Effect of friction stir processing on the strengthening of the 2024 aluminum alloy

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Abstract. A study of the influence of the tool pin length on the strengthening of the 2024 aluminum alloy under friction stir processing (FSP) was carried out. According to the results of real and model experiments, it was found that for a workpiece with a thickness of 3.0 mm, the necessary and sufficient pin length is 2.0 mm, because in this case, mixing throughout the thickness of the workpiece is provided. It was found that during the FSP of the 2024 alloy, solid-solutional hardening of the processed area occurred due to the release of particles of intermetallic phases.

1. Introduction
Friction Stir Processing (FSP) modifies the surface of the metals and provides considerable changes in microstructure and other properties [1-3]. FSP induces the processes of thermomechanical activation in selective areas on the surface and changes properties of specimens of metal. FSP is based on the same concepts as Friction Stir Welding. The only difference is that FSP doesn't join the metals together, the workpiece is initially monolithic. As a result of FSP, the metallic material attains a fine grained structure and increased mechanical properties [3, 4].

The result of the FSP depends, in particular, on the design of the tool, which affects heat generation, material flow, forces, and other output characteristics [5-7].

This work is aimed to determine the dependence of the microstructure and hardness of the 2024 aluminum alloy on the immersion depth of the tool into the workpiece, as well as to simulate the temperature distribution in the processed area depending on the pin length.

2. Experiment Techniques
The industrial deformable heat-strengthened 2024 aluminum alloy in the form of sheets with a thickness of 3 mm was selected as the material for study. The model of a tool used to conduct FSP is shown in figure 1. The tool with an extendable pin with a left-hand thread and the shoulder with two spiral ledges was used. The pin length ranged from 1.6 mm to 2.2 mm. Treatment at a tool moving speed of \( v = 3 \) cm/min, a rotation frequency of 1000 rpm, and an axial force of \( P = 2 \) kN was carried out.

Microstructure formed at the processed zone during the FSP was tested using a light microscope and scanning electron microscopy (SEM). Measurements were performed on specimens with a width of 22 and a thickness of 3 mm cut from the friction stir processed zone.
Microhardness was determined using Vickers digital microhardness tester MVDM 8 “AFFRY” at a load of 0.5 N and a duration of 10 seconds. Measurements at the intersection points of imaginary lines in the specimen scheme shown in figure 2 were carried out, with an error not exceeding 5%.

![Microhardness measurement setup](image1)

**Figure 1.** Model of the tool for FSP. By the arrow, the pin rotation direction is shown.

![Specimen scheme](image2)

**Figure 2.** The scheme of the specimen with points in which microhardness was measured.

The modeling of the heat dissipation processes in the specimens during FSP was performed using the DEFORM-3D software application package. The numbers of elements of the workpiece and the tool were equal to 60000 and 32000, respectively. The behavior of the workpiece material was described using the Johnson-Cook model included in the standard DEFORM-3D library. To reduce the calculation error, the thermophysical properties of the 2024 alloy were taken to be constant and equal to the values acquired by the material at a temperature of 600 °C. When processing the workpiece, the conditions of heat exchange with the environment were set. The tool was taken as a rigid body. AISI-D2 tool steel was chosen as the material for the tool. We examined the pins in the form of a cylinder with different lengths: 1.6, 1.8, 2.0, 2.2 mm. The diameter of the lower part of the pin in all cases was equal to 2 mm. The friction coefficient was taken equal to 0.5.

3. Results and discussions
The results of microhardness measurements are shown in figure 3. The processing of the material by stirring led to a significant increase in microhardness in the center of the processed zone and on the advancing side from 53±4 HV to 110±8 HV.

![Microhardness measurement results](image3)

![Microhardness measurement results](image4)
Figure 3. Microhardness of specimens treated with a pin of different lengths: 1.6 mm (a), 1.8 mm (b), 2.0 mm (c), 2.2 mm (d). The horizontal line shows the initial microhardness.

It can be seen that with a pin length of 1.6 mm, a change in microhardness occurs only in the upper part of the specimen, to a depth of 1.6 mm. With an increase in the pin length to 1.8 mm, changes in microhardness are observed in deeper layers of the specimen (up to 2.1 mm) (figure 3b). When processing with a 2.0 mm pin, strengthening occurs in all layers of the specimen (figure 3c). It should be noted a fairly strong (two-fold) hardening of the advancing side, while the highest values of microhardness practically do not depend on the length of the pin. A further increase to 2.2 mm, similarly increases the microhardness of all layers of the specimen and provides a more uniform hardening of both sides of the processed zone.

The study of the microstructure of the processed zone by light microscopy method made it possible to see pronounced bands on the etched surface, the so-called “onion rings”, as well as the zone of thermomechanical impact (figure 4). The presence of the so-called onion-ring structure was also reported in other FSP studies [8-10]. As the stirring pin rotates rapidly during FSP, the cylindrical sheets of processed metal are extruded in each rotation.

Figure 4. Composed macroscopic image of specimens treated with a pin of different lengths: 1.6 mm (a), 1.8 mm (b), 2.0 mm (c), 2.2 mm (d).
Scanning electron microscopy studies show the following. In the initial state particles of S(Al$_2$CuMg) and θ(Al$_2$Cu) excess phases exist in equilibrium with the $\alpha$-solid solution of copper and magnesium in aluminum matrix [11]. After FSP, particles of two excess phases with different morphologies are observed. Large complex (skeletal) particles are mainly located on the advancing side. Smaller compact particles are present throughout the zone of thermomechanical impact. A study of the chemical composition of particles, performed by energy dispersive analysis, allows us to attribute them to the strengthening Al$_{15}$Si$_2$(CuFeMn)$_3$ and θ(Al$_2$Cu) phases, respectively.

The formation and coagulation of the stable θ(Al$_2$Cu) phase, as well as the appearance of the Al$_{15}$Si$_2$(CuFeMn)$_3$ phase, are usually observed after heating to 300–400 °C [12]. Apparently, during the FSP, the material is heated to such temperatures and the cooling time of the sample to room temperature is quite long. This time was sufficient for particles that were formed and the hardness of the processed area of the 2024 alloy increased.

![Image](image_url)

**Figure 5.** The arrangement of the controlled points in the specimen (a) and the cooling dependence for different pin lengths: 1.6 mm (b), 1.8 mm (c), 2.0 mm (d), 2.2 mm (e).

These results are partially confirmed by the data of the temperature distribution in the zone of thermomechanical effects obtained by finite element modeling. In Figure 5 the location of the
temperature monitored points, as well as the graphs of the specimens cooling after the end of the FSP, carried out by a tool with a different pin length.

It can be seen that the temperature for all pin lengths, at least below the pin, reaches or exceeds 300 °C, which is consistent with the observation of the $\theta(\text{Al}_2\text{Cu})$ phase and the $\text{Al}_{15}\text{Si}_2(\text{CuFeMn})_3$ phase. Also, processing a workpiece with a 2.0 mm long pin provides more uniform heating in the entire zone of thermomechanical action (Fig. 5d). Thus, based on the results of computer simulation, it can be concluded that for the most noticeable modification of properties in the zone of thermomechanical action, the required and sufficient length of the pin is 2.0 mm.

**Conclusions**

1. According to the results of real and model experiments, it was found that for specimens from the 2024 aluminum alloy with a thickness of 3.0 mm, a necessary and sufficient pin length at friction stir processing is 2.0 mm, because mixing throughout the thickness is observed in this case.
2. During friction processing with stirring of a 2024 aluminum alloy at the treated area solid-solutional hardening occurs with the formation of intermetallic $\text{Al}_{15}\text{Si}_2(\text{CuFeMn})_3$ and $\text{Al}_2\text{Cu}$ phases.

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**References**

[1] Liu H J, Shen J J, Huang Y X, Kuang L Y, Liu C and Li C 2009 *Sci. Technol. Weld. Join.* **14** 577.

[2] Sarvghad Moghaddam M, Parvizi R, Haddad-Sabzevar M and Davoodi A 2011 *Mater. Des.* **32** 2749.

[3] Xue P, Xie G M, Xiao B L, Ma Z Y, Geng L 2010 *Metall. Mat. Trans. A* **41** 2010.

[4] Vinothkumar H, Saravanakumar S, Ramesh C, Prakash P, Ragul Vignesh A and Naveen S 2020 *Mater. Today: Proc.* In press.

[5] Elyasi, Derazkola H, Hosseinzadeh M 2016 *J. Eng. Man.* **230** 1234.

[6] Assidi M, Fourment L, Guerdoux S, Nelson T 2010 *Int. J. Mach. Tools Manuf.* **50** 143.

[7] Mc Nelley T R 2015 *Lett. Mater.* **5**(3) 246.

[8] Chai F, Zhang D, Li Y, Zhang W 2013 *Mater. Sci. Eng.* A **568** 40.

[9] Chen Y, Ding H., Li J, Cai Z, Zhao J, Yang W 2016 *Mater. Sci. Eng.* A **650** 281

[10] Chen X, Zhang Y, Cong M 2020 *Vacuum* **175** 1.

[11] Rudskoy A I, Naumov A A, Chernikov E V 2014 *Tsvetnye Metally* **4** 36 (in Russian).

[12] Mondolfo L F1979 *Structure and Properties of Aluminum Alloys* (Moscow: Metallurgy) p 640 (in Russian).