Aluminium-steel plating by press welding

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Abstract. A series of researches related to aluminium-steel plating by press welding are presented in the paper. In this sense, the influence of the roughness of the aluminium and steel test samples was taken into account, but also of the post-welding heat treatment on the characteristics of the joints made. S355 steel specimens and AlMgSi0.7 F27 aluminium specimens were analyzed. The samples were processed and roughness Ra = 2.51-51.09 µm were obtained. Also, after making the joints, a post-welding heat treatment was applied which consisted of a heating at a temperature of 425 °C with a duration of 6.5 hours and a slow cooling to room temperature. Six distinct samples were made in terms of surface roughness in the joint area. After making the joints and applying the heat treatment, the samples were analyzed in terms of metallographic structure, the thickness of the interface layer and the hardness of the material in it. Thus, it was found that both the roughness of the test tube surfaces and the post-weld heat treatment have a substantial influence on the metallographic structure and the hardness of the material in the interface layer. The highest hardness of the material in the interface layer and its lowest thickness were obtained for the samples with the lowest roughness of the joint surfaces.

1 Introduction

At present, cold pressure welding offers the most satisfactory way to achieve cladding with aluminium or copper without the appearance of brittle inter-metallic compounds. Also, this cold plating avoids the appearance of the head affected zone (HAZ) which can have a number of unsuitable properties [1, 2].

Internal stresses and, in particular, deformations of crystal lattice substantially influence the diffusion process. Distortions of crystal lattice caused by plastic deformation accelerate diffusion. As a result, diffusion is faster in hardened metal parts. The acceleration of the diffusion is found especially on the sliding planes and on the grain limits, i.e. where the energy of the remaining elastic tensions is kept. In the case of an inhomogeneous state of tension, the atoms with larger radii tend to move in the areas required to stretch, and the atoms with smaller radii towards the compressed areas (upward diffusion). Dislocations also influence diffusion, favouring it. Thus, the diffusion along marginal dislocations possesses a lower activation energy and is important in the case of processes that take place at relatively low temperatures. [3, 4].

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Thus, finding technical solutions that allow the plating of different materials by cold plating are quite beneficial to industrial activities due to the technical and economic advantages they offer. However, the cladding of materials with very different physical properties involves the use of quite complex technologies [5].

Plating processes based on cold pressing have the advantage that a restriction of the welding area can be obtained from the materials interface. Of particular interest is the plating of steels with aluminium alloys because in this way it is possible to obtain structures that have a number of properties obtained by combining the high mechanical strength of steel and the corrosion resistance of stainless steel. [6].

Many times, in order to achieve a good plating of steel parts with aluminium, different intermediate layers made of other materials have been used, but this has a number of disadvantages in the sense that, by adding a new material to the welded structure, an increase in the weight of the structure is obtained, but also in the costs, especially if intermediate layers made of expensive materials such as niobium, tantalum or titanium are used. [7, 8].

Making Al-steel joints is very difficult, due to the complexity of metallurgical phenomena that occur when joining materials with different properties. However, given the fact that welding processes are constantly evolving, new concepts are emerging, an improvement in the quality of joints can be achieved. A problem that arises in the case of these types of welded joints refers to the fact that a series of intermetallic compounds appear at their interface. Thus, in order to avoid the appearance of these types of intermetallic compounds, different technological solutions have been proposed, namely: hybrid welding, optimization of welding process parameters, use of interlayer material, heat input control and post-welding heat treatment processes. These intermetallic compounds occur mainly due to the large deformation to which the piece of Al is subjected, and this causes more variations in the size of the grains in the Al part compared to the basic steel material. [9].

In these conditions, despite numerous researches on Al steel joints, there is still a wide field of research in this regard. Thus, at present there is not enough information on the optimal technological parameters that can be used to make Al-steel joints, depending on the thickness of the parts used in the joint, respectively the surface roughness of the joined parts. Given all this, in the research presented in this paper, it was considered to optimize the parameters used to make Al-steel joints by pressing depending on the roughness of the parts and heat treatment applied to welded joints.

2 Materials and methods

2.1 Materials

The specimens used in the welding process were of cylindrical type with a diameter $\Phi = 30$ mm and a length of 20 mm in the case of the steel specimen and 4 mm in the case of the aluminium specimen. The aluminium specimens were made of aluminium alloy AlMgSi0.7 F27, EN-AW-6005A T6. Obtaining these specimens was done by cutting them from the bars with the help of a band saw type 0273 produced by Fervi. Regarding the chemical composition of this aluminium alloy it is presented in Table 1.

Table 1. Chemical composition of the aluminium alloy sample/wt./%

Si	Mg	Fe	Cr	Cu	Zn	Mn	Ti	Other elements	Al
0.2-0.6	0.45-0.9	0.35	0.10	0.10	0.10	0.10	0.10	Max. 0.05	remaining

This aluminium alloy is largely weakly alloyed. The solubility of aluminium alloying materials is relatively low and therefore the number of technically usable alloys is limited. Thus, aluminium alloys contain other alloying elements intentionally added to aluminium in order to improve their mechanics, physics, metallurgy and technological properties. They are most commonly used as alloying elements Mn, Mg, Cu, Zn and Si. Also, aluminium and aluminium alloys do not have a solid state recrystallization transformation. Therefore, they cannot be normalized. Each heating of aluminium alloys to temperatures above 200°C results in a decrease in strength and hardness. This decrease is more pronounced at higher heating temperatures. At heating temperatures above 400°C, the curing effect is completely lost and the hardness of the alloy decreases.

It should be noted that the presence of iron and Al causes the formation of bonds between different atoms, which is usually greater than the bonding force between atoms of the same kind, increasing the possibility of the formation of the intermetallic compound in the welded interface [10−12]. Chemically, the reaction of Fe with Al forms several types of FexAly intermetallic compounds. Table 2 shows some of the properties of some of the intermetal compounds that may occur in the area of the welded joint.

Table 2. Properties of intermetallic compounds Fe_xAl_y, [13].

Phase	Al content/at%	Structure	Micro hardness, Hv	Density/
Fe_3Al	25	BCC	250-350	6.67
FeAl	50	BCC	400-520	5.37
Fe_2Al_7	63	BCC	650-680	-
$FeAl_2$	66-67	Rhombohedral	1000-1050	4.36
Fe_2Al_5	69.7-73.2	Orthorombic	1000-1100	4.11
$FeAl_3$	74-76	Monoclinic	820-980	3.96

The material from which the specimens from steel were made was a hot rolled steel, S355, which is a non-alloy steel (EN 10025-2). It is very often used to make welded structures where more strength is needed. This steel specified above are intended for use in heavily loaded parts of welded structures such as, bridges, flood gates, storage tanks, water supply tanks, etc., for service at ambient and low temperatures. Regarding the chemical composition, according to SREN 10025-2, they are presented in Table 3.

Table 3. Chemical composition of the steel sample/wt./%

C	Si	Mn	Al	Ni	Cr	Cu	Ti	O	Ce
0.13	0.18	1.5	0.02	0.02	0.03	0.05	–	–	0.39

Ce=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15.

2.2 Methods

To realization of welded joints used a hydraulic press MPH-300S, which has the following characteristics: press force: 300 kN; maximum working pressure: 160 bar; ram stroke: 200 mm; pressing speed: 100 mm/sec. This type of press was chosen because it allowed a very high pressing speed, and this parameter is very important in the pressing process.

Also, the surfaces of the specimens made of both steel and aluminium were processed so that different roughness values were obtained. Thus, an experimental research program was established, Table 4, which took into account 6 distinct samples. An SJ-210 Surface Roughness Tester produced by Mitutoyo was used to measure surface roughness.

Table 4. The roughness of the samples used in experimental research

Number of sample	Roughness of aluminium samples, Ra, µm	Roughness of steel samples, Ra, µm
S1	2.51	2.74
S2	10.61	11.13
S3	20.27	19.89
S4	30.72	31.47
S5	40.29	41.23
S6	51.09	50.07

The samples made by welding were subjected to a treatment. The post-welding heat treatment was performed in an oven under the following conditions: argon protection; temperature: 425 °C; duration: 6.5 hours. The samples were cooled after heating to room temperature. The oven used for the heat treatment was ThermCocept KLS 45/13 produced by ThermCocept.

In order to observe how in the interface layer was obtained an interpenetration of the material from the steel samples, respectively aluminium, a measurement of the hardness of the material from the interface layer was performed both before and after the applied heat treatment. Hardness measurement was performed by the Vickers method using a ZHV30 Indentec Zwick Roell hardness tester.

In order to identify the correlation between the formation of intermetallic compounds and the hardness of the materials in the interface layer, an analysis of the metallographic structure of the material in this layer was performed. The microstructure analysis was performed with the help of a metallographic optical microscope Basic VIS microscope produced by KERN.

3 Results and discussions

Following the operation of plating the steel with aluminium, 6 samples were obtained with the characteristics presented in Table 4 and whose shape is shown in Figure 1.

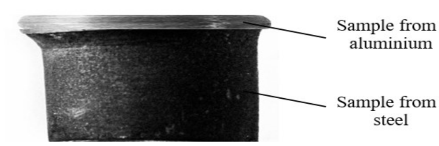


Fig. 1. The shape of the samples obtained by plating the steel with aluminium.

In the first stage of the research, the samples were cut longitudinally so that the area of the interface layer could be observed and, at the same time, an analysis of the metallographic structure and a hardness measurement for the material in the interface layer could be performed. These analyzes were performed for the 6 samples presented in Table 4, following the influence of the roughness of the sample surfaces both on the metallographic structure and on the hardness of the material in the interface layer. A macroscopic image of the section made by the S3 sample is shown in Figure 2.

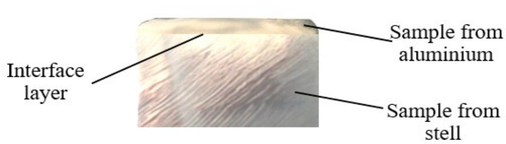
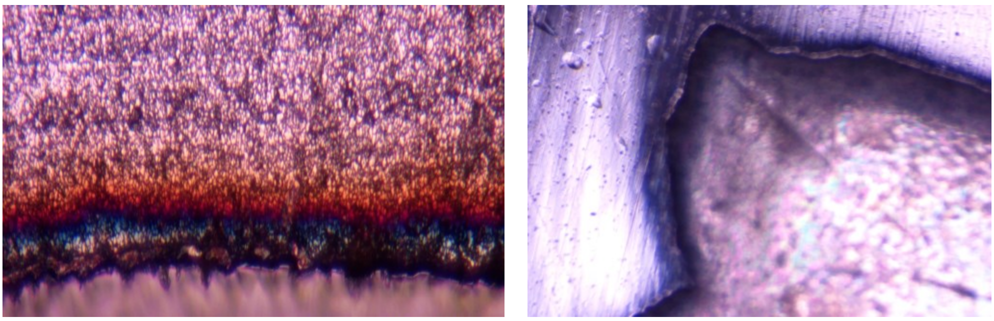


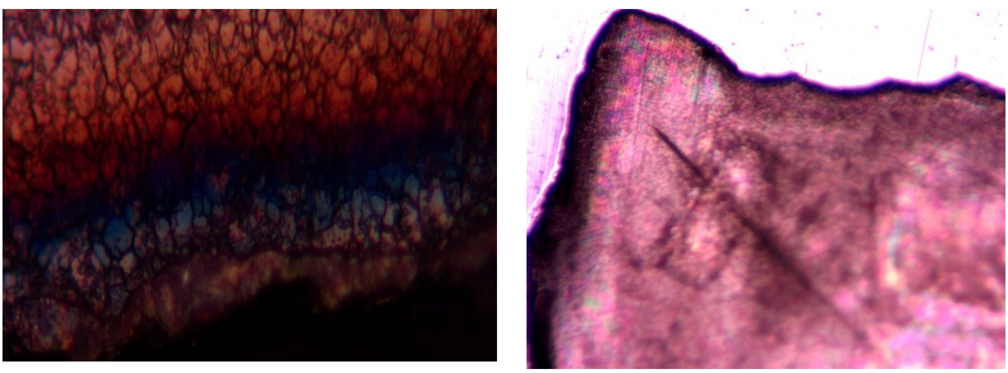
Fig. 2. Section through S3 sample

Also, by analyzing the samples with the help of a metallographic microscope, the size of the interface layer could be established very clearly, but the structural constituents formed after welding could also be identified. All these analyzes were performed for each sample both before and after the application of the post-welding heat treatment. As for the microstructures obtained, for example for the S3 sample, they are shown in Figure 3 before the application of the respective heat treatment in Figure 4 after the application of the heat treatment.



a b

Fig. 3. Metallographic structure of the S3 sample before heat treatment: a – x200; b – x1000



a b

Fig. 4. Metallographic structure of the S3 specimen after heat treatment: a – x200; b – x1000

From the analysis of the microstructures presented in Figure 3 and Figure 4, respectively, it was found that the application of the post-welding heat treatment determines a substantial modification of the metallographic structure. Thus, following the application of heat treatment, there was a more uniform distribution of structural constituents and a reduction in grain size. Of course, this also causes a change in the hardness of the material in the interface layer, but also an increase in its width. Under these conditions, in the next stage a measurement of the width of the interface layer was performed using a metallographic microscope, but also a measurement of the hardness of the material using the hardness tester ZHV30 ZHV30, and the results are presented in Table 5.

From the analysis of the values presented in Table 4 it was observed that an increase in the surface roughness of the steel and aluminium test specimens causes an increase in the thickness of the interface layer and a decrease in hardness. The higher hardness, in the case of low roughness, can be explained by the fact that in the case of such low roughness there is a strong deformation of the surface layer of the sample material. The smaller thickness of the interface layer for low roughness can be explained by the fact that the lower the roughness, the lower the interpenetration of the material layers [14, 15].

Table 5. Maximum interface layer thickness and hardness HV, before and after postwelding heat treatment

Sample number	Before post-welding heat treatment			After post-welding heat treatment		
	Maximum thickness, μm	Hardness, HV	Intermetallic compounds in the interface layer	Maximum thickness, μm	Hardness, HV	Intermetallic compounds in the interface layer
S1	10.51	948	$FeAl_3$	12.57	1031	$FeAl_2$
S2	27.24	853	$FeAl_3$	31.18	946	$FeAl_2$+ Fe_2Al_5
S3	51.73	758	$FeAl_2$+ Fe_2Al_7	76.49	679	Fe_2Al_5
S4	65.81	678	Fe_2Al_7	85.11	611	Fe_2Al_7+ FeAl
S5	83.58	534	FeAl+ Fe_2Al_7	92.43	467	FeAl
S6	91.56	483	FeAl	103.17	397	Fe_3Al

Also, during the research it was found that, if the roughness of the sample surfaces is low (S1, S2), a high hardness of the material is obtained in the interface layer, which increases with the application of the post-welding heat treatment. Thus, in the case of samples S1 and S2 in the interface layer before the heat treatment, hard intermetallic compounds of the FeAl3 type were obtained, which are transformed after the heat treatment into even harder intermetallic compounds, of the FeAl2 and Fe2Al5 type. At the same time, the application of post-welding heat treatment causes a decrease in hardness in the case of specimens that have a higher roughness. This confirms that the application of an annealing heat treatment in the case of aluminium alloys causes a reduction in their hardness, but this is possible only if the metal structure contains intermetallic compounds such as FeAl, Fe3Al, Fe2Al7 [16, 17].

Thus, the research demonstrates that the roughness of the surfaces of the specimens used for pressing plating of aluminium steels is one of the parameters that has a special role in obtaining certain characteristics for the joints made. It has also been shown that, depending on the roughness of the surfaces, aluminium-steel cladding can be obtained which has certain intermetallic compounds in the interface layer.

4 Conclusions

The researches demonstrated that both the roughness of the samples surfaces and the post-welding heat treatment have a substantial influence on the metallographic structure and the hardness of the material in the interface layer. The highest hardness of the material in the interface layer and its lowest thickness were obtained for the samples with the lowest roughness of the joint surfaces. Also, depending on the roughness of the test pieces, intermetallic compounds of different types were obtained in the interface layer, starting from soft intermetallic compounds Fe3Al to hard intermetallic compounds FeAl2. It should be noted that the application of post-weld heat treatment causes a reduction in the hardness of the material in the interface layer if the specimens have high roughness, but also an increase in the hardness of the material if the specimens had low roughness.

Future research will aim to optimize the roughness of the specimen surfaces by combining specimens with different roughness so as to obtain aluminium-steel cladding with superior characteristics that can be used successfully in machine construction.

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