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МАТЕРІАЛОЗНАВСТВО

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I. A. VAKULENKO[1*], YU. L. NADEZHDIN[1], V. A. SOKIRKO[2], I. P. VOLCHOK[3],
A. A. MITIAEV[3]

[1*]Dep. «Materials Technology», Dnipropetrovsk National University named after Academician V. Lazaryan, Lazaryan Str., 2, 49010, Dnipropetrovsk, Ukraine, tel. +38 (056) 373 15 56, e-mail dnyzt_texmat@ukr.net
[2]LTD «DS», Bolshaya Morskaya Str., 63, 54001, Nikolaev, Ukraine, tel. +38 (0512) 41 52 07, e-mail ds@mksat.net
[3]Dep. «Materials Technology», Zaporizhzhya National Technical University, Zhukovskiy Str., 64, 69063, Zaporizhzhya, Ukraine, tel. +38 (061) 769 82 71, e-mail volchok@zntu.edu.ua
[3]Dep. «Materials Technology», Zaporizhzhya National Technical University, Zhukovskiy Str., 64, 69063, Zaporizhzhya, Ukraine, tel. +38 (061) 769 82 71, e-mail mityaev@ zntu.edu.ua

ELECTRIC PULSE TREATMENT OF WELDED JOINT OF ALUMINUM ALLOY

Purpose. Explanation of the redistribution effect of residual strengthes after electric pulse treatment of arc welding seam of the aluminum alloy. **Methodology.** Alloy on the basis of aluminium of AK8M3 type served as the research material. As a result of mechanical treatment of the ingots after alloy crystallization the plates with 10 mm thickness were obtained. After edge preparation the elements, which are being connected were butt welded using the technology of semiautomatic argon arc welding by the electrode with a diameter of 3 mm of AK-5 alloy. Metal structure of the welded joint was examined under the light microscope at a magnification of 200 and under the scanning electronic microscope «JSM-6360 LA». The Rockwell hardness (HRF) was used as a strength characteristic of alloy. Hardness measuring of the phase constituents (microhardness) was carried out using the device PMT-3, with the indenter loadings 5 and 10 g. The crystalline structure parameters of alloy (dislocation density, second kind of the crystalline lattice distortion and the scale of coherent scattering regions) were determined using the methods of X-ray structural analysis. Electric pulse treatment (ET) was carried out on the special equipment in the conditions of the DS enterprise using two modes A and B. **Findings.** On the basis of researches the previously obtained microhardness redistribution effect in the area of welded connection after ET was confirmed. As a result of use of the indicated treatment it was determined not only the reduction of microhardness gradient but also the simultaneous hardening effect in the certain thermal affected areas near the welding seam. During study of chemical composition of phase constituents it was discovered, that the structural changes of alloy as a result of ET first of all are caused by the redistribution of chemical elements, which form the connections themselves. By the nature of the influence the indicated treatment can be comparable with the thermal softening technologies of metallic materials**. Originality**. The observed structural changes of alloy and related to them microhardness change in the areas near the welding seam after ET are conditioned by both the change of morphology of structural constituents and the redistribution of chemical elements. In case of invariability of chemical elements correlation in the phase constituents of alloy the reduction effect of gradient microhardness should be far less. **Practical value**. In practice, the negative effect of the wares embrittlement made using the casting technologies, excluding the pressure casting and quite difficult selection of chemical composition of alloy can be significantly reduced during the treatment of alloy with electric pulses.

Keywords: hardness; phase; chemical compound; silumin; welding seam

Introduction

The welded joints formation using the technology of melting is accompanied by significant changes in the metal internal structure of the edges, which are being joined. Proportional to the temperature of heating and depending on the cooling conditions the processes of structural transformations develop in the metal of pool and heat affected zone. These transformations have an unchanging influence on the property package of the welded joint. Moreover, the observed structural changes are in fact resulted from the simultaneous influence of several factors, notably the processes of diffusion mass transfer and redistribution of internal stresses of different origin [7]. The residual stress diagram after the welded joint forming might be of such form that the summing of one sign of residual stresses and the stresses from exploitation of constructions [11, 12]. In this case, the unaviodable exceed of computed values from actual stresses will lead to the breach of the guaranteed conditions of trouble-free service for the welded joint. On this basis, the development of measures to reduce the value and gradient of residual stresses in the welded joint is quite an urgent problem of modernity [3, 13].

Except the thermal and mechanical ways to decrease the residual stresses, such as a reversible deformation [1, 2], the use athermal technologies is of some interest too. The technologies based on the use of strong magnetic and electric fields should be included to these treatments [5].

Purpose

Work purpose is the explanaion of redistribution effect of residual stresses after electric pulse treatment of the silumin arc welded seam.

Methodology

An alloy on the basis of aluminium of AK8M3 type served as the research material. 10 mm thick plates were obtained as a result of the ingot mechanical treatment after alloy crystallization. After the edge preparation the elements, which are being connected were butt welded using the technology of semiautomatic argon arc welding by the electrode with 3 mm diameter of AK-5 alloy. Metal structure of the welded joint was examined under the light microscope at a magnification of 200 and under the scanning electronic microscope «JSM-6360 LA». [6]. The Rockwell hardness (HRF) was used as a strength characteristic of alloy. Indenter is a ball of 1.58 mm diameter with the loading of 60 kg (State Standard 9013). Hardness measuring of the phase constituents (microhardness) was carried out using the device PMT-3, with the indenter loadings 5 and 10 g. The crystalline structure parameters of alloy (dislocation density, disturbance of the crystalline lattice and the scale of coherent scattering regions) were determined using the methods of X-ray structural analysis [4]. The electric pulse treatment (ET) was carried out on the special equipment in conditions of the DS enterprise. The electric current density was 14 and 16 $\frac{A}{\text{mm}^2}$, respectively modes A and B.

Findings

Taking into account the existence of qualitatively different structural condition of the metal after the arc welded joint formation the studies were carried out for two superheated areas (by two sides from the welding pool, marked I and III, respectively) and for the volume of the pool itself (II). After averaging of four - five values the alloy hardness after welding without ET was 62 and 61 for I and III regions respectively, when for the II region (weldin pool region) – 46.

The microstructural studies showed that the alloy represents a multiphase composition consisting of a matrix in the form of a solid solution, and the second-phase particles (Fig. 1). The metal of welded joint has a structure of as-cast condition, with almost the same dispersion (Fig. 2). As it is shown above the volumes of alloy have multiphase structure. Second-phase particles, which are similar in form to the plates, have an non regular distribution in the metal matrix.

Micro-hardness measurements of the alloy structural components showed quite significant difference in the absolute values. For the second phase particles, depending on the distance of tested alloy volume from the welding pool, the microhardness exceed as compared to the matrix has reached from ten to a few times.

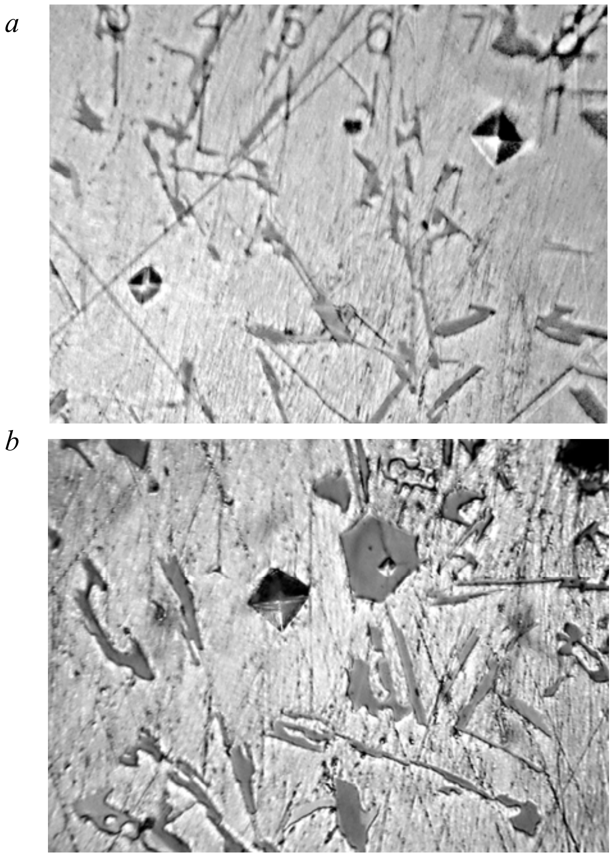

Fig. 1. Edge structure of the AK8M3 alloy after the welded joint formation at a distance 3 mm (*a*) and 6 mm (*b*) from the melting boundary. Magnification 200

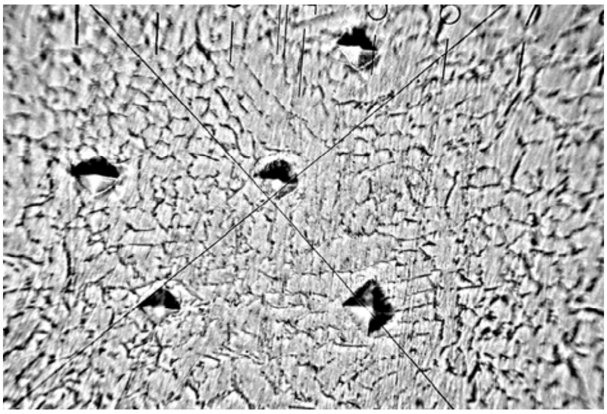

Fig. 2. The structure of the welding pool metal. Magnification 200

For the alloy without electrical pulse treatment, the parameters change of alloy crystalline structure showed qualitative correspondence with the nature of strength characteristics change, which is typical for the majority of metallic materials [1, 2]. Dislocation density increase (ρ) and distortions of the second kind (μ) during the coherent scattering regions decrease (L) is accompanied by quite natural hardness increase about 25–27%.

After ET irrespective of its mode a progressive softening of alloy in the heat affected zone was observed.

The intensity increase of the electrical pulse treatment was accompanied by the decrease of hardness characteristics as compared to the original (without ET), for the regions I and III by 11% after the A mode and 15% decrease after the B mode. For metal volume of the welding pool the situation is somewhat different. Initially the hardness measurements showed increase in hardness from 46 (without ET) up to 56 for A mode and 48 for B mode. The observed effect of changing the hardness of the metal weld pool can be seen as evidence of structural changes in the electric pulse treatment in cast metal, and for heat-affected zone [3, 12]. Moreover, the welding pool metal having a different phase composition [9] with a simultaneous change of aggregative state (during the welding) as a whole leads to the qualitative change in the nature of hardness change. On the other hand, the metal of heat-affected zone having a multi phase structure may be subjected to the phase hardening to a greater extent as a result of the thermal stresses during the welding joint formation.

The experimental data analysis confirmed the existence of qualitatively different nature of relationship between the metal hardness, ρ and L for the alloy subjected to ET (Fig. 3). So, regardless of the research areas I, II or III, the hardness increase is accompanied by the decrease in defect number of crystal structure and coarsening of coherent scattering regions. In other words, for the vast majority of steels and alloys the nature of these relationships (HRF $\sim f(\rho, L)$) should correspond to the development of softening process, not strengthening. At the same time, it is unclear due to what effects the nature of HRF $\sim f(\mu)$ relation remained corresponding to the hardening.

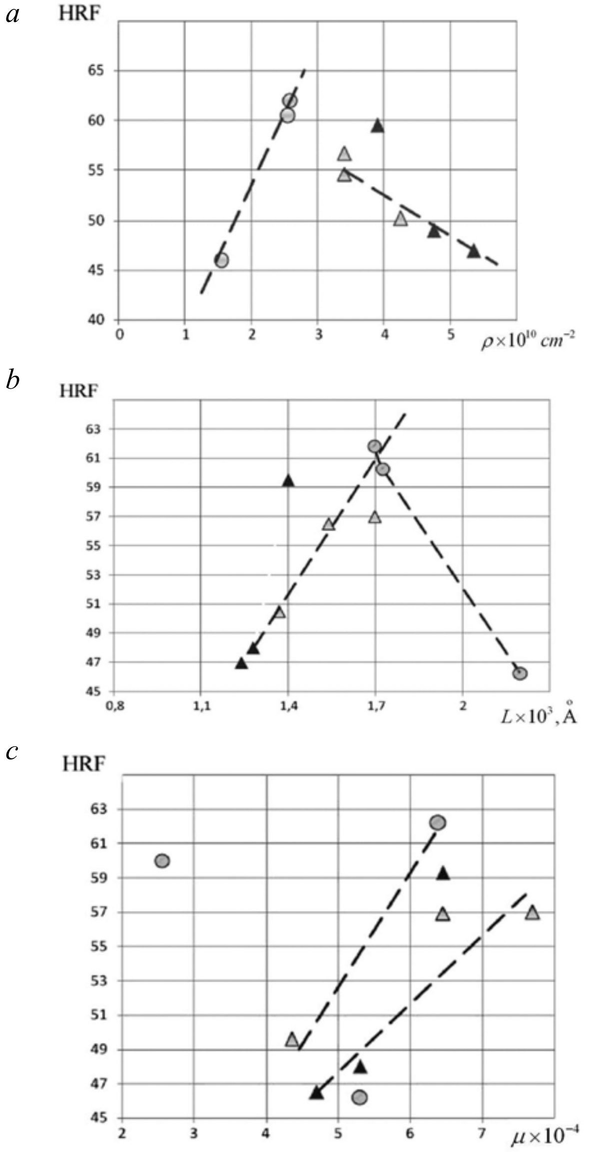

Fig. 3. Parameter influence of the crystalline structure of AK8M3 alloy on its hardness (dislocation density according to interference (111) – (*a*), the size of coherent scattering regions – (*b*) and the distortion of the second kind – (*c*). Sign: ⊙ – without ET, Δ – after ET, mode A, ▲ – after ET mode B

On the basis of studies the previously obtained softening effect of aluminum alloy welding joint as a result of electrical pulse treatment was confirmed [5]. Explanation of the observed phenomena on the basis of study of the crystalline structure characteristics only did not uniquely determine the main influence factors. It is hoped that the use of scanning electron microscopy would give the opportunity to get more information on the observed softening effect. Moreover, the qualitative changes of the relation nature between the hardness and the parameters of crystalline structure after the ET shown on the Fig. 3 may be associated with the changes of alloy phase composition. In case the observed relations of crystalline structure and hardness of alloy will be associated with the redistribution of chemical elements forming the phase components of the alloy, the processes of diffusion mass transfer should explain the effects nature in the ET.

The microhardness distribution in the aluminum matrix (H_{μ}) depending on the distance from the welding pool is shown on the Fig. 4. The extreme nature of dependency indicates a rather complex distribution of residual internal stresses.

Subjecting the heat-affected zone of alloy after the welding joint formation to the electric pulse treatment the nature change of microhardness distribution is detected.

The analysis of the dependencies indicates the existence of qualitative differences, especially for the superheated area of alloy. Moreover, based on the comparative analysis of absolute values of the alloy matrix hardness (α – solid solution Si in Al), as a result of ET a decrease in hardness difference (approximately 10% from the minimum to maximal values) is achieved. Something like that by the nature of its manifestation is noted for the areas of the second phases (Fig. 5).

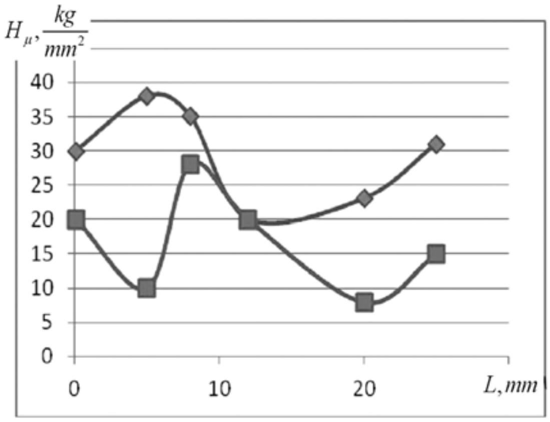

Fig. 4. The microhardness change of AK8M3 alloy matrix depending on the distance from the welding pool (□ – after the welding, ◊ – after the welding and electrical pulse treatment, mode B)

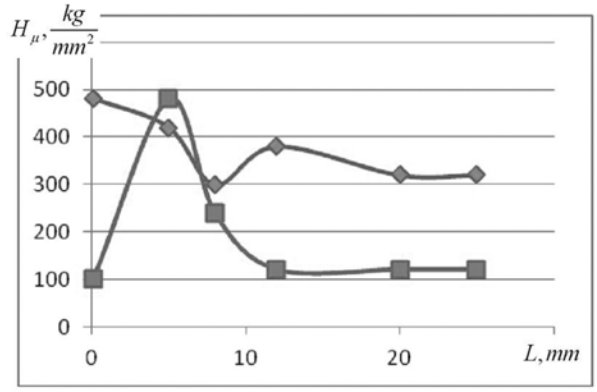

Fig. 5. The microhardness change of the sections of chemical compounds of AK8M3 alloy depending on the distance from the welding pool (the signs are the same as in Figure 4)

Comparative analysis of the absolute values of chemical compounds hardness shows that as a result of ET the reduction of hardness difference is also achieved. Although this reduction is more significant: before ET the hardness difference was 75%, and after that – approximately half as large (36%).

The experimental data analysis of microhardness distribution indicates that as a result of ET use of arc welding joint it is detected not only the gradient microhardness decrease, but the simultaneous reinforcing effect. Indeed, on the basis of the dependencies shown on Figures 4 and 5, for both the matrix and the chemical compounds for the full range of distances (from the welding pool) a quite unambiguous hardness increase is observed.

The results of studies of the alloy structure using the scanning electron microscopy are presented on Fig. 6 and 7. The structure of heat-affected zone section of the welded joint, which corresponds to the alloy superheated area, is shown on the Fig. 6.

As compared to the microstructure observed under a microscope PMT-3 (Fig. 1 and 2) when it can only be classified as a two-phase, the electron microscopy indicates the existence of at least more two chemical compounds and two solid solutions. The obtained results of the study are in good agreement with well known published data [9, 10, 12]. Despite this, the shown dependencies of change H_μ for the solid solution areas and sections of chemical compounds before and after ET (Fig. 4 and 5) still represent a particular scientific interest.

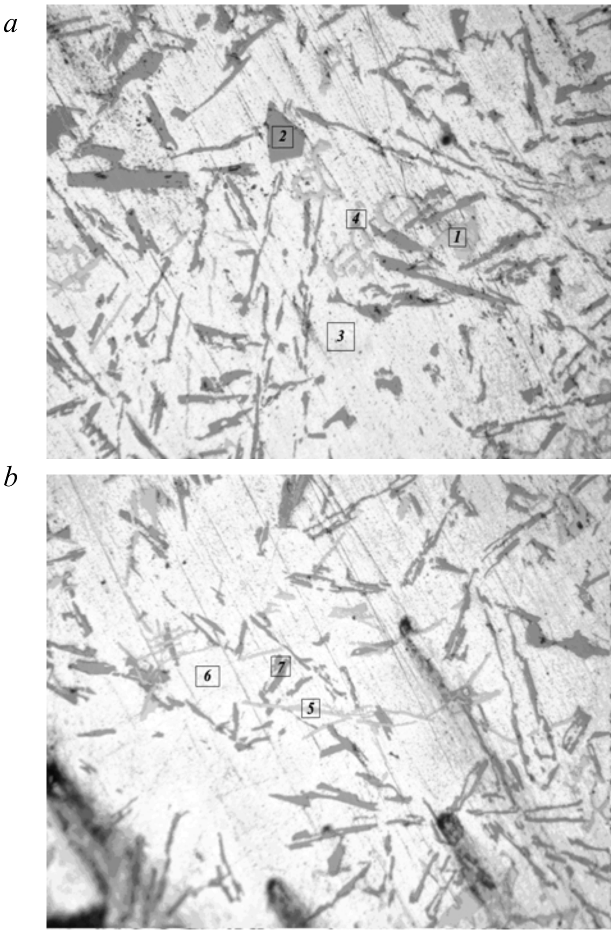

Fig. 6. Different plases (*a*) and (*b*) AK8M3 alloy microstructure after the welded joint formation. Numerals indicate the locations determining the alloy phase composition using the raster scanning electron microscope «JSM-6360 LA»
(1, 4 – particles of a chemical compound $Al_{15}(Fe,Mn)_3Si_2$; 5 – Al_5FeSi; 2, 7 – solid solution; 3, 6 – solid solution Si in Al)

This is caused by the fact that actually the represented dependencies are the result of the hardness values averaging according to the two solid solutions and some (although they are different) chemical compounds.

The microstructure studies revealed that according to the characteristic features of the alloy structure before and after the welded joint formation are practically the same that corresponds to the metal condition after casting.

The observed minor differences have more to do with segregation phenomena of chemical elements during the alloy manufacturing and its crystallization.

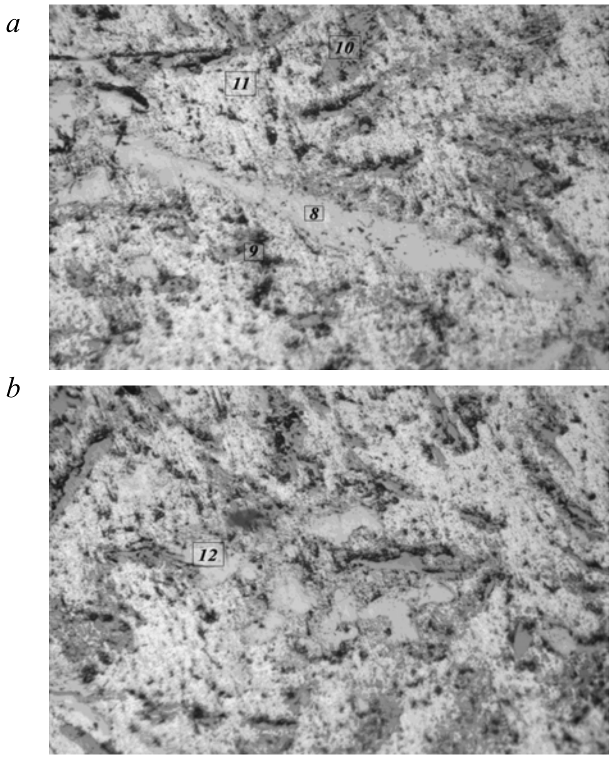

Fig. 7. Different plases (*a*) and (*b*) AK8M3 alloy microstructure after the welded joint formation and following ET. Numerals indicate the locations determining the alloy phase composition using the raster scanning electron microscope «JSM-6360 LA» (8 – Al_5FeSi; 9 – Al_2Cu; 10 – a solid solution Al in Si; 11 – solid solution Si in Al; 12 – particles of chemical compound $Al_{15}(Fe,Mn)_3Si_2$)

After ET of the alloy welded joint the developed processes of structural transformations have led not only to the changes of the structural component dispersion, but also to the changes of their distribution in the matrix (Fig. 7). Thus, the comparative analysis points to a qualitatively different structural condition of the alloy after ET. Indeed, in case the as-welded alloy has obvious signs of cast condition, then after ET these signs are almost absent. In the majority of cases the phase components are presented in the form of globular particles (mark 9) or areas with definite length, marks 8, 12, Fig. 7.

When studying the chemical composition of the phase components, it was found out that the observed structural changes of alloy as a result of ET first of all may be caused by the redistribution of chemical elements, which form the compounds themselves. Something similar was observed during the variation of silumin chemical composition [3, 12], the use of special modifiers [9, 13] or by changing the crystallization conditions [1]. Indeed, studies have shown that the relation of chemical elements that are involved in the formation of certain compounds changes after ET. On this basis, these chemical compounds in most part should be referred to the compositions of «berthollides» type. Moreover, if the chemical compounds, which are being formed, were referred to the «daltonides», i.e. to the compounds with the fixed chemical composition, the effect of the microhardness gradient lowering should be less significant.

The microhardness nature of the phase components confirms the above mentioned. If we consider the microhardness change of the alloy matrix (Fig. 4), then it is safe to assume that as a result of ET the slight hardness increase as a whole should not be accompanied by changes of solid solutions concentration. The micro spectral analysis data of solid solutions of the alloy matrix confirmed their practical constancy. Indeed, α – a solid solution (Si in Al), which consisted of 96% Al, 1.5% Si and 2.5% Cu after ET remained almost the same: 96% Al, approximately 1% Si and 3.0% Cu. The same can be said of β in the solid solution (Al in Si). Before ET its composition was: 3.0% Al and 97% Si, elsewhere 10% Al and 90% Si, which indicates the substantial liquation of the chemical elements in solid solutions. After ET the following relation of chemical elementswas found out: 6.0% Al and 94% Si. Concentration averaging of elements in the solid solutions alloy matrix shows almost unchanged relation before and after ET. Consequently, as a result of ET the relation of chemical elements in the alloy matrix (α – solid solution), and in the sections of β solution after termination of electrical pulses remains almost unchanged. In this case the observed changes during ET, should be more fully explained by structural changes, such as changes in grain size and shape, concentration and distribution of dislocations, coherent scattering regions that in fact is confirmed by the results of X-ray analysis. (Fig. 3). During the behavior analysis of the chemical compounds the nature of changes is much more difficult. The analysis of such chemical compound as Al_5FeSi has shown the constancy of elements relation, both before and after the ET with a sufficiently high accuracy. Before treatment the compound included 60% Al, 16% Si and 24% Fe, and after treatment 60% Al, 17% Si and the same 23% of Fe.

Another chemical compound, such as $Al_{15}(Fe,Mn)_3Si_2$ showed the relation change of the certain elements only. Indeed, if before ET the phase consisted of 52% Al, 12% Si, 18% Fe and 18% Mn, then after the electric pulse treatment, it was depleted by 6% Al and 1.5% Si. The concentrations of Fe and Mn remained unchanged (18%). Moreover, within the chemical compound $Al_{15}(Fe,Mn)_3Si_2$ in addition about 7% Cu was found. Unexpected results should also include the appearance (after ET) of the new chemical compound Al_2Cu (50% Al, 2% Si and up to 48% Cu).

Taking into account the relatively high sensitivity of aluminum alloys to the presence of iron in their composition that reduces the plastic characteristics supply the reduction of the negative influence of Fe is an important technological problem. This effect is caused by the formation in the system $Al-Si-Fe$ of brittle eutectic in the form of the plates (Al_5FeSi – mark 5, Fig. 7 *b*, or more complex compositions: $Al_{15}(Fe,Mn)_3Si_2$ – marks 1, 4, Fig. 7 *a*). On these plates the crack is quite easy to develop. In practice, one reduces the embrittlement effect by the change of casting technology, using the injection casting and chill casting, or changing the chemical composition of the alloy [8]. Indeed, the harmful iron influence can be reduced by the manganese or chromium introduction [9, 10]. On the basis of data of the work [12], the complexity of these phases results in the change of their morphology: the form of plate is replaced by the skeletal form. In this case, the eutectic components location at the grain boundaries of the alloy matrix results in the deviation from the strict plate form. As a result, a decrease of the embrittlement effect is observed. And even higher level of plastic characteristics is observed for globular structures. In this case, the plasticity increase can reach the level of 3%.

The results indicate quite significant influence of electrical pulse treatment on both the morphology of alloy structural components and the relation of chemical elements involved in the formation of certain phases. Indeed, if after the welding (in the heat affected zone) the alloy had the majority of the signs of the cast condition with characteristic plate forms of the eutectic components (Fig. 6), the use of ET has led to the quite significant qualitative changes in the internal structure. The globular structures formation (Fig. 7) indicates a high degree of ET influence on the development of structural change processes. In some cases the above mentioned treatment can even compete with the thermal technologies. On this basis, the effect of gradient microhardness reduction (gradient of internal stresses) in the heat-affected zone during the welded joint formation is actually quite clearly explained by structural changes.

Originality and Practical Value

The observed silumin structural changes and the microhardness change in the heat-affected zone of the welded joint after ET related to them are causeed by not only the change of the structural components morphology, but also by the redistribution of chemical elements that form the compounds themselves. In case of stabiility of the chemical element relation in the alloy phase components, the effect of gradient microhardness lowering should be less significant.

In practice, the negative embrittlement effect of products made according to casting techgnologies except the injection casting and quite complex selection of the alloy chemical composition can be efficiently reduced during the electric pulse treatment of alloy.

Conclusions

1. After the electric pulse treatment of the welded joint, the silumin hardness increase is accompanied by the decrease in the number of crystal structure defects and coarsening of coherent scattering regions. The observed behavior of these relations corresponds to the development of softening processes in metallic materials.
2. As a result of silumin ET the change of phase composition, form and dispersion of the structural components was found out.
3. The development of the redistribution processes of chemical elements during the electric pulse treatment is accompanied by the morphology changes and the structural components distribution, the appearance of additional chemical compounds.

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І. О. ВАКУЛЕНКО[1*], Ю. Л. НАДЕЖДІН[1], В. А. СОКІРКО[2], І. П. ВОЛЧОК[3],
О. А. МІТЯЄВ[3]

[1*]Каф. «Технологія матеріалів», Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, 49010, Дніпропетровськ, Україна, тел. +38 (056) 373 15 56, ел. пошта dnyzt_texmat@ukr.net
[2]ТОВ «DS», вул. Велика Морська, 63, 54001, Миколаїв, Україна, тел. +38 (0512) 41 52 07, ел. пошта ds@mksat.net
[3]Каф. «Технологія матеріалів», Запорізький національний технічний університет, вул. Жуковського, 64, 69063, Запоріжжя, Україна, тел. +38 (061) 769 82 71, ел. пошта volchok@zntu.edu.ua
[3]Каф. «Технологія матеріалів», Запорізький національний технічний університет, вул. Жуковського, 64, 69063, Запоріжжя, Україна, тел. +38 (061) 769 82 71, ел. пошта mityaev@ zntu.edu.ua

ЕЛЕКТРИЧНА ІМПУЛЬСНА ОБРОБКА ЗВАРНОГО З’ЄДНАННЯ АЛЮМІНІЄВОГО СПЛАВУ

Мета. Пояснення ефекту перерозподілу залишкових напружень після електричної імпульсної обробки електродугового зварного шва алюмінієвого сплаву. **Методика.** Матеріалом для дослідження був сплав на основі алюмінію типу АК8М3. Пластини товщиною 10 мм отримували в результаті механічної обробки злитків після кристалізації сплаву. Після підготовки кромок з’єднувані елементи були зварені в стик за технологією напіватоматичного аргонно-дугового зварювання електродом діаметром 3 мм зі сплаву АК-5. Структуру металу зварного з’єднання досліджували під світловим мікроскопом при збільшенні 200 і за допомогою растрового скануючого електронного мікроскопа «JSM – 6360 LA». Як характеристика міцності сплаву була використана твердість за Роквеллом (HRF). Твердість фазових складових (мікротвердість) вимірювали, використовуючи прилад ПМТ-3, при навантаженнях на індентор 5 і 10 г. Параметри тонкої кристалічної будови сплаву (густина дислокацій, викривлення другого роду кристалічних ґрат і розмір областей когерентного розсіювання) визначали із застосуванням методик рентгеноструктурного аналізу. Елек-

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тричну імпульсну обробку (ЕО) здійснювали на спеціальному устаткуванні в умовах підприємства «DS», за двома режимами – А і В. **Результати.** На основі виконаних досліджень був підтверджений раніше отриманий ефект перерозподілу мікротвердості в області зварного з’єднання після ЕО. У результаті використання зазначеної обробки було визначено не тільки зменшення градієнта мікротвердості, а й одночасний зміцнювальний ефект у певних зонах термічного впливу поблизу шва. Під час досліджень хімічного складу фазових складових було визначено, що структурні зміни сплаву в результаті ЕО в першу чергу зумовлені перерозподілом хімічних елементів, що утворюють самі з’єднання. За характером впливу зазначену обробку можна порівняти з термічними технологіями пом’якшення металевих матеріалів**. Наукова новизна**. Структурні зміни силуміну, що спостерігаються, і пов’язана з ними зміна мікротвердості в області зварного з’єднання поблизу шва після ЕО зумовлені не тільки зміною морфології структурних складових, а й перерозподілом хімічних елементів. У разі незмінності співвідношення хімічних елементів у фазових складових сплаву ефект зниження градієнта мікротвердості повинен бути значно меншим. **Практична значимість**. На практиці негативний ефект окрихнення виробів, виготовлених за ливарними технологіями, окрім лиття під тиском і досить складного підбору хімічного складу сплаву, може бути ефективно зниженим під час обробки сплаву електричними імпульсами.

Ключові слова: твердість; фаза; хімічна сполука; силумін; зварний шов

И. А. ВАКУЛЕНКО[1*], Ю. Л. НАДЕЖДИН[1], В. А. СОКИРКО[2], И. П. ВОЛЧОК[3], А. А. МИТЯЕВ[3]

[1*]Каф. «Технология материалов», Днепропетровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, 49010, Днепропетровск, Украина, тел. +38 (056) 373 15 56, эл. почта dnyzt_texmat@ukr.net
[2]ООО «DS», ул. Большая Морская, 63, 54001, Николаев, Украина, тел. +38 (0512) 41 52 07, эл. почта ds@mksat.net
[3]Каф. «Технология материалов», Запорожский национальный технический университет, ул. Жуковского, 64, 69063, Запорожье, Украина, тел. +38 (061) 769 82 71, эл. почта volchok@zntu.edu.ua
[3]Каф. «Технология материалов», Запорожский национальный технический университет, ул. Жуковского, 64, 69063, Запорожье, Украина, тел. +38 (061) 769 82 71, эл. почта mityaev@ zntu.edu.ua

ЭЛЕКТРИЧЕСКАЯ ИМПУЛЬСНАЯ ОБРАБОТКА СВАРОЧНОГО СОЕДИНЕНИЯ АЛЮМИНИЕВОГО СПЛАВА

Цель. Объяснение эффекта перераспределения остаточных напряжений после электрической импульсной обработки электродугового сварочного шва алюминиевого сплава. **Методика.** Материалом для исследования служил сплав на основе алюминия типа АК8М3. Пластины толщиной 10 мм получали в результате механической обработки слитков после кристаллизации сплава. После подготовки кромок соединяемые элементы были сварены в стык по технологии полуатоматической аргонно-дуговой сварки електродом диаметром 3 мм из сплава АК-5. Структуру металла сварочного соединения исследовали под световым микроскопом при увеличении 200 и при помощи растрового сканирующего электронного микроскопа «JSM-6360 LA». В качестве прочностной характеристики сплава использовалась твердость по Роквеллу (HRF). Измерения твердости фазовых составляющих (микротвердость) осуществляли с применением прибора ПМТ-3 при нагрузках на индентор 5 и 10 г. Параметры тонкокристаллического строения металла сплава (плотность дислокаций, искажения второго рода кристаллической решетки и размер областей когерентного рассеивания) определяли с использованием методик рентгеноструктурного анализа. Электрическую импульсную обработку (ЭО) осуществляли на специальном оборудовании в условиях предприятия «DS» по двум режимам – А и В. **Результаты.** На основании проведенных исследований был подтвержден ранее полученный эффект перераспределения микротвердости в области сварочного соединения после ЭО. В результате использования указанной обработки обнаруживается не только уменьшение градиента микротвердости, но и одновременный упрочняющий эффект в определенных околошовных зонах термического влияния. При изучении химического состава фазовых составляющих было обнаружено, что наблюдаемые структурные изменения сплава в результате ЭО в первую очередь обусловлены перераспределением химических элементов, образующих сами соединения. По характеру влияния указанная обработка может быть сравнима с термическими технологиями разупрочнения металлических материалов. **Научная новизна.** Наблюдаемые структурные изменения силумина и связанное с ними изменение микротвердости в околошовной области сварочного соединения после ЭО обусловлены не только сменой морфологии структурных составляющих, но и перераспределением химических элементов, образующих сами соединения. В случае неизменности соотношения химических элементов в фазовых составляющих сплава эффект снижения градиента микротвердости должен быть менее значительным. **Практическая значимость.** На практике негативный эффект охрупчивания изделий, изготовленных по литейным технологиям, кроме литья под давлением и достаточно сложного подбора химического состава сплава, может быть эффективно снижен при обработке сплава электрическими импульсами.

Ключевые слова: твердость; фаза; химическое соединение; силумин; сварочный шов

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