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PROPERTIES OF Fe-Al TYPE INTERMETALLIC LAYERS PRODUCED BY AC TIG METHOD

ABSTRACT

The paper presents the results of two new *in-situ* methods of Fe-Al intermetallic compounds layers fabrication on the steel substrates. The layers were produced by hardfacing of pure aluminum and titanium on the steel (S235JR) substrate as well as in the two-step process: the thermal spraying of pure aluminum on a steel substrate and subsequent remelting of aluminum coating with iron from the substrate using AC TIG method. As a result of the synthesis of Fe, Al and Ti components (for the hardfacing method) the new layer material based on the ordered intermetallic phases was achieved. The effects were confirmed by metallographic examinations, hardness tests and the diffraction patterns of the analyzed remelted layers. In addition, measurements of residual stresses in the layer and substrate were carried out.

***Key words**: Intermetallic phases, hardfacing, thermal spraying, AC TIG*

INTRODUCTION

The most commonly used materials based on intermetallic phases are the materials of the following systems: Fe-Al, Ti-Al and Ni-Al. Due to the properties and the cost of base materials the most interesting material in recent years are Fe-Al type intermetallics.

Materials on the basis of ordered intermetallic phases of Fe-Al system are characterized by high strength and resistance to oxidation, and low density. Together with other advantages it makes them very popular in the power industry, automotive, aerospace, and food [1, 2].

Excellent results are obtained by using the FeAl intermetallics for structure components operating at elevated temperatures - good thermal stability and the maintenance of high hardness and structure parameters were confirmed during heating intermetallic material to a temperature of 950°C for 10 hours. It was shown that the alloy containing 37-49% Al maintain stability of the structure and chemical bonds up to a temperature of 1340°C.

In this paper, the authors proposed two new methods for producing intermetallic layers of Fe-Al type. Both processes are carried out by conventional methods commonly used in welding.

The first method involves a two-step process - arc spraying of pure aluminum on steel substrate, then remelting the resulting coating together with part of the substrate material. Currently, intermetallic layer formed by thermal spraying with commercial intermetallic powders are very expensive. In addition, such layers are prone to delamination, have high porosity and reduced adhesion to the substrate. The process of remelting allows for a fine-grained microstructure of the base material. With this treatment structural defects after metal forming are eliminated and the base material has a high homogeneity and fatigue resistance [3]. The combination of these two processes (spraying and remelting) allows to obtain a layer based on intermetallic phases and with properties typical for the melted layers [4].

The second method used for intermetallic layer formation is simultaneous deposition of aluminum and titanium material by TIG method using alternating current (AC). Hardfacing is classified as one of the most universal methods of surface modification. Due to small structural changes in the substrate material, this method is used in the manufacturing of machine parts and tools, especially during their remanufacturing. Currently, the production of non-defective intermetallic layers by hardfacing of aluminum over steel is practically impossible due to the fact that a forming layer cracks and peels off. The addition of titanium in the deposition process, aims to change the structure of the produced layer which will provide a continuous intermetallic layer of high adhesion to the substrate. Furthermore, during hardfacing process the titanium fed into the weld pool, where the synthesis of aluminum and iron from the substrate takes place, can also diffuse to the aluminum to form an intermetallic phase of Ti-Al type. The resulting Ti-Al phase dispersed in the Fe-Al layer can favorably affect its properties. The introduction of a new phase may have a positive impact on the residual stresses developing in a layer-substrate system.

METHODS AND RESULTS

The two methods were applied using an AC TIG machine during investigations of production of Fe-Al intermetallic layers on steel substrate.

Production of Fe-Al based intermetallic layers

Fe-Al layer with ‘intermediate layers’

The layer was prepared in a two-step process of thermal spraying and subsequent remelting. In the first step, the unalloyed steel substrate (98.5 wt.% Fe) in the form of a plate with dimensions of 30 x 20 mm and a thickness of 2 mm, was thermally sprayed with aluminum by arc wire method to produce coating with a thickness of about 0.2 mm.

In the second stage, the sprayed aluminum coating was remelted together with part of the steel substrate (for a total depth of about 0.5 mm) by the AC TIG method. In order to obtain a Fe-Al layer the melting conditions had to ensure formation of the metal bath that was composed equally of aluminum coating and partially melted steel substrate. This process is shown schematically in Fig. 1. The remelting was performed using alternating current parameters: the current 65 A, argon shielding gas (11 l/min), the distance from the nozzle to the remelted surface - 4 mm, the travel speed of the torch - 120 mm/min.

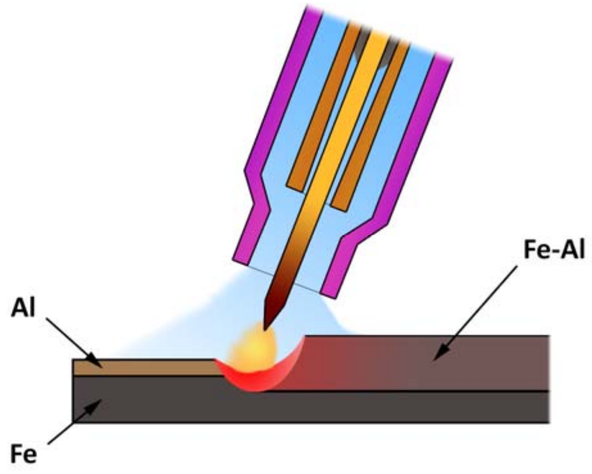

Fig. 1. The scheme of components remelting by the AC TIG method

Fe-Al layer with Ti addition

The layer was produced in a one-step hardfacing process. Aluminum and titanium in a ratio of 3:1 were hardfaced using AC TIG on steel (98.5 wt.% Fe) plate-shaped with dimensions of 30 x 20 mm and a thickness of 2 mm. This process is shown schematically in Fig. 2. An aluminum wire (99.7% Al) with a diameter of 2.4 mm and a titanium wire (Ti 99.9%) with a diameter of 0.8 mm were fed to the weld pool alternately. The process was carried out with the following parameters:

a) current of 70 A, argon shielding gas (11 l/min), the distance from the nozzle to the remelted surface - 3 mm, the travel speed of the torch - 150 mm/min,
b) current of 80 A, argon shielding gas (11 l/min), the distance from the nozzle to the remelted surface - 3 mm, the travel speed of the torch - 150 mm/min.

The application of higher current was used to obtain deeper penetration and better mixing of the substrate material with aluminum and titanium fed in the form of wire.

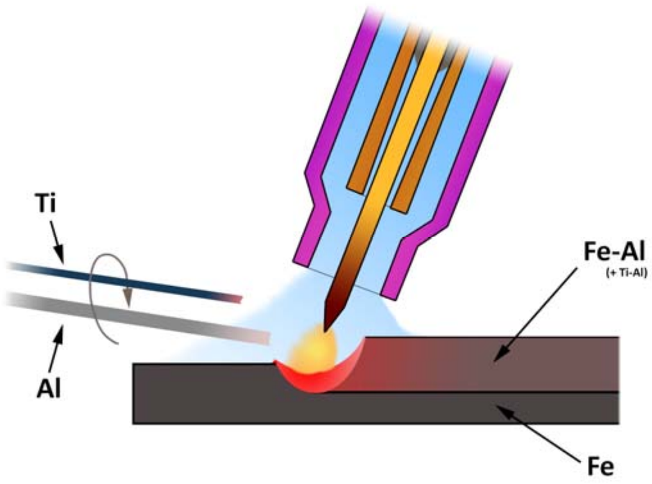

Fig. 2. The scheme of hardfacing process of aluminum and titanium over steel substrate by the AC TIG method

Microstructure examination

In order to characterize the microstructure of produced coatings and layers the metallographic testing was performed. The list of microstructure images taken from the layer-substrate interface is shown in Fig. 3.

The surface after thermal spraying (Fig. 3a) has a high roughness, the coating is tight and uniform, and its microstructure confirms the tightness of aluminum coating on steel. The coating is continuous, has a high porosity, the coating particles are anchored to the substrate mechanically.

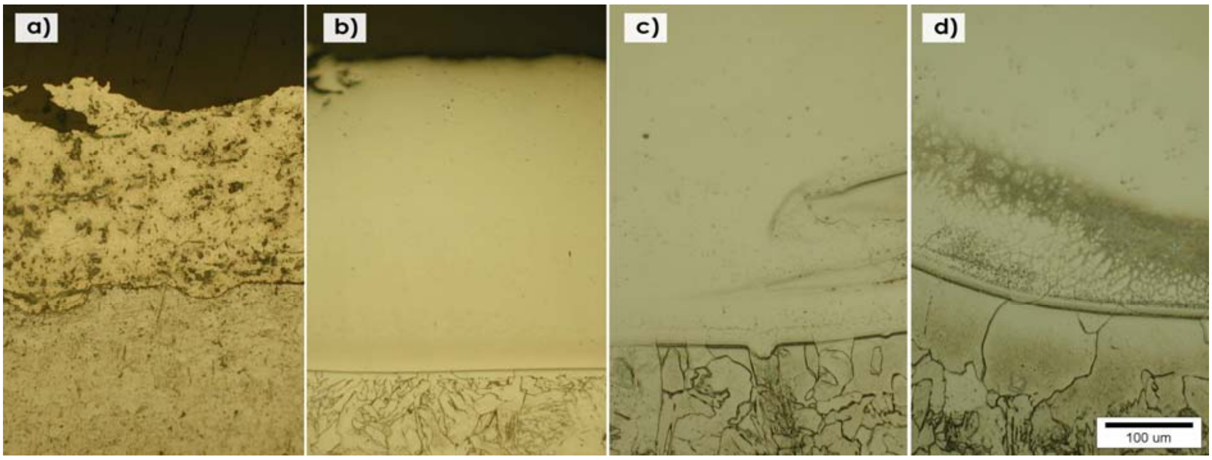

Fig. 3. The microstructure of: a) thermally sprayed coating, b) the remelted Al layer, c) the layer after Al hardfacing with Ti addition (high Ti-Al input content), d) the layer after Al hardfacing with Ti addition (low Ti-Al input content)

The layer formed by remelting of aluminum on steel (Fig. 3b) is free from cracks and porosity typical for thermally sprayed coatings. This ensures a high level of integrity and lack of geometric notches playing the role of stress concentrators. Any porosity can occur only in the upper part of the layer. The greatest advantage of the process carried out comparing to the directly sprayed intermetallic coatings is metallurgical bonding between the layer and the substrate. Obtained layer is uniform and continuous.

The layer formed by the hardfacing of aluminum and titanium on the steel substrate (Fig. 3c-d) also does not have cracks and porosity. In the region of the newly formed alloy one may see precipitation of other phases probably from the Ti-Al system. The presence of evenly distributed particles inside the deposit which are made of other phases can have positive effects on the mechanical properties of the produced layer.

Inside the heat affected zone a significant grain growth is observed, especially for the layer deposited using a higher current (Fig. 3d).

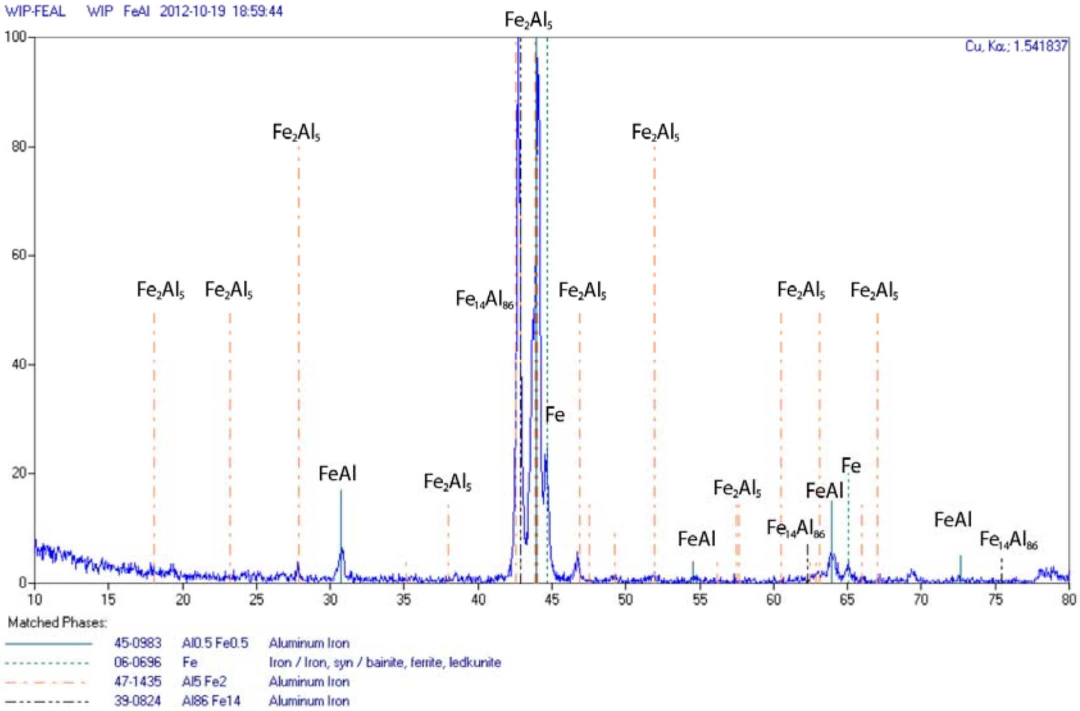

Fig. 4. The X-ray diffraction pattern of remelted Al coating by AC TIG method

Figure 4 shows the diffraction patterns of the resulting layer formed after aluminum remelting on steel substrate. The results of X-ray diffraction analysis confirmed the presence of the secondary FeAl phase solid solution and simultaneously confirm the participation of another Fe_2Al_5 phase as the main structural component.

The result of X-ray diffraction analysis of aluminum plus titanium layer hardfaced on steel (high input content of Al and Ti – shallow penetration into the substrate) is shown in Fig. 5. The pattern confirms the presence of FeAl phase, however, the FeTi intermetallic phase prevails in the structure with precipitations of Fe_2Ti phase.

A similar phenomenon has been observed for the last sample analyzed by x-ray diffraction (Fig. 6). Despite the deep penetration into the substrate and mixing of the components, the FeTi phase was obtained as the main structural component. In addition, the precipitation of FeAl and Ti_3Al phases was obtained, which is not observed for a sample with lower penetration of aluminum plus titanium layer.

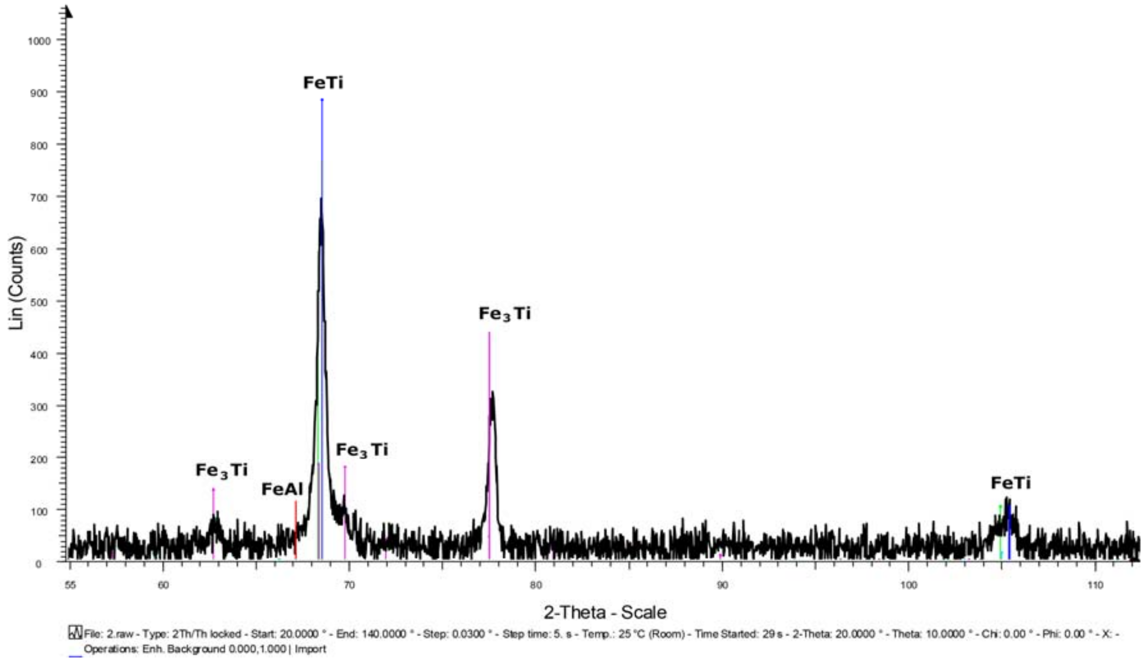

Fig. 5. The X-ray diffraction pattern of the layer after Al hardfacing with Ti addition (high Ti-Al input content)

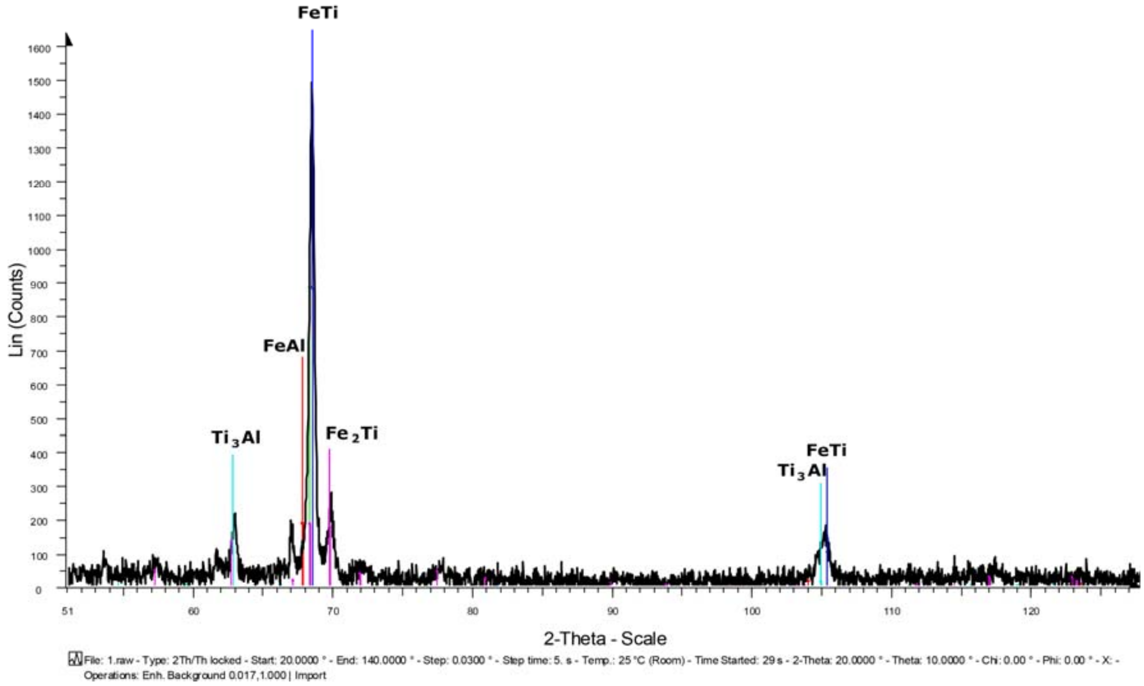

Fig. 6. The X-ray diffraction pattern of the layer after Al hardfacing with Ti addition (low Ti-Al input content)

Microhardness measurements

The microhardness test were conducted in the steel substrate and the layer produced for both applied methods (Fig. 7). The hardness was measured on a whole section of the sample in order to reveal possible impact of the thermal cycle on the substrate material.

There was an increase in the substrate hardness to approximately 350 $\mu HV_{0.1}$ only in the heat-affected zone (HAZ), which covered the region of about 0.25 mm width for the method of aluminum coating remelting and 0.4-0.6 mm width for the method of aluminum and titanium hardfacing. A slight increase in hardness was also observed in the substrate for the deposition process with increased current.

The hardness recorded in the proper layer was in the range of 890-1020 $\mu HV_{0.1}$ for the AC TIG remelting method, 480-1050 $\mu HV_{0.1}$ for the hardfacing of Al and Ti over the steel substrate and 450-570 $\mu HV_{0.1}$ for hardfacing with increased current. For all the methods, the measured microhardness fit in the appropriate range for the secondary Fe-Al solid solution and their values are likely to be dependent on the amount of other precipitated phases. The results reflect the chemical and structural homogeneity of the produced coating.

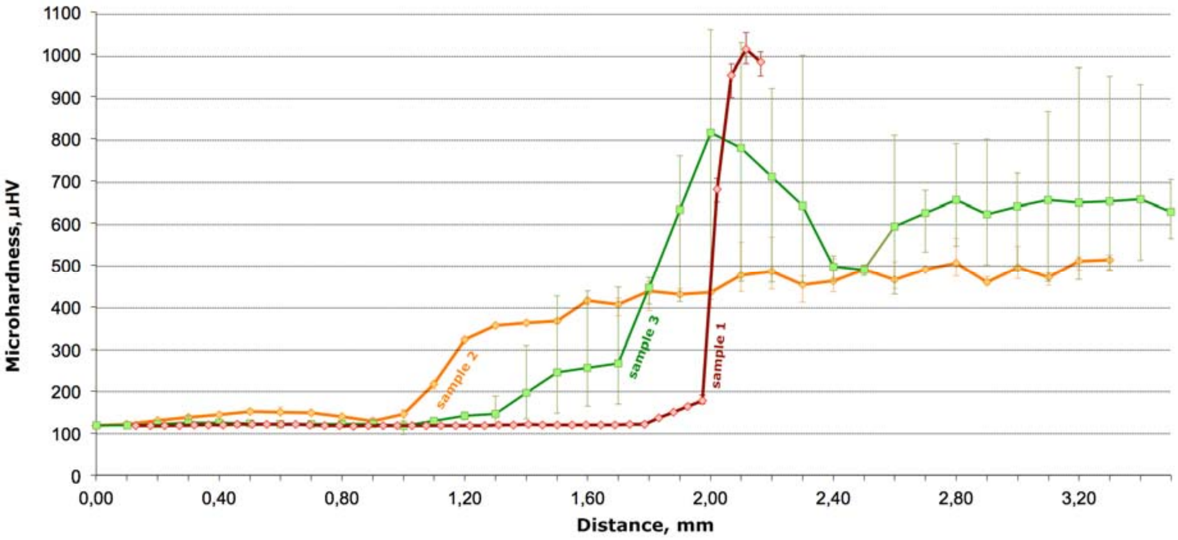

Fig. 7. Microhardness distribution in steel substrate and produced layer: sample 1 – after remelting of Al coating, sample 2 – after hardfacing with Al and Ti addition (high Ti-Al input content), sample 3 – after hardfacing with Al and Ti addition (low Ti-Al input content)

The microhardness tests were also carried out on the "usable" surface of formed layer. This plane was prepared by grinding to a depth of 10% of the layer. The uniform surface was examined in the 0.4 x 0.45 mm zone. The measurement results are shown in the graphs in Fig. 8. The surface after remelting of the aluminum layer has a uniform hardness in the entire measuring area and is in the range of 900-1000 $\mu HV_{0.1}$. The surface after hardfacing of aluminum and titanium (Fig. 8b) is similar in nature but its hardness is much lower, and covers a range of 450-600 $\mu HV_{0.1}$. Large hardness changes (500-1000 $\mu HV_{0.1}$) are observed for the final graph (Fig. 8c) depicting the hardness distribution of the surface obtained by using higher current.

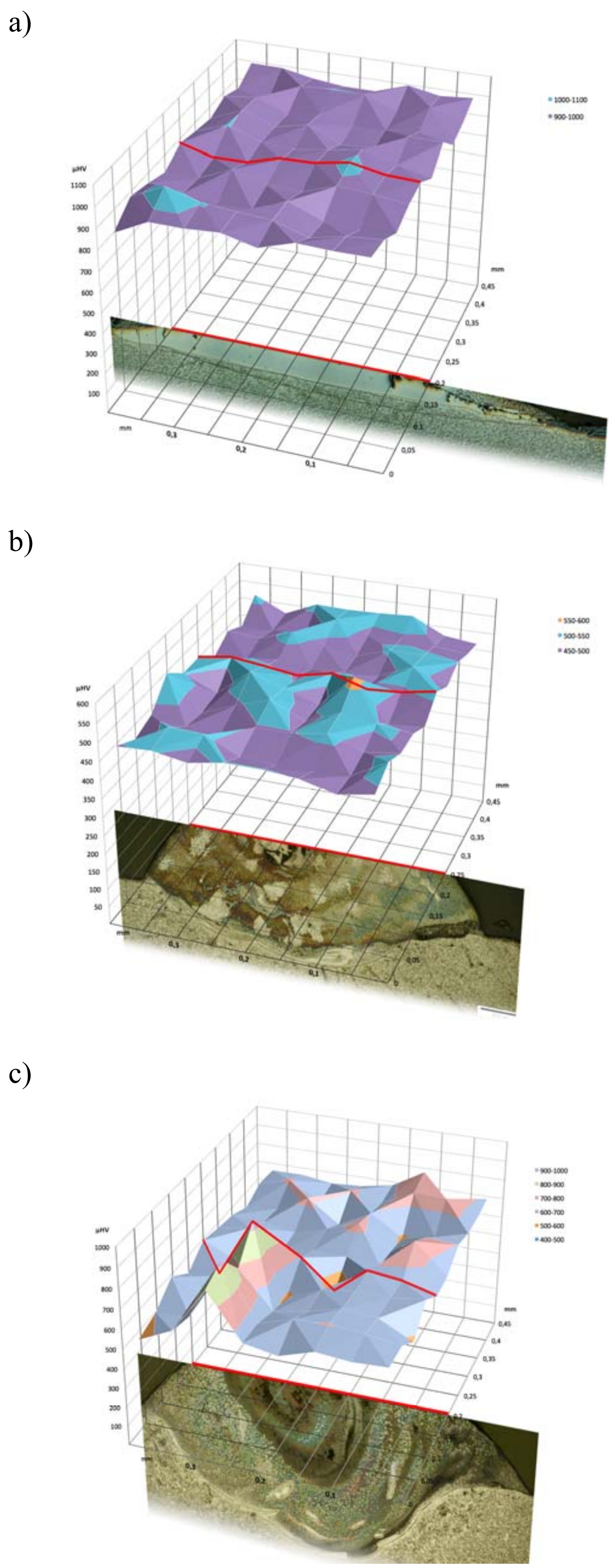

Fig. 8. The surface distribution of microhardness for: a) surface layer obtain after remelting of Al coating, b) surface layer after hardfacing with Al and Ti addition (high Ti-Al input content), c) surface layer after hardfacing of Al with Ti addition (low Ti-Al input content)

Residual stress estimation

The measurement of the residual stress generated in the produced layers and the substrate was carried out. The test was performed using a specially built gauge stand (Fig. 9a). The measured deflection of the sample (Fig. 9b) was used in the formula based on Stoney's equations to evaluate the residual stresses in the sample.

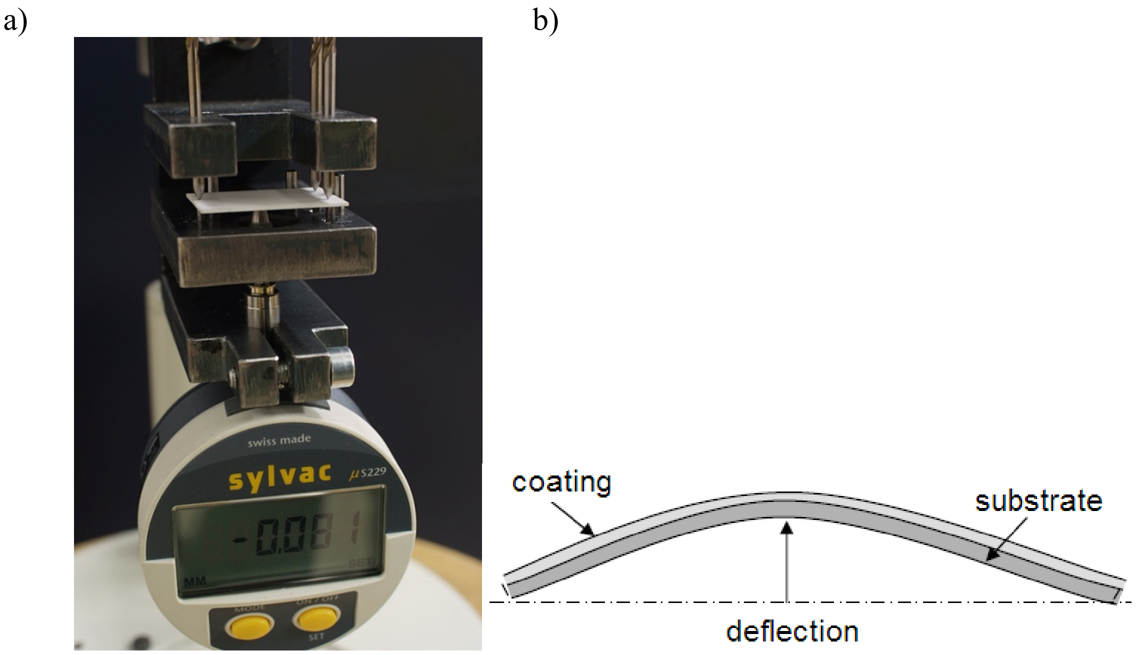

Fig. 9. The picture of the instrument used (a) and the scheme of deflection measurement (b) in produced layers

Assuming the thickness of the coating is much lower than the thickness of the substrate the mean residual stress in the coating can be calculated using simple Stoney's equation [5]:

$$\sigma = \frac{1}{6}\frac{E_s}{(1-\nu_s)}\frac{h_s^2}{h_c}\left(\frac{1}{R_2}-\frac{1}{R_1}\right) \tag{1}$$

where:
E_s – Young's modulus,
ν_s – Poisson's ratio,
h_s – substrate thickness
h_c – coating/layer thickness
$R_{2,1}$ – radius of curvature after (2) and before (1) deposition process

When the condition of much lower layer to substrate thickness is not satisfied the stress distribution in the substrate should be taken into account. The Stoney's equation may be modified accordingly to obtain the solution for stress in the layer and in the substrate. Clyne [6] described above in the analytical model to give the solution for determination of the stresses in the x direction both in the layer and the substrate:

the stress on the top surface of the layer:

$$\sigma_l\big|_{y=h} = \frac{-P}{bh} + E_l\kappa(h-\delta) \tag{2}$$

the stress on the bottom surface of the layer:

$$\sigma_l\big|_{y=0} = \frac{-P}{bh} - E_l\kappa\delta \tag{3}$$

the stress on the top surface of the substrate:

$$\sigma_s\big|_{y=0} = \frac{P}{b\,h} - E_s\kappa\delta \tag{4}$$

the stress on the bottom surface of the substrate:

$$\sigma_s\big|_{y=-H} = \frac{P}{b\,h} + E_s\kappa(h+\delta) \tag{5}$$

where:

$\sigma_{l,s}$ – the stress in the layer (l) and in the substrate (s),
$\Delta\varepsilon=(\alpha_s-\alpha_l)\Delta T$
$\alpha_{l,s}$ – coefficient of thermal expansion of the layer (l) and substrate (s),
ΔT – temperature difference,
h – the thickness of the layer,
H – the thickness of the substrate,
$E_{l,s}$ – Young's modulus of the layer (l) and substrate (s)
κ – curvature (1/R),
δ - distance from the neutral axis ($y_c=0$) to the layer/substrate interface

where:

$$\frac{P}{b} = \Delta\varepsilon\left(\frac{hE_lHE_s}{hE_l + HE_s}\right) \tag{6}$$

$$\delta = \frac{h^2E_l - H^2E_s}{2(hE_l+HE_s)} \tag{7}$$

Taking into account the above relations for the Fe-Al layers on the steel substrate we can draw the distribution of residual stress (σ_x) across the layer/substrate (Fig. 10).

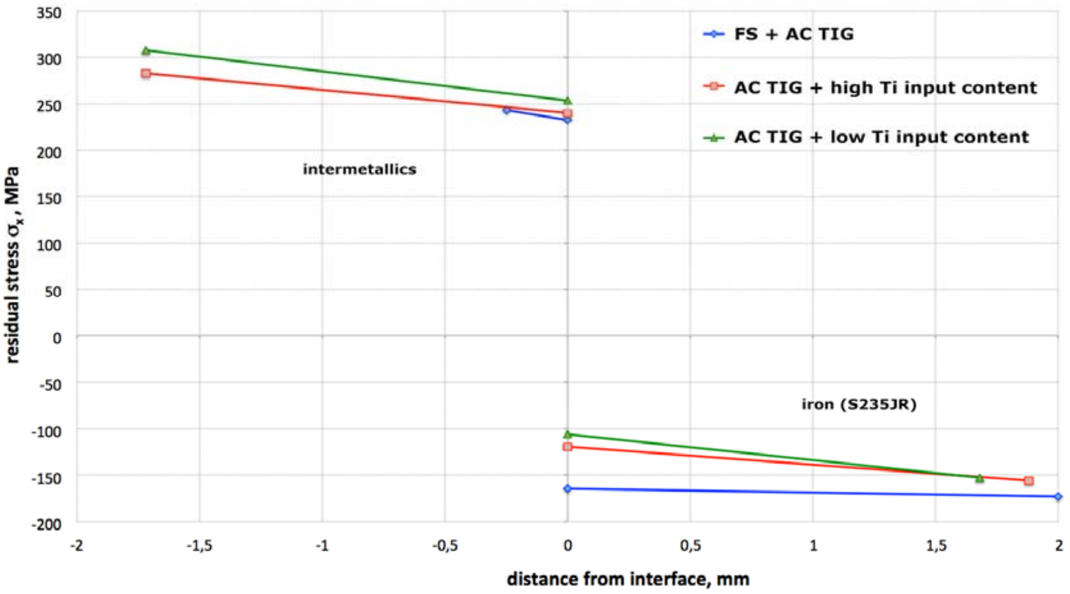

Fig. 10. The distribution of σ_x residual stresses across the thickness of Fe-Al layer and steel substrate calculated using modified Stoney's equations as proposed by Clyne (eq. 2-5)

The tensile stresses are observed in produced layers and compressive stresses in the substrate. The highest residual stresses (with maximum peak slightly above 300 MPa) are generated in the layer hardfaced with aluminum and titanium over steel substrate using a higher current. There is a sudden change in stress at the layer/substrate interface resulting from joining materials with different properties (eg. thermal expansion coefficient, Young's modulus).

CONCLUSIONS

The proposed methods for producing intermetallic layers of Fe-Al type using AC TIG method may provide an alternative to current methods of surface modification of steel, based on coating with expensive commercial intermetallic phases (usually in powder form). Using one of the cheapest welding method - AC TIG, the intermetallic layer based on the Fe-Al compound has been produced.

The observed changes in the structure and microhardness of the layers produced by hardfacing is similar to that of the layer obtained by remelting the Al coating and covers a range of 450-1050 $\mu HV_{0.1}$. The results indicate the formation of intermetallic phase of Fe-Al type and give rise to a further study of the proposed method.

Forming a layer of a compound based on Fe-Al and Fe-Ti in the future may be used as the intermediate layer for joining steel structures with aluminum components. Currently, the only methods used for this purpose are brazing and CMT method (Cold Metal Transfer) used in Fronius devices. The industry does not yet apply welding methods for the preparation of aluminum-steel joints.

The increase of the layer thickness leads to the increase of the residual tensile stresses reaching maximum values at the level of 240-310 MPa. The greater the influence of high temperature on the substrate, the higher the stress after formation of the layer.

The presented approach and used methods provide the ability to produce *in-situ* protective layers based on the secondary solution of Fe-Al compound. The structure of the layers and their mechanical and service properties enable the creation of new directions of their applications to machine parts operating at high thermal and mechanical loads in corrosive environments or in severe wear conditions.

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