Dependence of the microstructure and microhardness of the AA2024-O alloy on the thermal and mechanical action on the weld during friction stir welding

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Abstract. The microstructure of the weld from the AA2024 alloy is highly dependent on the heat input in the weld, and therefore it is necessary to understand the relationship between these characteristics to improve the mechanical properties of the weld. The effect of the microstructure in various zones of the weld on its microhardness has been ascertained. The structure of various weld zones was studied depending on the heat input to the weld. Therefore, the experiment was performed at different values of the external axial force and the values of the constant speed of the rotation of the tool and welding. The dependence of the microhardness and microstructure of the weld zones on the temperature gradient in both normal and traverse directions has been established.

1. Introduction
Alloys with low melting temperature (e.g. Al-Cu-Mg) are not weldable by melting processes, but they are easily welded by friction stir welding (FSW). The main sources of heat during FSW are the work of the sliding friction force and the rolling friction torque generated between the tool and the welded surfaces, as well as the strain energy of the work pieces. During FSW, the unit thermal power is determined by the dependence:

\[ q = q_1 + q_2 = \frac{4M_{r.f.} \cdot \omega}{\pi D^2} + \frac{4F_{s.f.} \cdot V_W}{\pi D^2} \] (1)

where \( q \) is the total specific heat capacity, \( q_1 \) is the specific thermal power under rotational motion of the tool about its axis, \( q_2 \) – is the specific thermal capacity when the tool is moving along the interface of the work piece, \( M_{r.f.} \) is the rolling friction torque, N\( \cdot \)m; \( \omega \) is the tool rotation speed, s\(^{-1}\); \( D \) is the tool diameter, m, \( F_{s.f.} \) is the sliding friction force, N; \( V_W \) is the linear speed of movement of the tool or welding speed, m/s\(^{-1}\) [1, 2].

Intensive transfer of metal in combination with high thermal conductivity of aluminum leads to a rapid temperature equalization on the surface of welded parts. Therefore, the tool moving along the connection line at the initial stage of weld formation constantly draws a colder metal into the plastic strain. When welding proceeds at high traverse speeds, as well as a slow tool rotation speed, the material receives less work per unit length of the weld, i.e. fewer tool rotations per millimetre. Under such conditions, the plasticised material may not reach a sufficiently high temperature. Aluminium alloys can withstand only a certain shear strain rate, which is dependent on temperature. Insufficient
axial force on the tool and, as a consequence, insufficient mechanical action and frictional warming of the weld do not contribute to achieving an evenly welded joint [3].

At the present time, there are a large number of papers devoted to the analysis of the microstructure evolution of the weld and the width of the heat affected zone (HAZ) depending on the tool rotation speed ($w$), welding speed ($V_w$) and forces ($P$) occurring during FSW [4]. The purpose of this work is to study the influence of the external axial force acting on the tool on the change in microstructure and microhardness in various zones of the aluminum alloy AA2024-O, welded at values of constant speed of rotation of the tool and welding.

2. Material and Experimental Test Procedures
Sheets of the AA2024-O alloy (12 mm thick) with technological plating were investigated. The chemical composition is given in table 1. The welding process was carried out by friction stir welding equipment I-ISTIR PDS-5. The tool made from MP159 material (Cr-Ni-Co alloy) consisted of a shoulder with a diameter of 25.4 mm, along with a threaded pin with a diameter of 12.7 mm and a length of 12 mm. Sheets were welded with constant values of $w=300$ rpm, $V_w=300$ mm/min, and different heat and mechanical input due to the change in force on the tool: $P=23$ kN (low), 26 kN (medium), and 29 kN (high). The maximum depth of the tool plunge into the workpiece and the angular deviation from the vertical axis were maintained at 11.3 mm and 1.50, respectively. The welding parameters were kept the same for all samples in order to obtain comparable conditions.

Table 1. The chemical composition of the AA2024-O alloy, wt%

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | others | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|--------|-----|
| AA2024-O | 0.5 | 0.5 | 3.8-4.9 | 0.3-0.9 | 1.2-1.8 | 0.10 | 0.2 | 0.15 | 0.20 | Bal. |

Rectangular samples of 50x25x12 mm in size were cut from the welding zone using a Discotom-50 (Struers) machine. One part of the samples was cross-sectioned in the normal direction of the welded sheets (figure 1), the second part was slitted in the transverse direction of the welded sheets (figure 2). Then each sample was cut into three portions to study the microstructure and defects in the normal and transverse directions. EBSD analysis was accomplished by an EDX 55 Ultra energy-analyzer of an ULTRA 55 electron microscope using OIM software. A macrograph of the weld cross-section is shown in figure 1. Points 1-9 are the locations of the EBSD characterizations. For the SEM and EBSD analysis, polished surfaces were etched with Keller’s reagent (100 ml HCl, 100 ml HNO$_3$, 25 ml HF, and 100 ml distilled water). The etched specimens were rinsed in ethanol, and then blow dried and observed by the ULTRA 55. Vickers hardness (HV$_{0.2}$) was measured in the transverse direction on surfaces 1, 2, 3 of the top, centre and bottom portions of each sample.
DuraScan 70 microhardness tester (EMCO-TEST) with a microanalysis system was used to measure microhardness in 0.3 mm increments. The microhardness of the three parallel tracks was averaged to refine the measurements and obtain a single microhardness map for the top, centre, and bottom portions of each sample (figure 2). The distance between the tracks was 9 mm.

The weld zones temperature was determined by the procedure of Ref. [5].

\[
T = T_m \cdot k \left( \frac{\omega^2}{V \cdot 10^4} \right)^{\alpha} = 502 \cdot 0.7 \left( \frac{300^2}{300 \cdot 10^4} \right)^{0.05} = 295^0C,
\]

where: \( T \) is the FSW temperature (°C), \( T_m \) is the melting temperature of the sheet material (°C); \( \alpha \) is reported to range from 0.04 to 0.06; \( k \) is constant, it is between 0.65 to 0.75; \( \omega \) is the tool rotation speed; \( V \) is the welding speed; 502 °C is the temperature of AA2024 solidus.

3. Results and discussion

Figure 3 presents IPX maps of tested areas, which are marked in figure 1 in the transverse direction and in the normal direction along the weld central axis (WCA). Microhardness profiles are presented in figure 4. Depending on the welding thermal cycle and vicinity to the nugget, several microstructural changes occurred within all zones. The nugget and the TMAZ (thermo-mechanically affected zone) on the advancing and retreating sides differ in size and shape of the grains. The upper part of the nugget, located under the tool shoulder, experiences a higher plastic strain and temperature than other weld points. The maximum microhardness values of the given part decrease along the WCA in the normal direction depending on the heat input: high – from 140-145 HV to 105 HV, medium - from 135 HV to 100 HV, and low - from 130 HV to 95 HV (figure 4). The microhardness decrease towards the bottom occurs due to the deterioration of the mixing degree of the material and a decrease in temperature and intensity of the plastic strain development during the FSW.

The side of the nugget on the advancing side with respect to the transverse direction, regardless of the heat input, is characterized by a fine-grained structure free of defects such as discontinuities, cracking, porosity etc (figure 3 a, b). This means that on the advancing side, the degree of plastic strain is higher. The grain diameter is about 1-3 µm. In addition to fine and equiaxial grains with predominantly (111) and (101) crystal orientations, the nugget contains fine rounded black particles of the strengthening phase \( \text{Al}_{2}\text{CuMg} \approx 300 \text{ nm} \) typical for the AA2024 aluminum alloy (figure 3 e, f). A significant displacement of the microhardness map at the weld bottom relative to its axis on the advancing side occurs due to an insufficient intensity of plastic strain, if the heat input is minimal. The wide nugget transition zone (NTZ) with alternating layers of elongated grains and fine crystallites between the TMAZ and the nugget is formed on the advancing side (figure 3 a, b). High microhardness is retained in this zone (figure 4). The fine-grained structure in the nugget on the advancing side is observed only with high heat input (figure 3 c). From figure 3 c, d it is clear that there is no smooth narrow interface between the nugget, NTZ, and TMAZ on the retreating side.

Figure 3. IPFX maps for regions examined from different locations indicated in figure 1 along WCA and in transverse direction: 3 (a,b); 6 (c,d); 7 (e); 8 (f). Heat input: high (a,c,e,f), low (b,d). Advancing side (a,b), retreating side (c,d). The color triangle shows poles aligned with the sheet normal direction.
The decrease in microhardness to 90 V on the retreating side is due to coagulation and misorientation of the grains as well as to the appearance of discontinuities and an increase in the dissolution of particles (figure 3 b, d; figure 4). Only a small amount of fine crystallites among the coarse grains appears in the NTZ on the retreating side (figure 3 d). This means that on the retreating side, the flow is greater, and the peak temperature is higher, because the metal in front of the rotating tool shifts to this side.

In both TMAZ, the grains are bent upwards indicating an additional displacement relative to the parent sheets, caused by the advancing pin somewhat similar to the flow around it (figure 3 a,b,d). It has been found that the grains within the TMAZ contain a high density of subgrains and dislocations (figure 3 b,d).

Significant coarsening of grains was observed in the TMAZ due to high-temperature exposure during FSW. The microhardness of the TMAZ decreases sharply to the microhardness of the base material (60 HV), corresponding to the AA2024-O alloy (figure 4).

4. Conclusions

The advancing side, irrespective of the thermal and mechanical effects, is characterized by finely dispersed and equiaxed grains with a diameter of about 1-3 µm, in which the crystallographic orientations (111) and (101) predominate. The maximum microhardness (140-145 HV) of this weld part is explained by the presence in the grains of fine rounded black particles of the Al2CuMg strengthening phase (~ 300 nm), typical for the aluminum alloy AA2024. The displacement of microhardness maps at the weld bottom relative to its axis on the advancing side is due to an insufficient intensity of plastic strain if the mechanical and thermal impact is minimal. Increasing the temperature on the retreating side leads to coarsening and misorientation of the grains, dissolution of the strengthening phase of Al2CuMg and, as a consequence, decreasing the weld microhardness on this side to 105 HV. This means that the degree of plastic strain is higher on the advancing side, and the peak temperature is higher on the retreating side. The reason for the weld microhardness decrease in the TMAZ to the base material of 60 HV is a significant coarsening of the grain due to the high temperature impact during the FSW process. The optimal welding parameters are: w = 300 rpm, V = 300 mm / min and P = 29 kN.

References
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