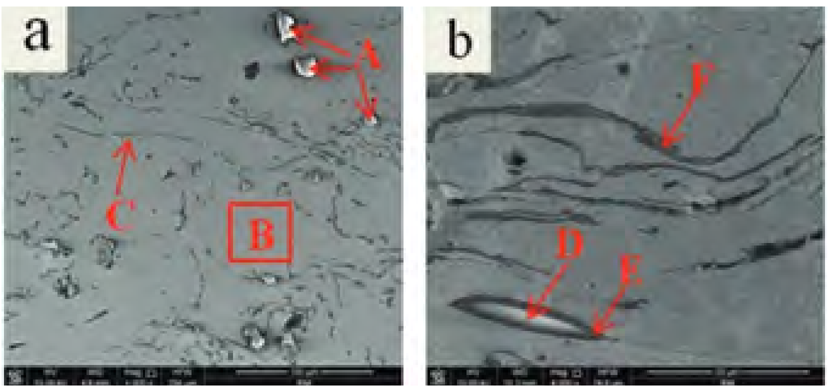

Fig. 11. Areas subjected to the EDS analysis: a) layer not subjected to remelting and b) layer subjected to TIG method-based electric arc remelting [36]

Table 4. Chemical analysis results [36]

Coating	Area	Chemical composition, %						
		Fe	Ni	Al	Cr	O	B	Nb
Without remelting	A	7,19	5,47	49,22	6,82	20,27	1,07	1,23
	B	60,65	11,7	8,78	10,07	2,41	1,47	1,39
	C	42,36	7,76	23,49	7,36	10,16	1,35	2,09
TIG remelting	D	5,49	6,57	57,36	6,87	20,43	0,24	0,64
	E	28,18	17,04	33,48	6,70	8,46	2,13	0,47
	F	29,58	33,70	19,19	6,54	4,58	1,76	2,33

27%. The TIG method-based remelting process enabled the reduction of porosity to 2% [36]. The results of the EDS analysis involving selected areas as shown in Figure 11 are presented in Table 2.

The remelting of layers thermally sprayed using the TIG method-generated electric arc was also the subject of tests discussed in publications [37, 38]. The authors examined the quality of plasma sprayed layers of the NiCrBSi powder. The layers were deposited on the substrate of steel AISI 1045. Before the deposition of the layer, the powder was heated and the surface was subjected to shot blasting. The tests involved the making of one layer having a nominal thickness of 800 μm.

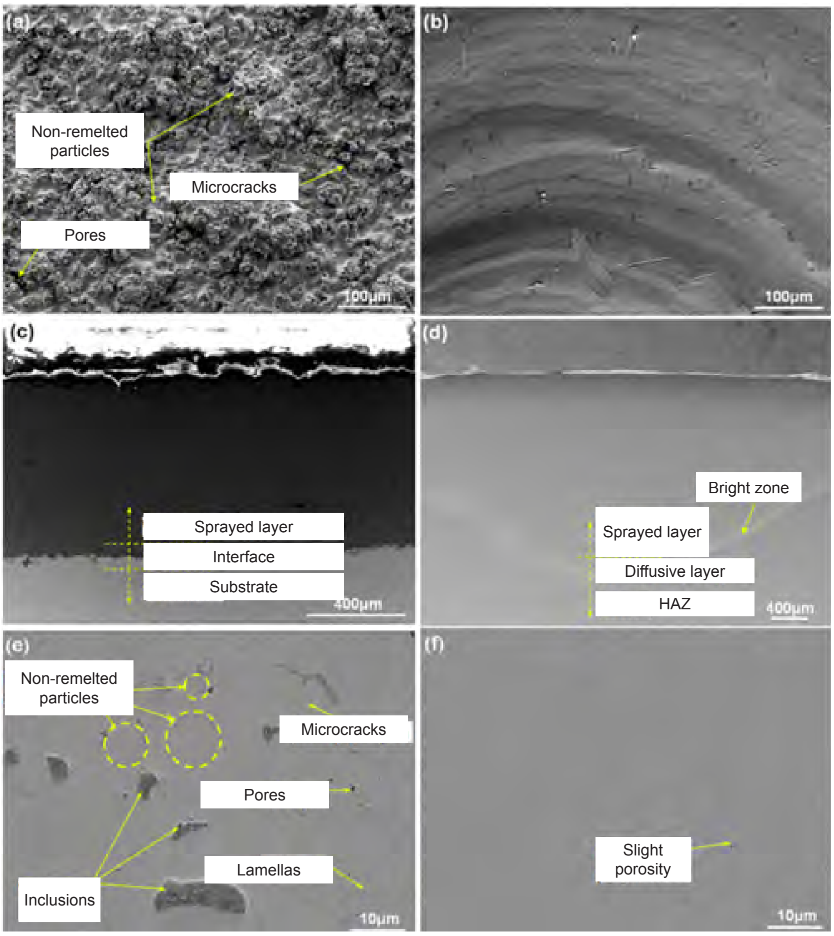

Fig. 12. SEM-based analysis of the layer, a) surface – non-remelted layer, b) surface – remelted layer, c) non-remelted layer – cross-section, d) remelted layer – cross-section, e) non-remelted layer and f) remelted layer [38]

Microstructural tests revealed that the thermally sprayed layer (Fig. 12) contained numerous imperfections including pores, non-remelted particles or microcracks. The surface of the remelted layer was more uniform and characterised by significantly fewer imperfections. Figures showing the cross-sections of the non-remelted layers (Fig. 12 c and e) present numerous imperfections such as non-remelted particles, inclusions, microcracks and pores. The above-named imperfections are typical of thermally sprayed layers. Figures 12 d and f present the cross-sections of the remelted layers. After remelting, the number of imperfections was lower and the microstructure was more homogenous. The tests also included porosity measurements involving both elements. The porosity of the non-remelted layer amounted to 5.6%. After remelting, the porosity was reduced to 0.2% [38]. The metallographic analysis of the non-remelted layer revealed the presence of amorphous and polycrystalline structures as well as single crystals. The grains present in the layer were characterised by irregular shapes and various sizes, which could significantly affect the strength of the layer. The fine-grained microstructure of the layer subjected to TIG remelting was primarily composed of dendrites [37, 38]. In addition, the remelting process resulted in the obtainment of the metallic bonding between the thermally sprayed layer and the substrate. Hardness measurements revealed that the remelted layer was characterised by significantly higher hardness (780 HV0.1) than that of the layer not subjected to remelting (580 HV0.1) [38]. The electric arc remelting process also increased abrasive wear resistance. In the thermally sprayed layer not subjected to remelting the decrement of mass amounted to 0.0152 g, whereas after remelting the mass decrement stood at 0.0055 g [37, 38].

The authors of publication [39] used TIG method-based remelting in the processing of thermally sprayed layers of the FeCrBSi powder deposited on the substrate of steel AISI1045. The tests revealed that the remelting process successfully eliminated most of the imperfections in the sprayed layer, reduced surface porosity by 43% and transformed the adhesion between the layer and the substrate from mechanical into metallurgical. The composition of the sprayed layer was primarily composed of α-Fe and a slight amount of the hard Fe_3B phase. In turn, after the remelting, the layer was composed of α-Fe and $(Fe, Cr)_{23}C_6$ as well as a slight amount of CrB. The tests also revealed that the remelting of the layer increased its crack resistance by 287.6% and mean microhardness by 33.4% and reduced the volume of wear by 47.5%.

Publication [40] presents results of tests concerning plasma sprayed layers of the NiCrBSiMnRe powder deposited on the substrate of steel grade AISI 1045. The tests revealed that the TIG remelting of the sprayed layer decreased its porosity from 7.2% to 0.4% and resulted in the obtainment of the metallurgical bonding between the layer and the substrate. The primary phase constituents of the sprayed layer were γ-Ni, Mn_5Si_2 and Cr_2B, whereas the phase composition of the remelted layer contained Fe_3Ni, $Cr_{23}C_6$, Cr_2B and Mn_5Si_2. The microhardness of the layer decreased from 724 HV0.1 to 608 HV0.1, whereas brittle crack resistance increased from 2.80 MPa $m^{1/2}$ to 197.3 MPa $m^{1/2}$ (after remelting). The remelting process also increased the abrasive wear resistance of the layer in a corrosive environment. After 10 hours of tests, the mass decrement of the sprayed layer amounted to 0.139 g, whereas that of the remelted layer amounted to 0.07 g.

Publication [41] presents results of tests concerning plasma sprayed layers of the FeNiCrBRe powder deposited on the substrate of steel AISI 1045 and subjected to TIG remelting. The process of deposition was performed in two stages. The first stage involved the making of an intermediate layer using the NiAl powder; the thickness of the layer was restricted within the range of 40 μm to 60 μm. The second stage involved the making of another layer, the thickness of which was restricted within the range of 200 μm to 250 μm. The tests revealed that remelting decreased the porosity of the layer from 4% to 0.4% and improved its mechanical properties.

The microhardness of the layer after remelting increased by 33.4% (from 640 HV0.1 to 854 HV0.1), whereas brittle crack resistance increased by 287.6% (from 0.355 MPa·$m^{1/2}$ to 1.376 MPa·$m^{1/2}$). The remelting process also improved the strength of the layer (from 0.67–1.59×10^4 cycles to 16.2–31.2×10^4 cycles). Metallographic tests revealed that the remelted structure was characterised by higher homogeneity as well as the lack of cracks and lamellar structure. The XRD phase analysis revealed that the two primary phases present in the remelted layer were $(Fe,Cr)_{23}C_6$ and a small amount of CrB.

Summary

In many cases, the technology enabling the remelting of thermally sprayed layers has no alternative. Spraying belongs to high-performance processes enabling the obtainment of dense layers. The process does not lead to the excessive heating of the substrate and enables the manual, automated or robotic deposition of layers on elements characterised by complicated shapes (which is connected with the specific manner of the thermal deposition of layers). However, previous research revealed that sprayed layers are characterised by the presence of porosity, numerous material discontinuities and the lamellar microstructure. In addition, the bonding with the substrate is of mechanical (i.e. dominated by cohesion and adhesion) and not of metallurgical nature, which, in turn, is responsible for the fact that, in many cases, the peel strength of layers is insufficient. The aforesaid situation has necessitated the development of knowledge concerning the remelting of sprayed layers using various sources of energy. Because of its simplicity and low investment costs, the most popular method is flame remelting. However, other processes, involving the use of high-energy beams of photons (laser) and/or electrons, are characterised by high investment costs. Alternatives to these expensive solutions could be remelting processes based on the induction method or the use of electric welding arc. Processed sprayed layers are in significant demand in many industrial sectors. The remelting processes discussed in the article are characterised by lower investment costs, high flexibility and the high availability of equipment. For the above-named reasons, the processes are enjoying particular popularity among SMEs, which are not always in possession of considerable financial resources for technological investments. The overview presented in the article demonstrated that induction and arc-based methods make it possible to homogenise the microstructure in sprayed layers, significantly reduce their porosity as well as eliminate microcracks and non-remelted particles of deposited materials (typical of sprayed layers). More importantly, remelting processes also make it possible to improve mechanical properties; they enable an increase in hardness, abrasive wear resistance and brittle cracking. The application of remelting processes also results in the obtainment of the stable metallurgical bonding with the substrate, significantly increasing the adhesion of sprayed layers.

The technologies proposed in the article fall within the worldwide trend in searching for effective methods enabling the fabrication of layers on the metal substrate and characterised by abrasive wear resistance.

Acknowledgements

The research was performed within the project entitled *Layers and Coatings Containing Rhenium, Its Compounds or Alloys – Properties, Application and Deposition Methods* (Agreement no. CuBR/II/4/2015), financed by the National Centre for Research and Development and KGHM Polska Miedź S.A.

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