

# The Influence of Welding Speed on Mechanical Properties of Friction Stir Welded Joints of AA2024 T351 Aluminum Alloy

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The aim of this study is to analyze how the process parameters affect the mechanical properties of butt joints obtained by friction stir welding (FSW). The experimental study was performed by the FSW of sheets having a thickness equal to 6 mm and made of aluminum alloys AA2024 T351, varying the process parameters, namely rotational speed and welding speed. The following welding parameters were used: the rotation speed of the tool did not change and amounted to 750 rpm, and the welding speed was 73, 116, 150 mm / min. The welds were obtained without the presence of errors and with an acceptable flat surface of the compound. Tensile tests were performed orthogonally to the welding direction on specimens having the welding nugget placed in the middle of gage length. Vickers hardness measurement was conducted perpendicular to the welding direction, a cross-section of the weld joint. The hardness profiles were obtained along 3 horizontal and 63 vertical directions. Bend testing was carried out according to EN 910 The bending specimens were tested using face and root side of the joint in tension.

*Key words:* friction stir welding, AA 2024 T351, welding speed, microstructure, tensile strength

## Introduction

ALUMINUM have been widely used in both the automotive and aerospace industries. Both industries are pushing the boundaries of new innovative products, a requirement for greater capacity and, at the same time, a lower weight with robust design. Aluminum alloys are characterized by high load capacity relative to the mass level at a relatively low price. In order to improve aluminum properties, aluminum alloys are used, which are obtained by alloying pure aluminum with the following elements: copper, zinc, magnesium, silicon, manganese and lithium. In aluminum alloys with copper (Series 2), copper is the main alloying element in this family whose mechanical values reach those in structural steel. There are no good anti-corrosive properties and as a rule, they are poorly welded by conventional welding procedures.

Welding is a fabrication process used to join materials, usually metals or thermoplastics, together. During welding, the pieces to be joined (the workpieces) are melted at the joining interface and usually a filler material is added to form a pool of molten material (the weld pool) that solidifies to become a strong joint. Aluminum alloys are the alloys in which aluminum is a predominant metal. For welding of aluminum alloys, fusion welding and solid state welding processes are used. In this work welding of aluminum alloy by MIG, TIG and FSW is done and effect is compared. Thus,

Friction Stir Welding - FSW is a very suitable, and increasingly used, for joining high strength aluminium alloys (2xxx, 6xxx, 7xxx and 8xxx series), currently applied to the aerospace, automotive, marine and military industries.

## Friction stir welding

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys [1,3]. The schematic arrangement for friction stir welding is shown in the Fig.1.

The tool geometry plays an important role in material flow and in turn decides the traverse rate at which FSW can be carried out. A FSW tool has two basic functions: (i) localized heating, and (ii) material flow. In initial stage of the tool plunge, the heating results primarily from the friction between pin and workpiece. The tool is plunged till the shoulder touches the workpiece. The friction between the shoulder and the workpiece results in the biggest component of heating.

For FSW, two parameters are very important: tool rotation rate ( $n$  / rpm) in clockwise or counterclockwise direction and tool traverse speed ( $v$  / mm/min) along the line of joint [2,4,5,8,9,12]. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of

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the pin and finishes welding process. The contribution of intense plastic deformation and high-temperature exposure within the stirred zone during FSW results in recrystallization and development of texture within the stirred zone. Based on the microstructural characterization of grains and precipitates identified are three distinct zones, stirred (nugget) zone (SZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ) [2,3,6,10].

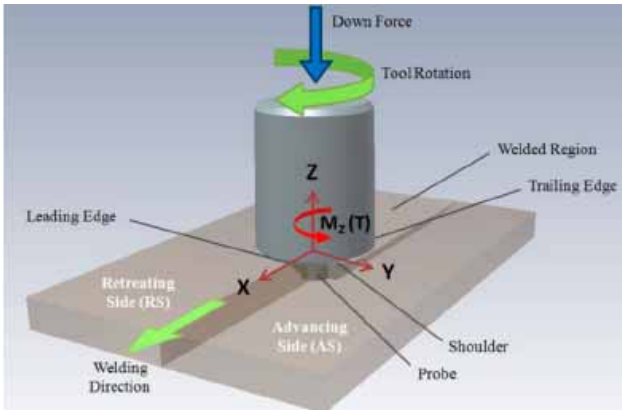


Figure 1. Schematic arrangement for friction stir welding

Defects in the FSW which occur due to an inappropriate combination of welding parameters (mainly translational/welding speed and rotational speed) [13].

In [11] is shown that the microstructure-based simulation is a reasonable tool to study the deformation behavior of FSW materials, which is difficult to be predicted within macroscopic models alone.

The main objective of these studies is to analyze the influence of parameters on the structural and mechanical characteristics of FSW welded joints AA 2024 T351.

### Experimental work

The experiment was aimed to find the influence of input kinematic parameters such as welding speed ( $v$ ) and tool rotation speed ( $n$ ) on metallurgical and mechanical characteristics of welded joints. The base material was aluminum alloy EN AW 2024-T351.

The chemical composition of experimental plates is provided in Tab. 1 and mechanical properties in Tab. 2 [3].

Table 1. Chemical composition of AA 2024 T351

Chemical composition	Cu	Mg	Mn	Fe	Si	Zn	Ti
wt. %	4,70	1,56	0,65	0,17	0,046	0,11	0,032

Table 2. Mechanical properties of AA 2024 T351

Yield strength $R_{eH}$ /MPa	Ultimate tensile strength $R_m$ /Mpa	Elongation $A_5$ / %	Hardness HV
370	481	17.9	137

The dimensions of welded plates were 500 mm×65 mm×6 mm. Both sides of the welding plates are machined on the grinder at a thickness of 6 mm. Before the start of welding, an austenitic plate is placed under the welding plates as a backing plate. A milling machine was used for welding. The weld length was approximately 400 mm. Fig.2 shows a conventional milling machine and Fig.3 a tool used for butt joint FSW.



Figure 2. Conventional Milling Machine for FSW

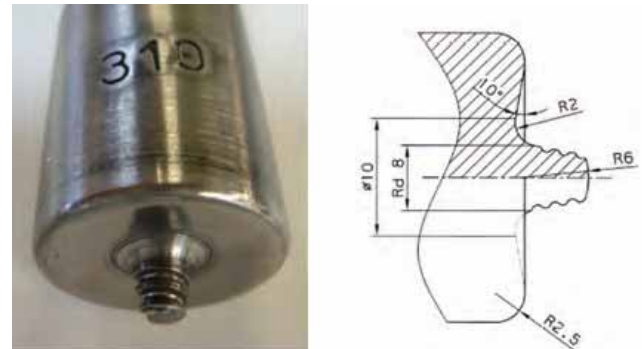


Figure 3. FSW tool

Welding was made in accordance with the planning matrix of the experiment, with variations in tool rotation speed ( $n$ ) and welding speed ( $v$ ), Table 3. Other parameters of welding were maintained constant.

Table 3. Friction stir welding parameters

Sample	Rotation rate $n$ rpm	Welding speed $v$ mm/min	Ratio $n/v$ rev/mm
A - I	750	73	10,27
B - II		116	6,47
C - III		150	5

After the welding process was completed, welds were tested. For that purpose, visual control was performed, on the weld face and root of the seam, as well as the radiographic control of samples. No defects were detected (visually, touch or magnifier).

Appearances of upper and bottom butt FSW joint surface are shown in Fig.4.

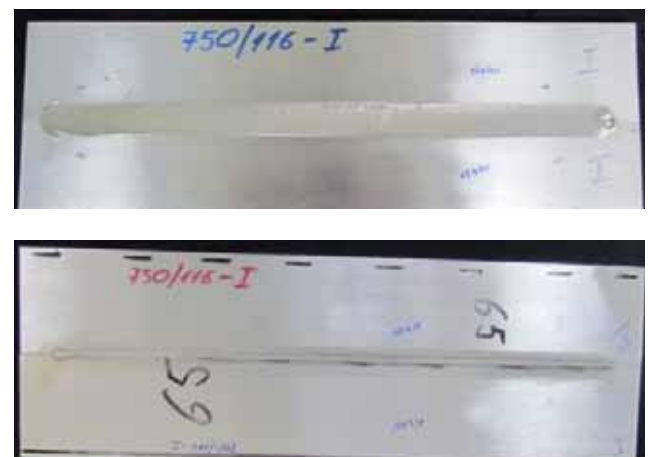


Figure 4. Butt FSW joint

From FSW welded samples were made tensile specimens, specimens for impact test with V-notch in different positions of the FSW joint, specimens for testing of fracture mechanics parameters.

A part of the made of tensile specimens,,impact test specimens and SENB specimens is shown in Fig.5.



Figure 5. Tensile specimens, impact test specimens and SENB specimens

**Results and discussion**

Typical cross section of the welded joints under different parameters is shown in Table 4. The formation of different zones in FSW such as stir zone (SZ), TMAZ, and HAZ are quite evident from the macrostructures. Depending on processing parameter, different shapes of SZ have been observed.

Table 4. Cross sections of butt FSW joints produced at various welding speeds

Welding speed	Macrostructures
73 mm/min	
116 mm/min	
150 mm/min	

All samples were welded at the same rotational speed of the 750 rpm tool. The welding speed was changed to 73, 116 and 150 mm / min. At the lowest welding speed, the energy input was the largest, or vice versa at the highest welding speed, the energy input was the smallest. And in one and the other situation in the lower zone of TMAZ appears microvoid. A significantly higher amount of microvoids is in the highest welding speed situation. With high heat input, that is, at a low welding speed, intensive mixing of the material and movement of the material towards the upper surface occurs.

At high-speed welding, it is contrary to the previous insufficient mixing of the material, which also leads to a greater production of the microvoid in the lower zone TMAZ.

Tensile testing was performed for all tree FSW joints. The tensile testing results in FSW joints are given in Table 5.

Table 5. Tensile testing results

Sample No.	Yield strength MPa	Ultimate tensile strength MPa	Elongation %	Joint efficiency %
A-I	303,7	398,33	2,3	0,83
B-II	336,6	469,09	7,2	0,97
C-III	339,7	373,34	0,65	0,77

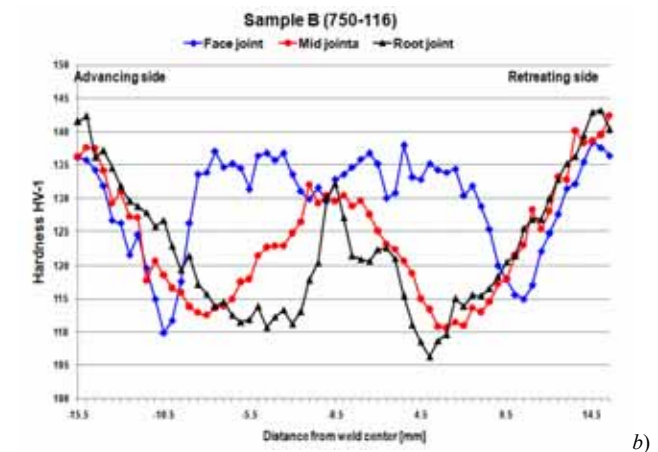
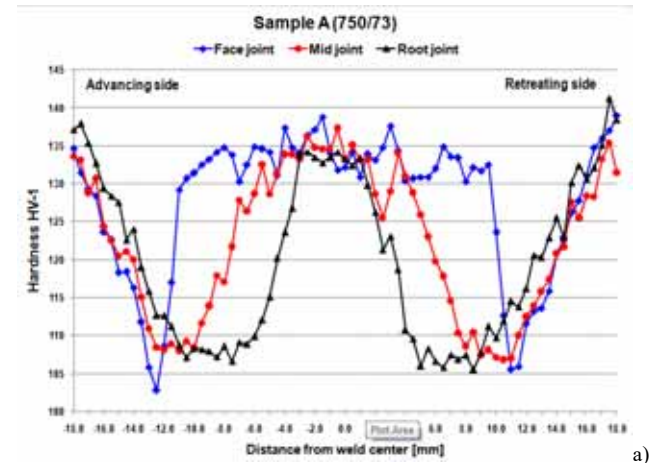
Among the tree FSW parameters studied, i.e., at 750/73, 750/116 and 750/150 rpm/(mm/min), the average tensile yield strength and ultimate tensile strength.

This variation of tensile strength with rotational speeds for a given traverse speed appears to be linked to the energy of the welds. Joint efficiency as high as 97% of base metal could be achieved at 750/116 rpm/(mm/min). The highest ductility of the welded joint is achieved with the welding parameters 750/116 and is 7,2%.

The highest elongation of the welded joint is achieved with the welding parameters 750/116 and is 7%.

Profile of distribution and allocation of microhardness depends on the level of temperature and plastic deformation which is highest under the tool shoulder and around the pin. For the used friction stir welding parameters 750/150, 750/116 and 750/73, it can be concluded that the largest amount of heat is generated in the mixing zone for the welding parameters 750/73.

Fig.6 shows hardness distribution across the welded joint at different applied rotation speed *n* and welding speed *v*.



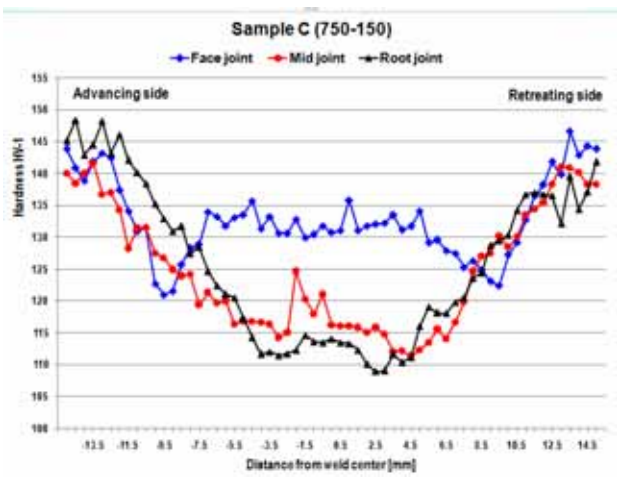


Figure 6. Hardness distribution across the welded joint for welding parameters: a) 750/73, b) 750/116 and c) 750/150 rpm/(mm/min)

Comparing the hardness distribution for welding parameters 750/150, 750/116 and 750/73 (Fig.7), it is noticed that the hardness of sample A-I in the mixing region is the highest and uniform throughout the height.

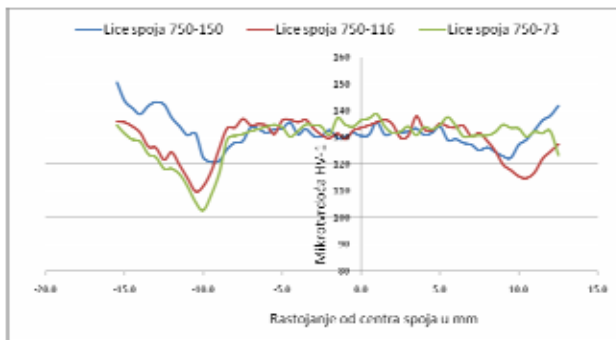


Figure 7. Comparative hardness profile of the welded joint obtained by measuring at a distance of 1 mm from the face of the joint for different welding parameters

Although at the lowest welding speed (the amount of heat input is the highest) the grain size in the mixing zone is the largest, the hardness increases as the welding speed decreases, regardless of the coarser grain in the SZ. This tendency suggests that a significant increase in hardness with decreasing welding speed is not a function of grain size, but a function of the size and distribution of second phase particles and precipitates.



Figure 8. Three-point bending test

The testing of welded joints was also performed on bending, around the face, and around the root (Fig.8).

The welded FSW joint has poor bending characteristics. Comparative results of bending of welded specimens around the face and around the roots are given in Fig.9.

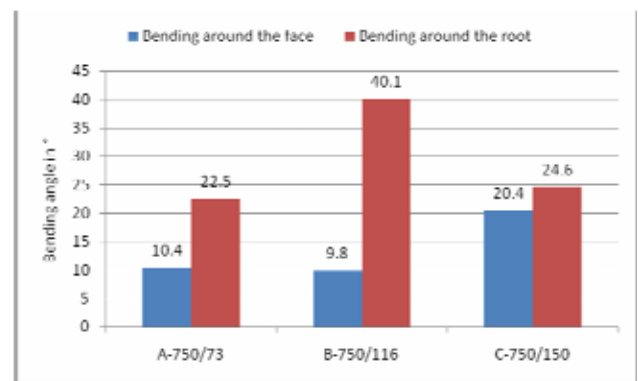


Figure 9. Comparative bending results of welded specimens around the face and around the root

The results of bending tests of welded joints around the root show slightly better deformation abilities than in the case of bending around the face. Comparing welded specimens, specimens B-750/116 have the best bending properties around the roots (Fig.9). The first crack occurred at a bending angle of 40,1°. The first cracks at 22,5° and 24,6°, respectively, appeared on the welded samples A-750/73 and C-750/150 (Fig.9).

### Conclusion

Friction stir welding is a process of joining materials which results in a welded joint whose mechanical and structural properties depend on a large number of mutually conditioned parameters of the welding process. Significant influence on friction welding with mixing have: the configuration of the welded joint, the thickness of the object, the aluminum alloy from which the workpieces are made, the geometry of the tool, the characteristics of the tool, the angle of inclination, the welding speed and the tool speed.

The paper analyzes the influence of welding parameters: welding speed and tool speed on the mechanical properties of butt joints obtained by friction stir welding (FSW). Based on the performed tests, the given results of the experiment and their comparison, the following conclusions can be made:

The minimum amount of heat generated is generated with welding parameters 750/150 rpm/(mm/min), and the maximum amount of heat for welding parameters is 750/73 rpm/(mm/min).

In the area of the nugget and ZTMU, due to simultaneous exposure to elevated temperature and mechanical load, a recrystallized fine-grained structure was obtained, which is especially pronounced in the area of the nugget.

Micro hardness in the mixing zone and the zone of thermomechanical influence decreases with increasing welding speed.

Profile of distribution and allocation of microhardness depends on the level of temperature and plastic deformation which is highest under the tool shoulder and around the pin.

Joint efficiency as high as 97% of base metal could be achieved at 750/116 rpm/(mm/min). The highest elongation of the welded joint is achieved with the welding parameters 750/116 rpm/(mm/min) and is 7.2%.

The properties of FSW welded joints on bending are poor. The largest bend angle to the first cracking phenomenon is for welding parameters 750/116 rpm/(mm/min) and amounts to 40,1°.

Butt-welded joints of aluminum alloy material AA 2024 T351 achieved by friction stir welding, in accordance with poor bending properties, should not be placed in construction zones with high bending loads.

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## Uticaj brzine zavarivanja trenjem sa mešanjem na mehaničke karakteristike zavarenog spoja AA2024 T351 aluminijumske legure

Glavni cilj ovog rada je analiza uticaja parametara zavarivanja trenjem sa mešanjem (FSW) na mehaničke karakteristike zavarenog spoja. Eksperimentalno zavarivanje izvedeno je na limovima debljine 6 mm, izrađenih od legure aluminijuma 2024 T351 variranjem brzine zavarivanja. Broj obrtaja alata je bio konstantan i iznosio je 750 o / min, a brzina zavarivanja je iznosila je 73 mm/min, 116 mm/min i 150 mm/min. Zavareni spojevi su izrađeni bez grešaka. Ispitivanje zavarenog spoja na zatezanje izvedeno je u pravcu upravnom na smer zavarivanja. Merenje tvrdoće je izvedeno u poprečnom preseku zavarenog spoja, duž tri pravca (na udaljenju 1 mm od lica zavarenog spoja, u sredini zavarenog spoja i na udaljenju 1 mm od korena zavarenog spoja). Ispitivanje savijanjem izvršeno je u skladu sa standardom EN 910 sa strane lica i sa strane korena zavarenog spoja.

*Cljučne reči:* zavarivanje trenjem sa mešanjem, AA 2024 T351, brzina zavarivanja, makrostruktura, zatezna čvrstoća.