The influence of friction stir welding (FSW) parameters on thermo-mechanical behaviour of the material during welding is analysed. An aluminium alloy is considered (Al 2024 T351), and different rotating speed and welding speed are applied. Finite element model consists of the plate (Al alloy), backing plate and welding tool, and it is formed and solved in software package Simulia Abaqus. The influence of the welding conditions on material behaviour is taken into account by application of the Johnson-Cook material model. The rotation of the tool affects the results: if increased, it contributes to an increase of friction-generated heat intensity. The other component of the generated heat, the plastic deformation of the material, is negligibly changed. When the welding speed is increased, the intensity of friction-generated heat decreases, while the heat generation due to plastic deforming increases. Combined, these two effects cause small change of the total heat generation. For the same welded joint length, the plate welded by lower speed will be heated more intensively. The changes of the heat generation influence both the temperature field and reaction force, which are also considered.

Key words: friction stir welding, welding speed, welding tool rotation speed, finite element analysis, heat generation

1. Introduction

Application of FSW is gaining more attention in different industries, like shipbuilding, aerospace, railway/road vehicle production, etc. In addition to aluminium, which is the most often subjected to FSW (e.g. [1-14]), other metallic materials can be joined as well: magnesium [15], titanium [16], copper [17] or steel [18]. Also, dissimilar metals can be joined - different Al alloys, but also completely different materials; e.g. study [19] deals with joining aluminium alloy 2024-T3 and titanium alloy TiAl6V4. Particle reinforced composites, such as aluminium matrix composites, have also been joined by FSW, as shown in [20].
The stages of the friction stir welding are shown schematically in Fig. 1, [21]. The process is initiated by plunging of the tool into the workpieces (tool rotation and vertical translation), while the welding stage starts after the thermo-mechanical conditions have been established. A review of equipment used for joining by FSW is shown in [22], and includes conventional machines, dedicated FSW machines, as well as industrial robots. Besides the machine itself, welding tools (which are non-consumable) have a pronounced influence; this refers to their shape/geometry [6] or state - whether the tool is worn or not [23].

![Fig. 1. Sketch of FSW welding (a) rotating tool before contact with plates; (b) tool pin in contact with plates; (c) shoulder of the tool in contact with plates - generation of heat and widening of heating zone; (d) relative movement of rotating tool and plates - production of welded joint [21]](image)

The FSW inevitably includes heat generation by two processes: the first one is the friction between the tool and the welded material, while the second one is significant plastic deforming of the material. The welding quality depends on this heat generation, which is why the initial stage, plunge stage, has a key role. The reason for this is the fact that the thermo-mechanical conditions required for subsequent welding are established during the plunge stage. Also, it should be mentioned that the most extreme conditions are reached in this stage - the highest temperatures and vertical (reaction) forces. Therefore, special attention has been devoted to the tool plunge stage in [8, 24]. Also, previous works of the authors include determination of influence of material properties on the plunge and linear welding stage [8, 25], analysis of the velocity fields in the material around the tool [26], comparison of numerically predicted temperature and force with the experimental findings [27] and experimental examination of joints formed by application of different welding parameters [11].

Here, the topic is the analysis of welding parameters (welding speed and tool rotation speed) on heat generation, temperature, force and plastic strains during the linear welding stage, by application of numerical analysis, i.e. finite element modelling. Also, some special cases with deliberately inadequate welding parameters are considered, and the weld defects (pores) are predicted in such models. Finite element simulations are generally very often used in literature to simulate the FSW process, e.g., [3, 7, 8, 13, 23, 28], with a comprehensive review given in [29]. However, there are some recent studies showing the application of other mathematical tools, such as cellular automaton model [15], or wavelet analysis [5]. Anyhow, simulation of the joint formation is not the only area of application of numerical simulations using FEM - they are also applied in more general approach in analysis of FSW joints and other welded joints, [30-32].

2. Material properties

The base metal considered in this work is aluminium alloy EN AW 2024 T351. The material properties of this alloy were used in previous authors’ works dealing with different aspects of friction stir welding, such as [7, 25, 26], and are repeated in Tab. 1.
### Tab. 1: Properties of aluminium alloy 2024 T351 [7, 33, 34]

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus of elasticity $E$ [GPa]</td>
<td>73.1</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$ [-]</td>
<td>0.33</td>
</tr>
<tr>
<td>0.2% Yield strength $R_{0.2}$ [MPa]</td>
<td>324</td>
</tr>
<tr>
<td>Tensile strength $R_m$ [MPa]</td>
<td>469</td>
</tr>
<tr>
<td>Elongation at fracture $A_5$ [%]</td>
<td>20</td>
</tr>
<tr>
<td>Thermal conductivity $k$ [Wm$^{-1}$ °C$^{-1}$]</td>
<td>121</td>
</tr>
<tr>
<td>Coefficient of thermal expansion $\alpha$ [°C$^{-1}$]</td>
<td>$24.7 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>Density $\rho$ [kg m$^{-3}$]</td>
<td>2770</td>
</tr>
<tr>
<td>Specific heat capacity $c$ [J kg$^{-1}$ °C$^{-1}$]</td>
<td>875</td>
</tr>
</tbody>
</table>

### 3. Finite element modelling

Numerical model which is used for analysis of heat generation during welding is shown in Fig. 2; software package Simulia Abaqus is applied [35]. As shown in the figure, it consists of three parts: the plate being welded, the welding tool with cylindrical pin and the backing plate. The model is described in [7, 25-27], while only some details and Fig. 2 are given here. Hexahedral finite elements C3D8RT are used, i.e. coupled thermo-mechanical elements with linear interpolation of displacement/temperature and reduced integration order, [35]. As for the backing plate and the welding tool, they are considered as rigid bodies. Tool pin has cylindrical shape with diameter 6 mm, while tool shoulder diameter is 18 mm. Lagrange-Euler technique for mesh adjustment is applied. This includes the following boundary conditions: the material ‘flows’ into and out of the model at the appropriate boundary surfaces.

Fig. 2 shows the positions of the two points used for tracking the change of temperature during the welding. The coordinates of these points are: T1 (17.5,0,3) and T2 (12,0,3).

**Fig. 2. Finite element model; modified from [7]**
### 3.1. Johnson-Cook elastic–plastic model

Dependence of the current yield stress $\sigma_y$ [MPa] on temperature $T$ [$^\circ$C], plastic strain $\varepsilon_p$ [-] and plastic strain rate $\dot{\varepsilon}_p$ [s$^{-1}$] is defined by Johnson-Cook material law [36]:

$$
\sigma_y = \left[ A + B(\varepsilon_p)^n \right] \left[ 1 + C \frac{(\varepsilon_p)}{\dot{\varepsilon}_p} \right] \left( 1 - \left( \frac{T-T_{room}}{T_{melt}-T_{room}} \right)^m \right) \tag{1}
$$

where $T_{room} = 20$ $^\circ$C is the ambient temperature, while $A$, $B$, $C$, $n$, $T_{melt}$, $T_{room}$ and $m$ are Johnson–Cook material/test constants. For the considered alloy (Al 2024 T351), the yield stress $A = 265$ MPa, the strain factor $B = 426$ MPa, the strain exponent $n = 0.34$, the temperature exponent $m = 1$ and the strain rate factor $C = 0.015$, [37]. Solidus temperature $T_{melt}$ is 502 $^\circ$C.

### 3.2. Heat transfer model

Energy balance related to heat transfer analysis is described by the Fourier law; the same approach (including the parameters in the rest of this subsection) was used in previous authors’ works for this alloy or Al 2024 T3, e.g. [8,25-27], also together with Johnson-Cook model for mechanical behaviour of the material. Here, we will mention the applied expressions for heat generation, because it is one of the main concerns in this work. Equation (2) defines the total heat flux $\dot{q}$ [J/s] as the sum of the following components: (i) the heat flux due to the shear plastic strain in the zone around the tool shoulder and tip $\dot{q}_p$ [J/s] and (ii) the heat flux due to the friction which happens during shearing between the tool and the plate $\dot{q}_f$ [J/s]:

$$
\dot{q} = \dot{q}_p + \dot{q}_f = \eta \tau \dot{\varepsilon}_p + \mu p \dot{\gamma} \tag{2}
$$

The first component of the heat flux depends on: factor of conversion of mechanical to thermal energy $\eta$ [-] (applied value: 0.9, in accordance with [4]), shear stress $\tau$ [MPa] and plastic strain; as shown previously, plastic strain also exists in the model material for mechanical behaviour, Eq. (1). The heat flux due to the friction, i.e. the second component of the heat flux, is calculated from the friction coefficient $\mu$ [-], contact pressure $p$ [MPa] and slip rate $\dot{\gamma}$ [mm/s].

As mentioned previously, the backing plate is modelled as the rigid body; also, it has no thermal degrees of freedom. Therefore, heat transfer which occurs through this plate is simulated by a high value of the heat transfer coefficient defined at the bottom surface of the welding plate: $h = 3000$ Wm$^{-2}$ $^\circ$C$^{-1}$, [38]. As for the surfaces of the welding plate which are in contact with the surrounding, i.e. air at room temperature, the value of this coefficient is 10 Wm$^{-2}$ $^\circ$C$^{-1}$ [4, 25, 27]. For definition of the contact between the material and the tool, it is necessary to define the value of friction coefficient: $\mu = 0.3$.

### 4. Results and discussion

#### 4.1. Welding speed effect

Figure 3 shows the change of the heat generation intensity during the welding. In this diagram, both components of heat generation are shown (from friction and from significant plastic deformation), as well as total amount. All these quantities are presented for two different welding speeds, in order to assess the influence of this welding parameter.
Fig. 3. Heat generated during friction stir welding - welding speed effect

From Fig. 3, it can be seen that the welding speed increase, with a constant tool rotation speed, causes decrease of friction heat generation and increase of deformation-generated component. However, total change is rather small. Actually, higher welding speeds cause the tool to interact with less-heated (insufficiently heated) material more quickly. Then the material will show an increased resistance to deformation and therefore a larger amount of heat is generated due to plastic deforming. Since the working temperature is reached near the tool tip, the influence of friction is less pronounced and friction-generated heat amount is decreased.

Figure 4 shows the temperatures in T1 and T2 during the welding process. The welding speed does not have a pronounced influence, neither in the area close to the tool tip (T2), nor further from it (T1). This can be regarded as a consequence of the previous result - the speed does not have a significant influence on the total generated heat when near-optimal welding parameters are applied.

Fig. 4. Temperature during the FSW - welding speed effect
The temperature fields in Fig. 5 are shown for two welding speeds, but for this comparison the weld length obtained by these speeds is the same. Of course, this means that more time is needed to achieve this length if the welding speed is lower. For the tool with 120 mm/min translation speed, 7 seconds was needed to reach this state, while 12 seconds was needed for the tool translation speed 60 mm/min. In both cases, tool plunge stage had the same duration - two seconds. For the same path, the plate welded at lower speed is more intensively heated outside the welding zone. This difference can also be seen in Fig. 4, if temperature at the position T1 is considered.

As a consequence of higher resistance to tool movement through the material, higher welding speeds cause higher force value in vertical direction. The diagram showing this influence during the welding process is given in Fig. 6.
4.2. Tool rotation speed effect

If we now apply different tool rotation speeds, maintaining the welding speed unchanged, it is determined that the rotation speed increase leads to an increase of friction-generated heat intensity. The intensity of the other component, deformation-generated, is changed negligibly (except in the first 3 seconds), Fig. 7. Actually, the increase of rotation speed increases so-called tool slip rate - this quantity is actually relative velocity (when tool movement is observed relative to the material, i.e. plate), which makes the friction and heat generation by friction more intensive.

![Fig. 7. Heat generated during FSW – tool rotation speed effect](image)

Due to the increase of total heat generation as the tool rotation speed increases, higher temperature values are observed both close to the welding tool and further from it - positions T1 and T2 in Fig. 8. Temperature values in the narrower welding zone, close to the tool pin, do not change after the first few seconds, since they have already reached their maximum.

![Fig. 8. Temperature during FSW – tool rotation speed effect](image)
The distribution of temperature is given in Fig. 9, where cross sections are shown; welding direction is from left to right. Two fields are obtained, for the tool rotation speeds 400 and 447 rpm; welding speed was held constant for both cases - 60 mm/min. A small difference between the two fields, caused primarily by change of the friction-generated heat intensity, can be noticed. From Fig. 7, it has been concluded that the other component, deformation-induced heat generation, almost does not change with the increase of the tool rotation speed.

![Fig. 9. Temperature field after 12 seconds of FSW – tool rotation speed effect](image)

Comparison of the reaction forces of the material for different tool rotation speeds are shown in Fig. 10. For the higher rotation speed (447 rpm), the material around the tool tip and shoulder is more intensively heated. Therefore, the reaction force in vertical direction (i.e. material resistance to deformation) will be lower, Fig. 10.

![Fig. 10. Force in vertical direction during FSW – tool rotation speed effect](image)
4.3. Numerical results for parameters set outside the optimal range

When welding parameters are outside the optimal ranges (e.g. too high welding speed in Fig. 11 or too low tool rotation speed in Fig. 12), the generation of heat in the working plate is insufficient. As a consequence, the material is not sufficiently plastic, and the tool does not convey sufficient amount of material from one side of the weld (retreating) to the other (advancing). Such behaviour leads to formation of defects in the shape of voids, marked in Figs. 11-14 by arrows, in the regions with low material velocity.

![Fig. 11. Void in the weld root - advancing side - n=400rpm, v=240mm/min](image)

![Fig. 12. Void in the weld root - advancing side - n=200rpm, v=60mm/min](image)
In the numerical models with the temperature field distribution, it can be observed that the error has occurred. In Fig. 11, it happens during the first second of the welding, while in Fig. 12 the defect emerges in the third second.

The above-mentioned problem can also be viewed by considering the flow rates of the material being welded, Figs. 13 and 14. If the fields of the flow rate are analysed, it is visible that the flow rate in the weld root is minimal on the advancing side, i.e. the material transfer is insufficient. This corresponds with the previous two figures (note: different cross section planes are used in Figs. 13 and 14 when compared with previous two figures, which can be seen by the marked welding direction).

![Fig. 13. Material flow rate field - n=400rpm, v=240mm/min](image1)

![Fig. 14. Material flow rate field - n=200rpm, v=60mm/min](image2)

The results shown in this work capture the influence of the welding parameters on the thermo-mechanical quantities, primarily temperature, plastic strain, force and heat generation. Also, appearance of FSW defects (voids) for inappropriate values of the welding speed and/or tool rotation speed is predicted. In the studies [24,25], the effect of difference of material properties on the similar set of thermo-mechanical quantities is analysed both during linear welding [25] and plunge [24] stage. The alloy 2024 T351 was one of the materials considered in these works, but with a single set of welding parameters, without variations which are applied here.
5. Conclusions

Based on the presented results, one can conclude the following:

- Increase of the welding speed, with a constant tool rotation speed, leads to a decrease of friction-generated heat intensity and increase the generation of plastic deformation-generated heat. Total change of heat generation is negligible.
- Change of the welding speed does not have a significant influence on the temperature change in the vicinity of the welding tool.
- For the same translation path of the tool, the plate welded with lower tool speed is more intensively heated outside of the welding zone.
- As a consequence of the more pronounced resistance to tool movement through the material, higher welding speeds lead to higher forces in vertical direction.
- When the tool rotates with increased speed, for constant welding speed, an increase of the friction-generated heat intensity is observed, while the other component of heat (caused by plastic deformation) is changed negligibly. Therefore, total heat generation intensity is increased.
- The force in vertical direction directly depends on the tool rotation speed; the material resistance is less pronounced for higher tool rotation speed, due to more intensive heating.
- Application of numerical modeling can be successful in assessment of the optimal values of the FSW parameters, thus decreasing the time and costs of the experimental examinations. Also, it can capture the formation of the defects due to inadequate welding parameters.

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Nomenclature

\( n_{rot} \) Rotation speed of the tool [rpm]
\( v \) Welding speed [mm/s]
\( \dot{\varepsilon}_p \) Equivalent plastic strain rate [s\(^{-1}\)]
\( \dot{q} \) Rate of total heat generation [J/s]
\( \dot{q}_f \) Rate of frictional heat generation [J/s]
\( \dot{q}_p \) Rate of heat generation due to plastic deformation [J/s]

Note: only several most important quantities are mentioned here. Most of the quantities are mentioned only once in the text (with defined units) and therefore are not included in the Nomenclature, in accordance with the Instructions for authors.

References


