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Comparative analysis of the chemical composition and mechanical properties of duralumin welded joint produced by friction stir welding

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Abstract: Friction stir welding is an advanced method of joining various metals and alloys in the aircraft and mechanical engineering industries. This type of welding is used to join materials that are difficult to weld or not weldable by conventional methods. The high-strength D16 aluminum alloy is difficult to weld by fusion, which is associated with the formation of a dendritic structure in the fusion zone leading to a decrease in the mechanical strength of the joint. In the work, the microstructure and microhardness of a welded seam of the D16 aluminum alloy produced by friction stir welding was studied. Using scanning electron microscopy and optical metallography, the authors identified the presence of three zones: the weld core, the thermomechanical impact zone, and the heat effected zone. In the central part of the welded joint (in the core), a laminated onion ring structure was discovered. A change in the chemical composition of the aluminum solid solution was identified in different areas of the weld zones, as well as the presence of a concentration gradient within each zone. In the upper part of the welded seam, the solid solution is silicon-enriched and depleted in copper. Due to the solid solution depletion in alloying elements, the aluminum content in the solid solution in the zone of the welded joint is higher compared to the initial state. The microhardness values in different areas of the welded joint correlate with changes in the chemical composition. In the welded joint zone, a significant decrease in microhardness was found compared to the initial state, and a change in microhardness associated with the chemical composition gradient within each zone was also observed.

Keywords: friction stir welding; duralumin; aluminum; laminated structure; onion ring structure.

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INTRODUCTION

Friction stir welding (FSW) is a relatively new method for producing permanent joints of materials, proposed in 1991 by the Welding Institute of Great Britain. Friction stir welding is a solid-state joining process, when no volumetric melting of the base material occurs [1; 2]. Research in recent years has shown that FSW is an effective way to produce high-quality connections of structures of various sizes and shapes, including sheets, three-dimensional profiles, and pipes. It is used to restore worn parts and to weld cracks and casting defects. Compared to conventional fusion welding methods, during FSW, there are no signs of a cast structure in the joint zone, the joined parts have little deformation and residual stress, there is no need to carry out operations to clean the surface from oxides before the welding process, and there are no defects resulting from melting and hardening.

To join parts, frictional heating and plastic deformation are used, as a rule, at temperatures below the absolute melting point of the alloys being joined. This is achieved through the interaction of a rotating tool consisting of a pin and a shoulder (pin) with the faying surfaces into which it is immersed until the shoulder contacts with the upper surface of the blanks, and then moves along the interface between the blanks (Fig. 1). Due to wide technological capabilities for producing permanent joints of parts or assemblies, FSW can be used as an alternative to rivet joints, electric arc welding, electron beam and laser welding, as well as for welding dissimilar materials.

A large number of works deals with the issue of selecting friction stir welding modes. Usually, the speed of tool rotation and movement [3; 4], pin shape [5], and sample preheating [6] are varied. However, no detailed study of changes in the chemical composition and mechanical properties in different welded joint areas, including its upper and lower parts, has been found in the literature.

High-strength D16 grade duralumin for aviation purposes, as a rule, is difficult to be welded by fusion, since, when using this type of welding, a dendritic structure is formed in the fusion zone leading to a sharp decrease in mechanical strength [7]. According to [8–10], during FSW, the metal

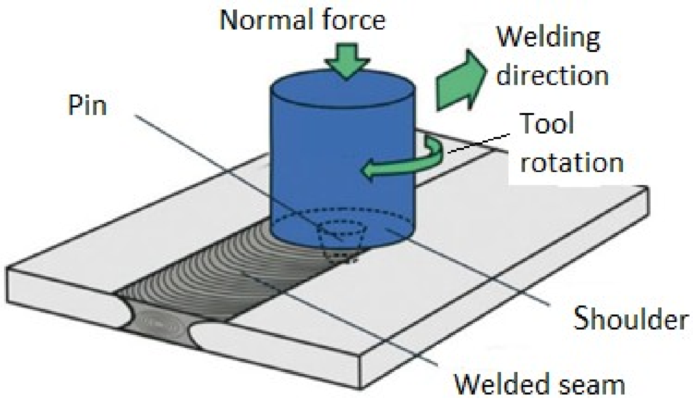

Fig. 1. *The diagram of the process of friction stir welding*
Рис. 1. *Схема процесса сварки трением с перемешиванием*

does not reach the melting temperature, so FSW can produce high-quality, defect-free welds when properly selecting the welding parameters for high-strength D16 alloys, as well as avoiding severe heating and cooling cycles that occur during fusion welding.

When using FSW, it is important to study the mechanisms and identify the physical patterns of the formation of the structural state, and factors leading to the formation of structural heterogeneities and discontinuities in the weld. Identification of such patterns will allow selecting the optimal FSW characteristics and making a forecast of the welded product operational properties. A change in the chemical composition of the alloy solid solution has a great influence on the mechanical properties. For dispersion-hardening aluminium alloys, except for the main strengthening intermetallic phases, the presence of secondary phases is possible. Under certain thermomechanical interactions, they can significantly deplete the solid solution, and due to coagulation of particles, reduce the general strength properties of the material [11; 12].

The purpose of this study is to analyse the distribution of the chemical composition and mechanical properties in the weld zone of a D16 alloy butt joint produced by friction stir welding.

METHODS

The authors used for the study the D16 GOST 4784-2019 (foreign analogues AA2024, $AlCuMg_2$) duralumin plates. A direct butt welded joint was produced by friction stir welding using a test stand. A welding tool made of high-speed R6M5 steel was used, the tool rotation speed range was 400–600 rpm, and the tool movement speed was 320 mm/min. Samples cut using an electrical discharge machine were examined in the transverse and longitudinal sections of the welded joint. Table 1 presents the chemical composition of the original D16 alloy plates and the chemical composition according to GOST 4784-2019.

Structural studies were carried out using a JSM 6490 scanning electron microscope with the Oxford Inca system for energy dispersive and wave microanalysis and a Micromed MET optical microscope, with the ability of imaging in polarized light. Analysis of the solid solution structure, and chemical composition in the weld zone was carried out along the A, B, C lines every 4 mm. The centre of the lower edge of the weld was taken as the first reference point. The area with a zero position corresponded to the original material. The size of the analysed area, which does not include the precipitation of intermetallic phases, was 5×5 µm, the diameter of the probe in a scanning electron microscope was 3 µm. Microhardness was measured using a Metalab-502 device, the load was 0.490 N, the time was 10 s. The microhardness value was determined from five measurements.

RESULTS

Fig. 2 shows an optical photograph of the cross section of the weld of the studied D16 alloy. In the optical image, differing in colour: the core zone, the thermomechanical impact zone, and the heat effected

Table 1. *Chemical composition of the D16 alloy, wt. %*
Таблица 1. *Химический состав сплава Д16, мас. %*

Composition	Al	Mg	Cu	Fe	Si	Mn	Zn	Ti	Cr
According to GOST 4784-2019	Base	1.2–1.8	3.8–4.9	<0.5	<0.5	0.3–0.9	<0.25	<0.15	<0.1
Original sample	93.34	1.31	4.23	0.3	0.16	0.54	0.08	0.04	0.004

zone. In the central part of the welded joint (in the core), the laminated onion ring structure is observed (Fig. 2, lines A, B). In our case, line C passes through the thermomechanical impact zone, and line D passes through the heat effected zone (Fig. 2).

Fig. 3 presents the results of measuring the chemical composition of the solid solution in various areas of the weld (along the selected lines) obtained using a scanning microscope. In the thermomechanical impact zone (region 7) in the lower part of the joint, an increase in silicon content (Fig. 3 a) and a decrease in aluminium (Fig. 3 b) are observed. Compared to the initial state, the aluminium content in the solid solution of the weld zone is generally higher (Fig. 3 b).

It is possible to note, as well, an increase in the copper content in the solid solution in the welded joint core, and in the thermomechanical impact zone compared to the initial state. At the same time, in the centre of the core (areas 2 and 3), the copper content decreases, and the silicon content increases. The main strengthening phase of the D16 alloy is the *S*-phase. However, we did not detect macroprecipitates of this phase.

Fig. 4 shows the results of measuring microhardness in various areas of the welded joint. In the zone of the welded joint, microhardness significantly decreases, compared to the initial state (point 0) (Fig. 4). Point 9 is the boundary between the core, and the thermomechanical zone, where a sharp increase in microhardness is observed.

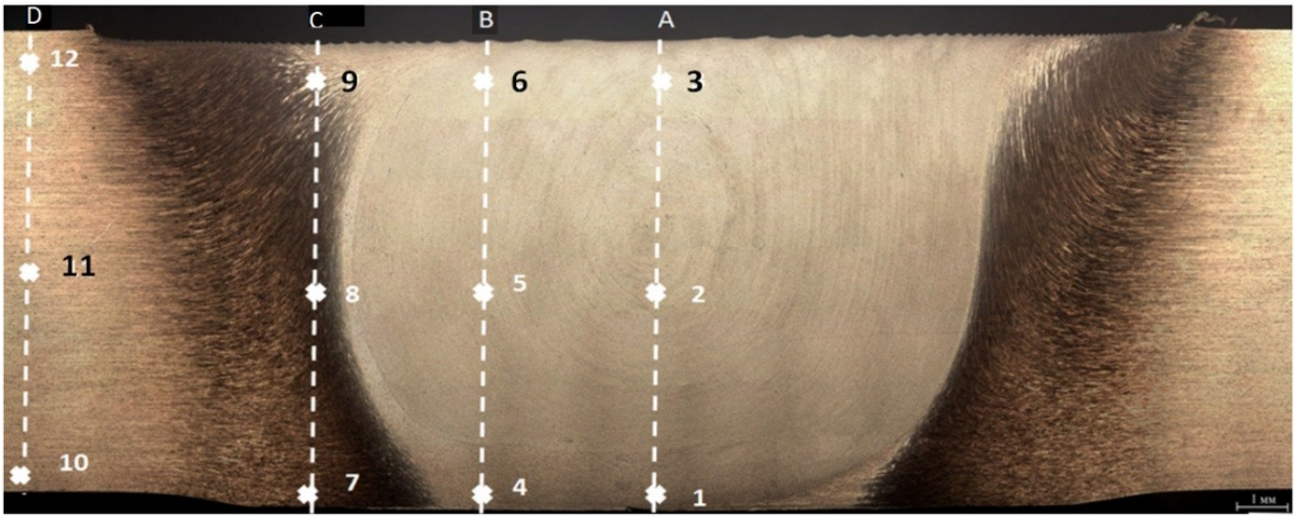

Fig. 2. *Microstructure of the welded joint cross section indicating areas of study*
Рис. 2. *Микроструктура поперечного сечения сварного соединения с указанием областей исследования*

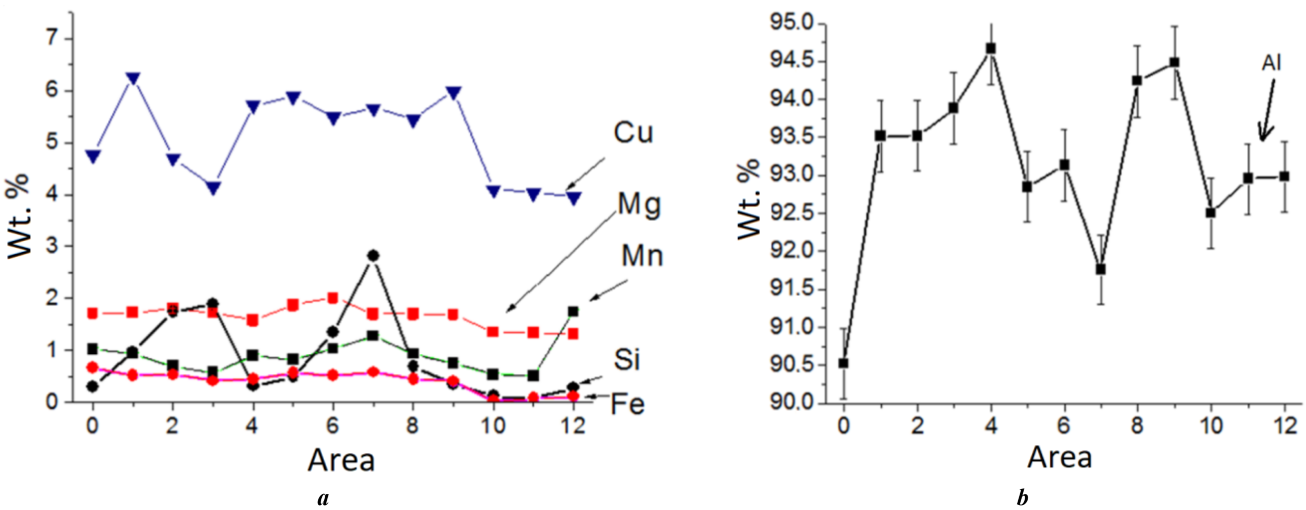

Fig. 3. *Distribution of alloying elements (**a**) and aluminium (**b**) in the welded joint area*
Рис. 3. *Распределение легирующих элементов (**a**) и алюминия (**b**) в зоне сварного соединения*

DISCUSSION

According to the literature, three zones can be distinguished in a welded joint: the weld core, the thermomechanical impact zone, and the heat effected zone [12]. These three zones are clearly visible in Fig. 2. According to [12], the laminated onion ring structure is formed when the tool rotates in the plasticised metal, which was observed in the centre of the welded joint.

Only using transmission electron microscopy, nanosised precipitations of the strengthening *S*-phase in the AA2024 alloy (Russian analogue is D16) after friction stir welding were detected in local areas of the welded joint, with increased microhardness [13]. This explains the absence of the *S*-phase in our case during optical and scanning electron microscopy studies.

The change in the chemical composition of the solid solution in the welded joint can be explained by the precipitation of secondary phases enriched in copper and silicon. In [14; 15], in the AA2024 alloy of the Al–Cu–Mg system (Russian analogue is D16) secondary intermetallic microcrystalline phases containing silicon and copper were discovered: Al_2Cu, AlCuFeMnSi, Mg_2Si, Al_7Cu_2Fe, $Al_{12}(Fe,Mn)_3Si$, $Al_{20}Mg_3Cu_2$. Both in the thermomechanical impact zone, and in the core of the welded joint, according to the literature, an increase in temperature up to 500 °C is possible [16–18], which can cause precipitation of secondary intermetallic phases leading to a change in the solid solution content.

An increase in temperature accelerates the diffusion of chemical elements in aluminium alloys. Table 2 presents the coefficients of diffusion of chemical elements in aluminium obtained in [16], from which it can be seen that silicon is the most mobile element at a temperature of 500 °C. Aluminium self-diffusion coefficient is close to the copper diffusion coefficient. Manganese is the "slowest" element. Considering the fact that the diffusion front moves at the speed of the "slowest" element, at this temperature, a slow growth of phases containing manganese can be expected. Therefore, the appearance of such phases can be caused both by thermal impact and by deformation.

Changes in the microstructure in various zones influence greatly the mechanical properties of the joint after welding [19]. A change in microhardness in the welded joint zone similar to that found in our work was observed in [20; 21]. In the work [3], it was found that the aluminium alloy microhardness depends on the rotation frequency of the pin and the speed of its movement. Comparing the results obtained in our work with the data of [3], one can talk of different rates of stirring the material in different areas of the welded joint. According to the literature, phase ageing in aluminium alloys leads to both strengthening, and softening of the material. Softening is associated with coagulation of particles of secondary strengthening phases [12]. A significant decrease in microhardness in the lower part of the thermomechanical impact zone (area 8 in Fig. 2),

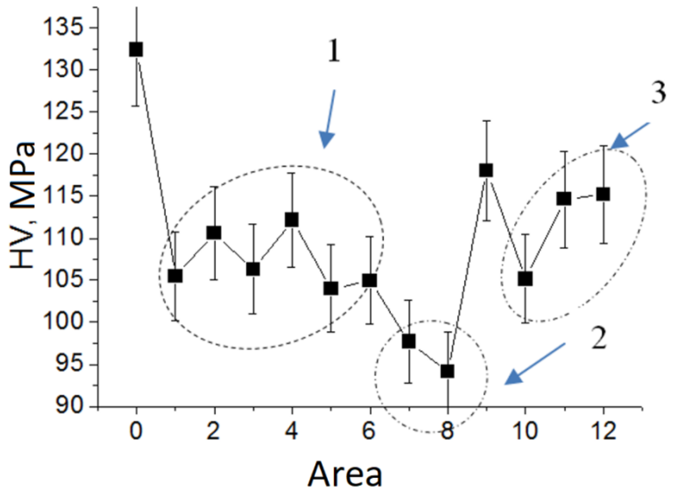

Fig. 4. *The results of measuring microhardness in the welded joint area:*
1 – core; 2 – thermomechanical impact zone; 3 – heat effected zone
Рис. 4. *Результаты измерения микротвердости в зоне сварного соединения:*
1 – ядро; 2 – зона термомеханического воздействия; 3 – зона термического воздействия

Table 2. *Coefficients of diffusion of elements in aluminium at 500 °C, m^2/s [Repr. from 16, p. 10]*
Таблица 2. *Коэффициенты диффузии элементов в алюминии при 500 °C, $м^2/с$ [Привод. по 16, с. 10]*

Al	Mg	Cu	Fe	Si	Mn
4.3×10^{-14}	9.9×10^{-14}	4.0×10^{-14}	8.9×10^{-16}	13×10^{-13}	7.4×10^{-18}

may be associated exactly with the enlargement of the precipitated secondary phases enriched in copper and silicon. In this case, the increase in microhardness in the upper part of the thermomechanical impact zone (area 9 in Fig. 2) may be associated with the precipitation of small secondary phases. These assumptions are consistent with the results of studies of the chemical composition of the solid solution in these areas (Fig. 3).

CONCLUSIONS

1. A change in aluminium content and a redistribution of alloying elements (Si, Cu) in the solid solution in various areas of the weld zones were detected. Compared to the initial state, the aluminium content in the zone of the welded joint in the solid solution is higher. An increase in the copper content in the solid solution in the welded joint core and in the thermomechanical impact zone was detected, compared to the initial state. At the same time, the copper content decreases and the silicon content increases in the core centre, which is probably associated with the precipitation of secondary phases such as $Al_{12}(Fe,Mn)_3Si$ or AlCuFeMnSi, enriched in copper and silicon, under the influence of deformation.

2. In the welded joint zone, a significant decrease in microhardness compared to the initial state is observed, which may be caused by the coagulation of particles of secondary strengthening phases enriched in copper and silicon.

3. Within each zone of the weld, a gradient in the solid solution chemical composition is observed, which also correlates with a change in microhardness.

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Сравнительный анализ химического состава и механических свойств различных участков сварного соединения дюралюмина, полученного сваркой трением с перемешиванием

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Аннотация: Сварка трением с перемешиванием в авиастроении и машиностроении является передовым способом соединения различных металлов и сплавов, плохо свариваемых или несвариваемых обычными способами. Активно используемый в авиастроении высокопрочный алюминиевый сплав Д16 плохо поддается сварке плавлением, что связано с образованием дендритной структуры в зоне сплавления, приводящей к снижению механической прочности соединения. В работе исследована микроструктура и микротвердость сварного шва алюминиевого сплава Д16, полученного методом сварки трением с перемешиванием. Методами сканирующей электронной микроскопии и оптической металлографии выявлено наличие трех зон: ядра шва, зоны термомеханического воздействия и зоны термического воздействия. В центральной части сварного соединения (в ядре) обнаружена слоистая структура «луковичных колец». Обнаружено изменение химического состава твердого раствора алюминия в различных областях зон сварного шва, а также присутствие концентрационного градиента внутри каждой зоны. В верхней части сварного шва наблюдается обогащение твердого раствора кремнием и обеднение медью. Благодаря обеднению твердого раствора легирующими элементами содержание алюминия в зоне сварного соединения в твердом растворе выше по сравнению с исходным состоянием. Значения микротвердости в различных областях сварного соединения коррелируют с изменением химического состава. В зоне сварного соединения обнаружено значительное снижение микротвердости по сравнению с исходным состоянием, а также наблюдается изменение микротвердости, связанное с градиентом химического состава внутри каждой зоны.

Ключевые слова: сварка трением с перемешиванием; дюралюмин; алюминий; слоистая структура; структура «луковичных колец».

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