Computer simulation of friction stir processing of plate from 2024 aluminum alloy

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Abstract. In the present work, three-dimensional finite element modeling of the friction stir processing of a 3-mm-thick 2024 aluminum alloy plates using DEFORM-3D software product has been carried out. The optimal pin length was determined based on the calculation of the distribution of effective deformation, temperature, and displacement of material points. Numerical modeling was done on pins in the form of a cylinder with a diameter of 2 mm and a length of l = 1.6, 1.8, 2.0, and 2.2 mm. Friction stir processing was carried out at a traversing rate of 2 mm/s, a tool rotation rate of 1000 rpm, and an axial force of 20 kN. The material behavior of the sheet was described using the Johnson-Cook model included in the standard DEFORM-3D library. The results showed that the most preferable under the considered processing conditions is a pin with a length of 2.0 mm because it allows one to obtain the widest and most symmetrical regions of intense heating and deformation.

1. Introduction
Aluminum alloys are widely used in many industries - automotive, shipbuilding, aerospace, etc. However, these alloys are poorly exposed to traditional welding methods due to hydrogen dissolution and oxidation, so structural parts are often assembled using permanent riveted joints. This method has its drawbacks such as waviness of the material, radial cracks around the holes, additional weight, etc. One of the methods of joining structural parts, which allows avoiding the listed disadvantages, is friction stir welding (FSW) [1].

According to this technology, a rotating tool consisting of a shoulder and a pin moves along the contact surface of two butted and rigidly pressed workpieces. The shoulder is in a firm contact with the surface of the workpieces and the pin is immersed into the material. The rotation and movement of the tool along the contact surfaces increase the temperature and softens the metal in the adjacent areas, which facilitates mixing of the material.

In the course of such welding, the material undergoes very large and high strain rate deformation, in which the true strain can reach the values of about 50, and the strain rate about 100 s$^{-1}$. A side effect of the welding process is the formation of a fine-grained microstructure in the weld zone. Thus, this method can also be used to obtain metal semifinished products with a modified microstructure. This technology is more commonly referred to as friction stir processing (FSP).
In the FSP process, frictional mixing of the metal being processed in the solid-phase state is done by a rotating tool, which is similar to the tool in the FSW. The difference between the FSW and FSP is that in the latter case the parts are not joined but a monolithic workpiece is processed.

The geometry of the tool pin, in particular its length, plays an important role in both the FSW and FSP, since affects the heat generation, material flow, forces, and other process output characteristics [2]. To select the effective parameters of the FSW/FSP process, it is advisable to use computer simulation, which can significantly reduce the cost of manufacturing an expensive special tool [3-5].

In this work, a three-dimensional finite element modelling of the friction stir processing of a sheet of 2024 aluminum alloy using DEFORM-3D software product has been carried out to select the optimal pin length based on calculating the distribution of effective deformation, temperature, and displacement of material points.

2. Computer simulation

Finite element modeling was carried out in order to select the optimal tool pin length in friction stir processing using DEFORM-3D software. To reduce the computation time and avoid the instability of the solution, the 2024 aluminum alloy plates were modeled as a single body 3 mm thick, 40, and 30 mm long and wide, respectively (figure 1).

Friction stir processing was carried out at a traversing rate of 0.5 mm/s, a tool rotation rate of 1000 rpm, and an axial force of 2 kN.

Pins in the form of a cylinder with a diameter of 2 mm and lengths of \( l = 1.6, 1.8, 2.0, \) and \( 2.2 \) mm were considered. A general view of a pin is shown in figure 2.

Figure 1. Schematic of the friction stir processing.

Figure 2. Pin profile.
The behavior of the workpiece material was described using the Johnson-Cook model included in the standard DEFORM-3D library. The following physical constants of the alloy were assumed: density - 2640 kg/m³; thermal conductivity - 122 W/(m²K); heat capacity at constant pressure - 0.922 kJ/(kg×K). During friction stir processing of the workpiece, the condition of heat exchange with the environment was set. The initial temperature of the workpiece, tool, and environment was assigned the value of 20 °C. Convection with a heat transfer coefficient of 11 W/(m²×K) was set on all external surfaces. The tool was taken as a perfectly rigid body since the yield stress of its material is much higher than that of the workpiece. AISI-D2 tool steel was chosen as the material for the tool. The friction coefficient was taken equal to 0.5.

3. Results and discussion

The FSP process is characterized by very high temperature and strain gradients across the thickness of the workpiece, which leads to an inhomogeneity of the microstructure formed in the treatment zone. One way to avoid this kind of inhomogeneity is to use the optimal pin geometry.

Figure 3 shows typical diagrams of the distributions of temperature, effective strain and displacement of material points in the cross-section of the workpiece under processing for different values of the length of the tip. The cross-section runs along a plane perpendicular to the seam through the center of rotation of the tool.

Based on the simulation results, it can be concluded that in the FSP process, nonuniform temperature distribution is formed in the treatment area in the transverse direction of the workpiece (figure 3 a), while the highest temperature value is observed on the advancing side. It should be noted that as the length of the pin increases, the maximum heating temperature of the workpiece also increases. At \( l = 1.8 \) mm, the temperature at the point of contact with the shoulder reaches about 300°C, and the area of its distribution is small. At \( l = 2 \) mm an extensive and fairly uniform region is formed with a temperature in the range of 383-455 °C. At \( l = 2.2 \) mm, the area heated to \( T = 383-455 \) °C decreases and shifts towards the advancing side closer to the joint root.

The results of study show that the workpiece area being worked out becomes more extended as the pin length increases, while the area of high values of effective strain (43.8-50 mm/mm) increases as the value of \( l \) increases and shifts to the root of the joint (figure 3 b). The widest and most symmetrical area of effective strain at the level of 43.8-50 mm/mm is observed at \( l = 2 \) mm.

According to [6-7], the highest quality treatment of the workpiece material occurs at temperatures of about 0.8 \( T_m \), since heating to such temperatures provides high plasticity and good mixing of the material. For 2024 aluminum alloy the value of 0.8 \( T_m \) depends on variations in composition and is 385-425 °C.

Analysis of the simulation results allows us to conclude that the material in the lower region of the workpiece is practically not subject to mixing, and the shorter the pin length, the larger is this area. The areas in the middle and upper parts of the workpiece are mainly mixed, the length of the areas being worked increases with the length of the pin. From the diagrams of the distribution of the displacement of material points (figure 3 c), it follows that the workpiece material from the advancing side is less involved in mixing, remaining mainly in its area, while the material from the retreating side actively moves to the advancing side and mixes with the material from this area. This pattern is observed for all pin lengths.
Figure 3. Distribution of temperature (a), effective strain (b), and displacement of material points (c) depending on the length of the pin in the cross-section of the workpiece during friction stir processing. It was found that a 2.0-mm-length pin is preferable for friction stir processing under these conditions from all the considered pin lengths.
Conclusions
Thus, by means of computer simulation, it has been established that of all the considered pins, a pin with a length of 2.0 mm is preferable for FSP / FSW under these conditions. When processing with such a pin, wide and symmetrical areas are formed with a temperature of about 0.8 $T_m$ favorable for the formation of a high-quality weld and the largest homogeneous area of high effective strain values.

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