ARCHIVES OF METALLURGY AND MATERIALS
Volume 58 2013 Issue 2
DOI: 10.2478/amm-2013-0047

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UTILISATION OF HIGH-ENERGY HEAT SOURCES IN MAGNESIUM ALLOY SURFACE LAYER TREATMENT

WYKORZYSTANIE WYSOKOENERGETYCZNYCH ŹRÓDEŁ CIEPŁA W OBRÓBCE WARSTWY WIERZCHNIEJ STOPÓW MAGNEZU

The main aim of the study was the evaluation of magnesium alloy surface treatment effectiveness using high-energy heat sources, i.e. a Yb-YAG Disk Laser and the GTAW method. The AZ91 and AM60 commercial magnesium alloys were subject to surface layer modification. Because of the physicochemical properties of the materials studied in case of the GTAW method, it was necessary to provide the welding stand with additional equipment. A novel two-torch set with torches operating in tandem was developed within the experiment. The effectiveness of specimen remelting using a laser and the GTAW method was verified based on macro- and microscopic examinations as well as in X-ray phase analysis and hardness measurements. In addition, the remelting parameters were optimised. The proposed treatment methodology enabled the achieving of the intended result and effective modification of a magnesium alloy surface layer.

Keywords: Surface layer modification; Magnesium alloys

Głównym celem pracy była ocena efektywności obróbki powierzchniowej stopów magnezu za pomocą wysokoenergetycznych źródeł ciepła, tj. Yb-YAG Disk Laser i metody GTAW. Modyfikacji warstwy wierzchniej poddano komercyjne stopy magnezu AZ91 i AM60. W przypadku metody GTAW z uwagi na własności fizykochemiczne badanych materiałów konieczne okazało się doposażenie stanowiska spawalniczego. W ramach eksperymentu opracowano nowatorski zespół dwupalnikowy z palnikami pracującymi w układzie tandem. Efektywność przetapiania próbek laserem i metodą GTAW weryfikowano na podstawie badań makro- i mikroskopowych oraz rentgenowskiej analizy fazowej i pomiarów twardości. Dokonano również optymalizacji parametrów przetapiania. Zaproponowana metodyka obróbki pozwoliła na osiągnięcie zamierzonego rezultatu i skuteczną modyfikację warstwy wierzchniej stopów magnezu.

1. Introduction

An effective method for improving the operational properties of machine and equipment components consists in shaping their structure and properties in the surface layer. The use of high-energy heat sources for that is one of the most prospective and dynamically developing areas of surface engineering. The nature of this treatment is based on inducing the effect of fast crystallisation due to which the remelted material structure is formed in conditions of very high temperature gradient and very short solidification time. As a result, the treatment and accompanying fast crystallisation can contribute to the limitation of any possible defects and imperfections existing in the remelted material or can result in obtaining properties that are difficult to achieve using classical heat or thermochemical treatment methods [1-3]. These issues are important not only from a cognitive but also utilitarian point of view. This constituted the reason to begin a research study for the paper's authors.

Numerous papers both in domestic and foreign journals [4-7] prove the importance of the above issues. The analysis of this data allows noticing a clear domination of laser techniques in the surface engineering. Both continuously operating and pulsed lasers are used in the surface layer treatment. However, these are most often Nd-YAG [8-10] lasers or CO_2 [11,12] continuously operating lasers. A short process time and a possibility of precise beam focusing on a selected surface and obtaining very high temperature gradients in the material weigh in favour of the laser techniques selection. Economic reasons are the main factor limiting its possible applications [13].

The authors of this paper, guided by the project's economics, made an attempt to find a solution alternative to laser techniques. They attempted to adapt the GTAW (Gas Tungsten Arc Welding) welding method to the needs of magnesium alloys remelting surface treatment, which, as found during the

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first tests, may be an attractive and competitive solution to the laser techniques, subject to reconstruction and the additional equipment of the welding stand. In the case of magnesium alloys, the welding stand modification is dictated by the necessity to take specific characteristics of this material into account and especially its strong affinity to oxygen. The attractiveness of welding heat sources is related to a low apparatus costs, operational simplicity and greater availability compared to more expensive laser technologies [14, 15].

This paper presents the effects of remelting surface treatment carried out using a Trumpf TruDisk 12002 disk laser, the classical GTAW method, and a novel torch set developed for the experiment needs. The influence of the assumed treatment parameters on the remelting zone geometry has been discussed, their optimisation has been performed, as well as the preliminary assessment of the implemented treatment effect on the studied alloys microstructure and selected mechanical properties.

2. Experimental procedure

The material studied consisted of series AZ and AM casting magnesium alloys manufactured by NTP Kędzierzyn-Koźle (Poland). Table 1 presents the chemical composition of the alloys used. Cuboidal specimens of AZ91 and AM60 magnesium alloys of dimensions 6×3×1 cm and 7×3×1 cm, respectively were subject to surface layer remelting.

TABLE 1

Chemical composition of AZ91 and AM60 alloys according to ASTM B93-94

Alloy	The percentage content of the elements				
	Al	**Zn**	**Mn**	**Si**	**Mg**
AZ91	8.5-9.5	0.45-0.9	0.17-0.40	0.05	rest
AM60	5.6-6.4	max 0.02	9.26-0.50	0.05	rest

A Trumpf TruDisk 12002 disk laser with the lens focal length of 3,000 mm and a 200 mm collimator was used in the experiment. The angle of head inclination to the specimen surface was 90°. The treatment was carried out in argon atmosphere. The shielding gas flow ranged between 4.6 and 14 l/min. To intensify the laser beam absorptive power and to reduce the reflectivity, the surface of the studied alloys was roughened with an abrasive paper of 1000 gradation.

The surface treatment by the GTAW welding method was performed using inverter current sources: FALTIG-315 AC/DC and MIGATRONIC PI 350 DC. The treatment was carried out under an atmosphere of 99.995% purity argon using non-consumable tungsten electrodes with ThO_2 addition.

Structural examinations were carried out using an Axiovert 25 optical microscope. Etched microsections were observed. The hardness measurements of specimens were performed on transverse microsections using a Future-Tech FM-7 microhardness tester. The applied load was 50 G, and the load duration was 6 s.

3. Summary of the results

3.1. Laser treatment

In the first phase of the experiment the magnesium alloys were subjected to a surface modification using the laser technology. In order to do so, a 12 kW Trumpf TruDisk disk laser with a system of fibre-optic cables and technological accessories was used. It is a device that allows carrying out of processes of laser welding, bifocal laser welding, or scanning beam (remote) welding, among others. The treatment parameters are specified in Table 2. A constant scanning speed of 2 m/min was used in the experiment, the laser power Q was a variable parameter, in the case of the AZ91 alloy, the value of Q ranged from 750 to 1500 W, and in the case of the AM60 alloy the laser power varied from 750 to 3000 W.

TABLE 2

Specification of laser treatment parameters

Alloy type	Band number	Laser power Q [W]	Bandwidth W_p [mm]	Depth of remelting G_p [mm]
AZ91	1	750	1.81	2.60
	2	1000	2.37	3.73
	3	1250	2.76	4.45
	4	1500	3.02	5.21
AM60	1	750	1.78	2.46
	2	1000	2.28	3.20
	3	1500	2.97	4.89
	4	3000	3.13	8.49

Macroscopic observations of remelted bands as well as the analysis of treatment parameters combined with measurements of the remelting zone dimensions allowed to notice a few significant regularities:

- an increase of bandwidth W_p with the increasing laser power Q,
- an increase of the depth of remelting G_p with the increasing laser power Q, however the risk of unfavourable changes in the surface geometry was increasing.

The relationships presented had a similar nature for both magnesium alloys subjected to the surface modification. To illustrate the relationships existing between the width and the depth of remelting and the laser power used in a better way, they are presented in graphical form (Fig. 1). For the adopted treatment parameters, the depth of remelting obtained for the AM60 alloy was 2.46 to 8.49 mm and for the AZ91 alloy – 2.60 to 5.21 mm. The widths of remelted bands fell into the range of 1.78-3.13 mm for the AM60 alloy and of 1.81-3.02 mm for the AZ91 alloy.

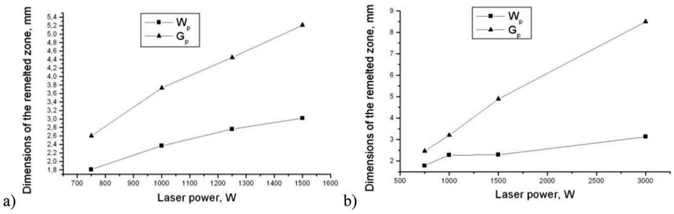


Fig. 1. Relationship between the dimensions of the remelted zone and the laser power for alloys: a) AZ91 and b) AM60

The performed tests allowed the determination of the optimum remelting parameters. The most favourable changes in macroscopic terms were registered in the case of bands remelted using the laser power of 750-1000 W. Although an increase in the laser power resulted in increased dimensions of the remelted zone, this was, at the same time, related to the occurrence of undesired changes in the geometric structure of the surface. Such changes were registered in the case of those specimens subject to remelting by using the laser power exceeding 1000 W.

3.2. GTAW treatment

The next step of the study comprised an attempt to adapt welding heat sources for the needs of magnesium alloys remelting surface treatment. A number of methodological difficulties were encountered during preliminary tests that were made using the GTAW welding method, making a proper performance of the task impossible. Because of the physicochemical properties of magnesium and its alloys, and in particular a strong affinity to oxygen, resulting in the existence of a compact MgO oxide layer on the material surface, it was impossible to effectively remelt the specimens using the GTAW method. The MgO oxide layer was an obstacle to the passing current, causing the arc bending and hence disturbing the remelting process. A characteristic feature of MgO oxides is their high melting point (approx. 2,800°C) substantially exceeding the range of melting points for the magnesium alloys studied (470-615°C). Such a significant difference in temperatures resulted in difficulties with overcoming the thermal barrier without causing the effect of “flow” of molten magnesium alloy existing under the oxide layer.

In the initial phase of the experiment, the welding supply source consisted of a DC power supply with a straight polarity and then with a reversed polarity. The application of straight polarity resulted in the quick heating of the electrode, limiting the permissible current, ultimately producing minute effects of surface treatment. In turn, the change of polarity to the reversed resulted in the high instability of the arc, limiting the possibility of remelting process implementation. The use of alternating current seemed to be the optimum solution, supported by a possibility to carry out the process of cathodic cleaning, resulting in the destruction of surface oxide layer. The advantage of alternating current over direct current, is the enabling of the obtaining of a similar effect, expressed in the lack of current limitations existing when using direct current with a straight polarity. A precise description of the adopted remelting parameters using alternating current is presented in Table 3. Two main parameters, i.e. the current intensity and the distance of the electrode from the specimen surface were used in the experiment. A constant scanning speed of 8.2 mm/s was applied. The remelting treatment using the GTAW method was carried out both in the conditions of the manual and of the automated remelting. The mechanised remelting was related to the ease of defining the treatment parameters, contrary to the manual method, to a large extent depending on the operator (welder) skills, who changed the parameters during the process in order to obtain the intended macroscopic effect.

Macroscopic examinations of the remelted layers showed the significant qualitative and quantitative differences in the geometrical structure of individual bands. The diversified effects of remelting resulted from the variability of treatment parameters applied. For the AZ91 alloy, the most favourable changes in the surface layer were registered using AC current without pulsation, with a current intensity equal to 100 A. The optimum effects of remelting using AC current with pulsation were obtained at a current pulse of around 90 A and a basic current of 51 A. For the AZ91 alloy, the application of the other current values included in Table 3 were related to the occurrence of unfavourable changes in the studied materials'

TABLE 3

Parameters of magnesium alloys remelting using the GTAW method

No	Alloy type	Treatment method	Current intensity I [A]	Duration of current pulse and duration of base [s]	Electrode distance from the specimen surface d [mm]	Bandwidth W_p [mm]	Depth of remelting G_p [mm]
1	AM60	manual	I_i =100 I_b =56	t_i =0.2 t_b =0.2	-	9.2	1.65
2	AZ91		I_b =100	-	-	9.4	-
3	AM60	automated	I_i =150 I_b =80	t_i =0.3 t_b =0.15	4	13.85	0.22
4	AM60		I_i =150 I_b =80	t_i =0.3 t_b =0.15	3	8.65	0.49
5	AM60		I_i =160 I_b =90	t_i =0.3 t_b =0.15	4	10.4	-
6	AZ91		I_i =130 I_b =90	t_i =0.3 t_b =0.15	4	9.1	-
7	AZ91		I_i =90 I_b =51	t_i =0.2 t_b =0.2	2	10.8	-
8	AZ91		I_b =74	-	2	8.2	-

I_i – pulse current, I_b – base current, t_i – duration of current pulse, t_b – duration of base surface geometry, resulting in the disqualification of the treatment. In the case of the AM60 alloy, the tests were carried out using only AC current with pulsation. The analysis of structural changes in the remelted layer indicated the occurrence of the most favourable effects when the value of the current pulse did not exceed 160 A and of the basic current – 90 A.

The analysis of the remelting zone dimensions combined with the applied treatment parameters allowed for the observation of a number of correlations and relationships, the value of which should be evaluated not only in a cognitive, but also in the application dimension. During the tests it was found that:

- an increase in the electrode distance from the specimen surface *d* results in an increased width of the remelting zone W_p. A departure from this rule was registered only for the AZ91 alloy subjected to remelting by AC current with pulsation of current values I_i = 90 A, I_b = 51 A. It is difficult to conclude whether this was caused by the apparatus or material issues,
- the depth of remelting zone G_p decreases with the increasing distance of the electrode from the specimen surface. It is worth mentioning that because of a very labour-consuming and time-consuming procedure for metallographic microsection preparation, the measurement of the remelting depth was limited to the AM60 alloy specimens, showing favourable macroscopic changes.

The analysis of remelting zone dimensions vs. adopted treatment parameters has shown that for the AM60 alloy, the width of remelting zone was on the order of 8.65–13.85 mm and for the AZ91 alloy this value was within the range of 8.2–10.8 mm. For the AM60 alloy, the remelting zone depth was from 0.22 to 1.65 mm.

The application of AC current did not always guarantee the repeatability of the effects. The difficulty in the mechanised remelting of magnesium alloys by means of the GTAW method using an AC current arc was related to the disturbances of arc burning caused by precisely adhering an oxide layer of non-uniform thickness. Unfortunately, an increased cathodic cleaning current, resulting in the improvement of the oxide removal effectiveness, caused a reduced remelting capability and lowered the thermoemission strength of a non-consumable electrode, resulting in its faster wear.

3.3. Modified GTAW treatment

Macro- and microstructural effects obtained from magnesium alloys remelting using the GTAW method, methodological difficulties, and the lack of repeatability induced the paper's authors to attempt to develop a solution that would help overcome these difficulties. The concept and design work carried out within the experiment has shown a possibility for the effective remelting of magnesium alloys using the GTAW method, subject to reconstructing and providing additional equipment of a classical welding stand. The nature of the solution developed consisted of a system with two independent torches working in tandem. The leading torch played the role of removing oxides on the path of cathodic cleaning, while the following main torch was supposed to remelt the cleaned surface. In the system, the cleaning torch was supplied with AC current and the main torch was connected to a power supply of unidirectional pulsating current. The welding set presented in Fig. 2a comprised two torches, each of which was equipped with a non-consumable electrode and a gas nozzle. The shielding gas fed by gas nozzles 7, 8 was protecting the surface of the remelted material against contact with the air, creating a protective zone. Fig. 2b presents a diagram of the current characteristics for individual torches of the tandem system. The application of a pulsating unidirectional current, based on a pulse introduction of electric arc heat by cyclically repeating welding current pulses, made it possible to achieve the main goal of the experiment, i.e. effective remelting of the magnesium alloy surface layer. What's more, the solution proposed excluded the necessity of mechanical or chemical removal of an oxide layer from the surface of remelted magnesium alloys, which was undoubtedly an improvement to the performed treatment.

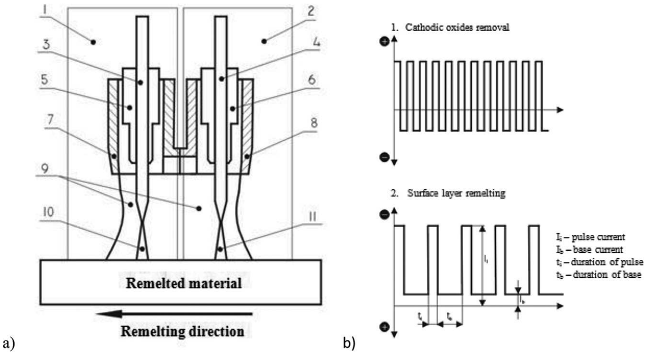


Fig. 2. Graphic diagram: a) two-torch system: 1,2-torches, 3,4-infusible electrodes, 5,6-current contact, 7,8-gas nozzles, 9-shield gas, 10,11-electric arc and b) current characteristics of individual torches working in tandem

Because of magnesium and its alloy physicochemical properties, the choice of the appropriate treatment parameters was an extremely time-consuming action, requiring great involvement and regularity. However, a skilful association of the basic parameters such as the current intensity, scanning speed, or electrode distance from the specimen surface for individual torches of the tandem system with the observed effects of remelting led to achieving the intended result. A specification of examples of parameters adopted during the remelting using the modified GTAW method is presented in Table 4. All remelts were implemented at a constant scanning speed of 8.2 mm/s.

TABLE 4

Operating parameters of the two-torch system and remelting zone dimensions

No	Alloy type	Current intensity in the remelting torch I [A]	Frequency of pulsating current f [Hz]	Electrode distance from the specimen surface d [mm]	Band-width W_p [mm]	Depth of remelting G_p [mm]
1	AM60	110	220	2	5.38	1.16
2	AM60	150	220	2	7.52	1.55
3	AZ91	80	330	2	4.47	1.05
The current intensity in the cleaning torch I = 98A						

Like in the case of the laser and GTAW method treatment, also during the analysis of remelting effects using the two-torch method relationships have been found between the treatment parameters applied and remelting zone dimensions. It has been found, inter alia, that the increase in current intensity in the remelting torch results in an increased width of the remelting zone W_p, and there is a directly proportional relationship between the depth of remelting G_p and the current intensity. The relationships described above are graphically presented in Fig. 3.

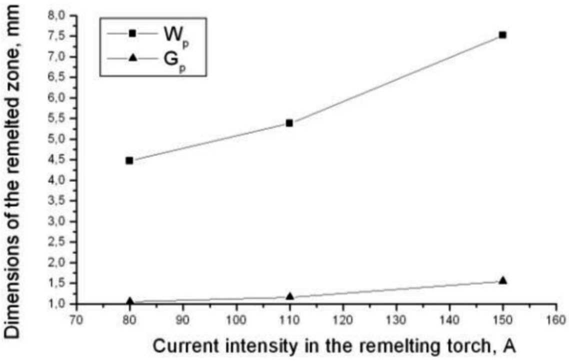


Fig. 3. Examples of relationships between the dimensions of the remelted zone and the current intensity in the remelting torch for magnesium alloys

3.4. Alloys structure after remelting and its influence on mechanical properties

The optical microscopy, scanning electron microscopy and X-ray phase analysis examinations revealed the existence of an α solid solution of aluminium in magnesium (of limited solubility) and of $\alpha+\gamma$ eutectic in the structure of commercial Mg-Al alloys in the initial state, where γ was an $Mg_{17}Al_{12}$ intermetallic compound. The addition of manganese in magnesium alloys is favourable to the formation of an intermetallic compound with aluminium. The structure and morphology of the Mg-Al alloy analysed is presented in Fig. 4.

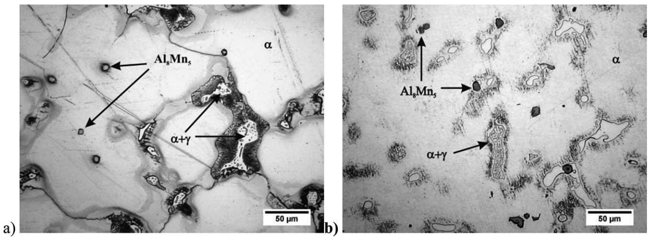


Fig. 4. Microstructure of alloys a) AM60 and b) AZ91 in the initial state; optical microscope, etched

The optical microscopy observations revealed substantial changes in the structure and morphology of surface modified compared with their non-remelted equivalents. Examples of structural effects of high-energy heat sources influence are presented in Fig. 5. The nature of changes observed in the surface layer structure of the alloys remelted using laser and welding techniques looked similar. Observations of transverse microsections showed the existence of three zones:

- a remelted layer,
- a remelting boundary,
- a non-remelted zone.

The size and character of the changes registered in the surface layer proved that the material was surface remelted at the place of the heat source influence. The effect of quick crystallisation occurred in the alloys studied under specific conditions of high temperature gradient and very short time of heat source influence. This was proved by the structural and morphological effects, such as the structure refinement or material homogenisation.

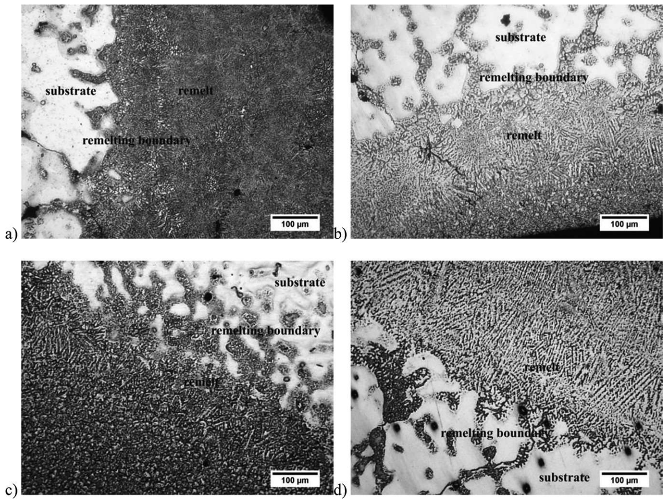
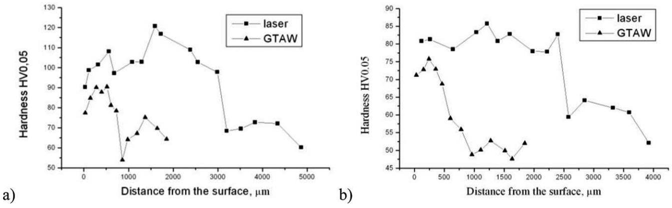


Fig. 5. Microstructures after remelting: a) by laser – AZ91 alloy, b) by GTAW method – AM60 alloy, c) and d) by modified GTAW method, for the AZ91 and AM60 alloys, respectively; optical microscope, etched

A comparative analysis of structural effects combined with measurements of remelting zone dimensions allowed the observation of certain relationships resulting from the applied methodology for the surface layer remelting of materials studied. In the case of laser treatment, it has been found that for the adopted parameters there was a clear increase in the depth of remelting as against the values obtained using welding heat sources. In turn, the GTAW method application led to obtaining an opposite effect, namely an increased width of the remelted band and a decreased depth of remelting. Moreover, the remelt-substrate boundary was not as clearly marked as in the case of laser-treated specimens because of the application of welding technologies. Therefore, the measurements of remelting zone geometry may contain some errors due to difficulties in the precise determination of the remelting boundary position.

Favourable changes in the remelted zone design and structure registered during microscopic examinations allowed the expectation of the occurrence of equally favourable changes in its mechanical properties. These expectations were confirmed by microhardness tests. However, structural differences in the GTAW method and laser remelted specimens became visible also in the recorded values of material hardness. Therefore, for the laser-remelted specimens the hardness ranged from 77 to 85 HV0.05 for the AM60 alloy and from 90 to 120 HV0.05 for the AZ91 alloy. In the case of specimens remelted using the GTAW method the values of around 55-71 HV0.05 were recorded for the AM60 alloy and 70-84 HV0.05 for the AZ91 alloy. Instead, after remelting using the modified GTAW method the hardness of 68-75 HV0.05 was obtained for the AM60 alloy and 77-90 HV0.05 for the AZ91 alloy. In comparison, the average hardness of the initial material was 53 HV0.05 for the AM60 alloy and 65 HV0.05 for the AZ91 alloy. Examples of hardness distribution vs. the distance from the surface of specimens remelted using a laser and the modified GTAW method are presented in Fig. 6. The increase in the remelted zone hardness compared with the material in the initial state results from structural changes that occurred in the material following the remelting treatment performed. The structure refinement and the material homogenisation are the main factors responsible for the hardness growth. Higher microhardness values registered in case of the laser technique application result from the specific nature of the treatment applied, leading to a stronger structure refinement, resulting in a clear improvement in mechanical properties of the remelted zone.



a) b)

Fig. 6. Results of hardness measurements for alloys a) AZ91 and b) AM60 after remelting using the laser and the modified GTAW method

A comparative analysis of both techniques applied for surface modification (laser and welding) is extremely difficult as we deal with tools of entirely different methods of operation; hence a parametric characteristic is impossible. However, it is possible to compare both techniques from the point of view of the structural effects obtained as a result of surface remelting. Making such an assumption and limiting the analysis only to specimens, in which no disqualifying changes of the surface geometry were found, it is possible to state that the nature of structural changes is very similar, because there is substantial structure refinement and material homogenisation. However, the temperature gradient was undoubtedly higher in the case of the laser treatment, with the implication of greater structure refinement and a more clearly marked remelting boundary. In economic terms, the GTAW method is unbeatable. This is a very convenient tool that does not require the special preparation of the remelted material surface (in this case, we refer to the tandem type two-torch method), also the availability of welding equipment and the ease of its operation weigh in favour of the GTAW method. Unfortunately, this method requires greater care in the treatment parameters selection than for the laser technique due to the possibility of unfavourable changes in the surface geometry occurrence. This does not change the fact that the GTAW method in the form of a solution developed by the authors of this paper may be attractive, competitive, and at the same time an alternative to the laser techniques prevailing now.

Received: 15 September 2012.

4. Conclusions

Based on the results of the studies carried out and on their analysis, the following conclusions have been formulated:

- a possibility of effective magnesium alloys remelting using the GTAW welding technology forces the need of welding stand redesigning and providing additional equipment;
- a two-torch system with torches working in tandem ensures the obtaining of the proper remelts quality, in which the leading torch removes the oxides layer via cathodic cleaning and the following main torch remelts the cleaned surface;
- the remelting zone geometry may be shaped by the appropriate association of basic treatment parameters;
- the surface remelting treatment results in the occurrence of favourable structural and morphological changes; Among others, a strong structure refinement and material homogenisation are observed;
- changes caused by the remelting and accompanying quick crystallisation contribute to a substantial increase in hardness in the remeleting area compared to the substrate material;
- the modified GTAW method can be an alternative solution to laser techniques.

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