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QUALITY AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED AA7075-T651 JOINTS USING DIFFERENT TOOLS AND WELDING MODES

Assoc. Prof. Danail Gospodinov, PhD

Department of Materials Science & Technology,
“Angel Kanchev” University of Ruse, Bulgaria
E-mail: dgospodinov@uni-ruse.bg

Assist. Prof. Nikolay Ferdinandov, PhD

Department of Materials Science & Technology,
“Angel Kanchev” University of Ruse, Bulgaria
E-mail: nferdinandov@uni-ruse.bg

Daniela Nenova – PhD Student

Department of Material Science and Technology
“Angel Kanchev” University of Ruse, Bulgaria
E-mail: dnenova@uni-ruse.bg

***Abstract:** Friction stir welding enables the joining of all types of aluminum alloys, including those belonging to the 2xxx and 7xxx series. The joining process is carried out in the solid state using a rotating tool, while the generated heat does not reach the melting temperature of the welded materials. The main factors determining the quality of the welded joint are the temperature and the material flow within the welding zone.*

The aim of this study is to present the feasibility of friction stir welding of the high-strength aluminum alloy AA7075-T651 using two different types of tools, as well as to investigate their influence on the quality and mechanical properties of the resulting joints.

***Keywords:** Friction Stir Welding, Mechanical Properties, Aluminum Alloy AA 7075-T651*

INTRODUCTION

Friction stir welding (FSW) is a relatively recent solid-state joining technique that largely overcomes the difficulties associated with welding high-strength aluminum alloys from the 2xxx and 7xxx series. These alloys are generally considered difficult to weld, and some are even regarded as unweldable when conventional fusion welding processes, such as MIG and TIG welding, are employed.

The quality and mechanical properties of friction stir welded joints are primarily governed by the material flow and the temperature within the welding zone. While the tool geometry and dimensions mainly affect the material mixing behavior, the temperature is predominantly controlled by the processing parameters, including the tool rotational speed, welding speed, axial force, and tool tilt angle (Godhani, P. et al., 2019, Anvari, S. & Mojarad, S., 2018, Gebreamlak, G. et al., 2024, Ferdinandov, N. & Gospodinov, D., 2021, Gospodinov, D. et al., 2021, Mishra, R.S. & Ma, Z.Y., 2005, Gospodinov, D. et al., 2024).

The temperature reached during the process is approximately 70–80% of the melting point of the materials (Ferdinandov, N. & Gospodinov, D., 2021), while the joint efficiency (defined as the ratio between the tensile strength of the base material and that of the welded joint) can, in some cases, reach or even exceed 90% (Gebreamlak, G. et al., 2024).

It has been established that the production of defect-free joints can be achieved only within a specific temperature window, depending on the type of materials being welded (Mishra, R.S. & Ma, Z.Y., 2005, Gospodinov, D. et al., 2024, Silva, A. et al., 2017). At excessively low temperatures (low tool rotational speeds and/or high welding speeds), insufficient material plasticity occurs, whereas at excessively high temperatures (high tool rotational speeds and/or low welding speeds), dissolution of the strengthening precipitates ($MgZn_{12}$) is observed, leading to a drastic reduction in weld strength (Mehri, A. et al., 2023, Rhodes, C. et al., 1997, Gospodinov, D. et al., 2024, Silva, A. et al., 2017) and, consequently, in welding efficiency. In Kosturek, R. et al., (2022), the mechanical properties of friction stir welded AA7075-T651 alloy were investigated at different welding speeds and tool rotational speeds. The obtained results demonstrated defect-free joints with a welding efficiency in the range of 68.5–76.7%. Similar results were reported by Singh, P. and Srivastava, M., (2025) and Sharma, A. et al., (2023), where the welding efficiency reached approximately 70% for the AA7075-T6 alloy.

A number of methods are available for the measurement and control of temperature in this welding process, each characterized by specific advantages and limitations. The combined use of two or more methods can be applied in order to ensure more accurate temperature determination (Gospodinov, D. et al., 2024, Mishra, R.S. & Ma, Z.Y., 2005, Silva, A. et al., 2017). Some of the applied approaches include:

- ✓ Temperature measurement using thermocouples;
- ✓ Detection of microstructural changes occurring in the welding zone;
- ✓ Application of infrared thermographic cameras;
- ✓ Numerical modeling, among others.

According to numerous experimental and simulation studies, the temperatures in the welding zone of aluminum and its alloys range between 400 and 550 °C, depending on both the type and thickness of the alloy, as well as the positioning of the thermocouples (Rhodes, C. et al., 1997, Threadgill, P. L. et al., 2009, Mishra, R.S. & Ma, Z.Y., 2005, Çam, G. & Mistikoglu, S., 2014, Tiwari, S. et al., 2013).

METHODOLOGY

The material investigated in this study was the aluminum alloy AA7075-T651, supplied in the form of plates with dimensions of 160 × 80 × 4 mm. The chemical composition of the alloy was determined by quantometric analysis, while its mechanical properties were characterized using an INSTRON universal testing machine with a maximum load capacity of 150 kN. The chemical composition and mechanical properties are summarized in Tables 1 and 2, respectively.

Table 1. Chemical composition of the AA7075-T651 alloy

Material	Chemical composition, %								
	Si	Zn	Cu	Mn	Mg	Fe	Ti	Cr	Al
AA7075-T651 used in the study	0.55	5.21	1.71	0.09	2.32	0.25	0.04	0.24	89.54

Table 2. Mechanical properties of the AA7075-T651 alloy in the as-received condition

Material	Yield strength, $R_{p0.2}$	Tensile strength, R_m	Elongation, A_{50}
	[MPa]		[%]
AA7075-T651 in the as-received condition	522	600	20

The welding process was carried out on a Heckert FUW 200/I milling machine with a maximum spindle speed of 1200 rpm. The workpieces were secured to the machine table using a

specialized fixture. Two types of tools were utilized in this study: tool P1, which has a concave shoulder and a hexagonal cross-section pin with left-hand threads (Fig.1a), and tool P2, which has a flat shoulder and a hexagonal cross-section pin without threads (Fig.1b).

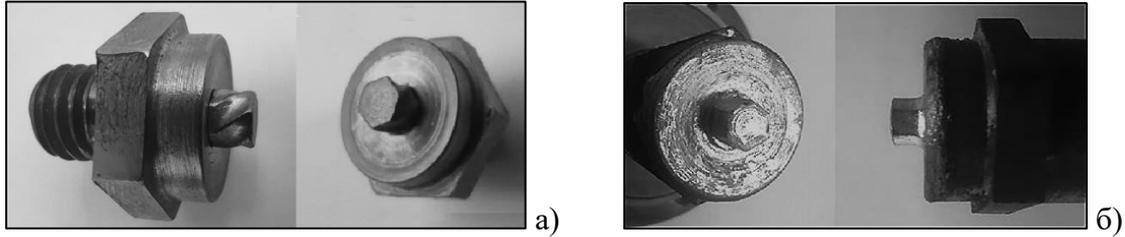


Fig. 1. General view of the tools used in the study: (a) tool P1 with a concave shoulder and a hexagonal cross-section pin with left-hand threads; (b) tool P2 with a flat shoulder and a hexagonal cross-section pin without threads

Table 3. Dimensions and geometry of the tools used

	P1	P2
Shoulder profile	concave	flat
Shoulder diameter	19 mm	19 mm
Pin profile	Hexagonal with left-hand threads	Hexagonal without threads
Pin diameter	7 – 6,1 mm	7 – 6,1 mm
Pin length	5,3 mm	4 mm
Penetration depth	3,9 mm	3,9 mm

The dimensions of the tools are presented in Table 3. The welding parameters were selected based on preliminary literature studies (Pinto, L. et al., 2024, Singh, P. & Srivastava, M., 2025) taking into account the type of aluminum alloy (AA7075-T651) and its thickness, and are presented in Table 4.

Table 4. Welding modes for AA7075-T651 alloy

Welding parameters				
Mode	Rotational speed, [rpm]	Welding speed, [mm/min]	Tool tilt angle, °	Tool type
Mode 1	1100	40	0	P1
Mode 2		60		
Mode 3	1100	40	2	P2
Mode 4		60		
Mode 5		80		
Mode 6		100		
Mode 7		120		

During the welding process, the temperature was measured using three thermocouples mounted on the welded parts. The thermocouples were of type K and were positioned 25 mm from the beginning of the weld, at the midpoint, and 25 mm from the end of the weld, at a distance of 2 mm from the tool shoulder.

After welding, specimens were cut from the produced joints for macrostructural analysis and tensile testing. The tensile tests were conducted in accordance with the requirements of EN ISO 6892-1:2020. An INSTRON testing machine with a maximum load capacity of 150 kN was used for this purpose.

RESULTS

Figure 2 shows the external appearance and unetched macrostructures of the welded joints. It was found that, for both tools and under all applied welding modes, defects of different types, sizes, *Copyrights*© 2025 ISSN 1311-3321 (print), ISSN 2535-1028 (CD-ROM), ISSN 2603-4123 (on-line) 56

and quantities were present. These defects are attributed to an inappropriate tool geometry or to welding parameters that determine the temperature in the welding zone and, consequently, the material flow.

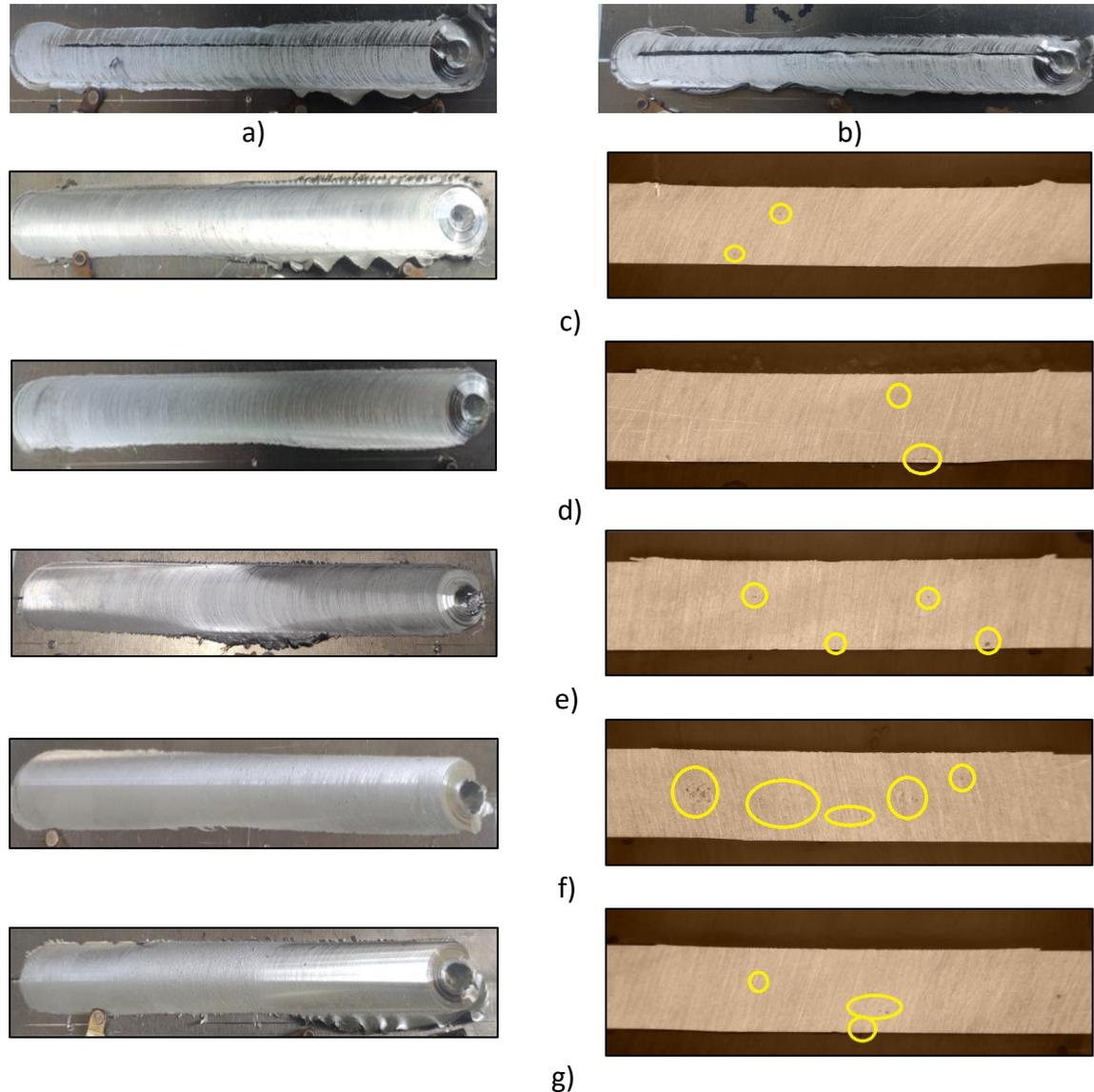


Figure 2. External appearance and unetched macrostructures of the welded joints: a) Mode 1; b) Mode 2; c) Mode 3; d) Mode 4; e) Mode 5; f) Mode 6; g) Mode 7

The obtained results show that when tool P1 was used, a tunnel defect was present along the entire length of the weld (Fig.2a, b). With an increase in the welding speed from 40 to 60 mm/min, the size of the tunnel defect increased both in length and in height of the weld (Fig.2b). This is attributed to an insufficient amount of plasticized material being transported by the pin into the region behind the tool, as a result of the lower temperature in the welding zone associated with the higher welding speed. An additional contributing factor is most likely the improper design of the working tool. As shown in Fig.1a, the pin tip lacks a rounded profile, which is essential for proper material flow. The lack of adequate spiral material flow leads to incomplete filling of the formed cavity and to metal expulsion on the surface in the form of flash. Since the thermal deficit and insufficient material flow simultaneously affect both the lower and upper layers in the weld zone, the tunnel defect forms as a cavity extending from the surface to the root of the weld along its entire length. With increasing welding speed, the size of the defect also increases. This behavior is typical

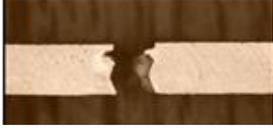
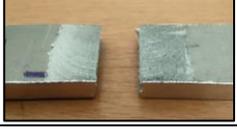
of tools with more complex geometries, where effective material mixing strongly depends on high material plasticity (Çam, G. & Mistikoglu, S., 2014, Mishra, R.S. & Ma, Z.Y., 2005).

The quality of the joint produced with tool P1 was unacceptable; therefore, no further investigations of its mechanical properties were conducted.

The results regarding the external appearance and the presence of weld defects for tool P2 are significantly better compared to tool P1 (Fig. 2c–g). There is a clear trend of defect reduction and improvement in the joint strength with decreasing welding speed. This is primarily due to the higher heat input and the longer dwell time of the material in the stirring zone, resulting from improved material flow, which is typical for pins with simple geometries. For polygonal pins, the flat sides and edges induce periodic local vortices and intense shearing around the corners, which enhances material mixing. The flat surfaces of the pin help transport the material and contribute to achieving higher temperatures in the welding zone (Thakkar, N. & Badheka, V., 2022).

The results regarding the mechanical properties of the joints produced under modes 3 to 7, as well as the temperatures measured near the weld, are presented in Table 5.

Table 5. Mechanical properties of AA7075-T651 after welding

	Yield strength $R_{p0.2}$, [MPa]	Tensile strength R_m , [MPa]	Efficiency [%]	Average measured temperature, °C	Fracture location
 Mode 3	246	369	62	350	
 Mode 4	294	340	57	264	
 Mode 5	287	356	59,3	246	
 Mode 6	294	300	50	228	
 Mode 7	289	321	54	258	

The joint strengths obtained under modes 1 and 2, as noted earlier, are extremely low due to the presence of multiple defects and are therefore not included in Table 5. The average measured temperatures for these modes were 303 °C for mode 1 and 284 °C for mode 2.

From Table 5, it can be observed that the results of the mechanical tests largely correspond with the macrostructural analysis discussed above. It can be noted that the strength properties, and consequently the efficiency of the produced joints, increase with decreasing welding speed. This is

evidently due to the reduced defect density at lower welding speeds. The higher temperatures recorded in the welding zone favor improved material mixing.

For modes 4, 5, 6, and 7, fracture occurred in the middle of the weld seam. The main reason for this is the high defect density in that region, which acts as stress concentrators and reduces the effective cross-section. For mode 3, carried out at the lowest welding speed, fracture occurred in the heat-affected zone (HAZ). This result is consistent with the elevated welding temperature observed under this mode, which promotes natural tempering processes in the HAZ. As a consequence of the structural changes in this zone, a significant reduction in both yield strength and tensile strength is observed.

CONCLUSIONS

1. Fusion welding (MIG/TIG) of high-strength, heat-treatable 7xxx series aluminum alloys is significantly challenging due to structural changes in the heat-affected zone (HAZ). This results in a reduction of strength in this zone by up to 50% compared to the base material.

2. According to literature data, friction stir welding of AA7075-T651 aluminum alloys can produce defect-free joints with tensile strengths ranging from 68.5% to 76.7% of that of the base material.

3. Both tools designed and manufactured for this study produced defects of varying shapes and sizes. The tool with a flat shoulder and a hexagonal, non-threaded pin provides higher-quality welds, with fewer defects in the joint.

4. Increasing the welding speed from 40 to 120 mm/min leads to a reduction in tensile strength and, consequently, joint efficiency from 62% to 50%, due to lower temperatures and insufficient material mixing in the weld zone.

5. For most of the produced joints, fracture occurred in the weld zone due to the high defect density. In the case where maximum tensile strength was achieved, fracture occurred outside the weld, in the heat-affected zone, due to softening resulting from the elevated temperatures recorded.

6. Producing high-quality joints with enhanced mechanical properties in high-strength, heat-treatable aluminum alloys via friction stir welding requires excellent material mixing and, if possible, lower temperatures in the weld zone. The first can be achieved through the use of an appropriate tool, and the second through optimized welding parameters.

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REFERENCES

Anvari, S., Mojarad, S. (2018). Friction Stir Welding of Al 2024 with Al 7075 Alloys and evaluate its structural and mechanical properties. *Journal of Advanced Materials and Processing*, Vol. 6, No. 4, 2018, 53-64.

Çam, G., & Mistikoglu, S. (2014). Recent Developments in Friction Stir Welding of Al-alloys. *Journal of Materials Engineering and Performance*, Volume 23(6), 2014, 1936-1953.

Ferdinandov, N., Gospodinov, D. (2021). Tools for Friction Stir Welding: Review. *PROCEEDINGS OF UNIVERSITY OF RUSE*, volume 60, 2021, 15-21.

Ferdinandov, N., Gospodinov, D. (2021) Peculiarities and Application of Friction Stir Welding. *International Journal NDT Days*, Volume IV, Issue 3, 2021, 170-177.

Gebremlak, G., Palani, S., Sirahbizu, B. (2024). Mechanical characteristics of dissimilar friction stir welding processes of aluminium alloy [AA 2024-T351 and AA 7075-T651]. *Manufacturing Rev.* 11, 19, 2024, 1-24.

Godhani, P., Patel, V., Vora, J., Chaudhary, N. & Banka, R. (2019). Effect Friction Stir Welding of Aluminum Alloys AA6061/AA7075: Temperature Measurement, Microstructure, and

Mechanical Properties. Innovations in Infrastructure. Advances in Intelligent Systems and Computing, vol 757, 2019, 2-58.

Gospodinov, D., Ferdinandov, N., Ilieva, M., Radev, R. (2021) Mechanical properties of aluminium alloy 1050 welded by friction stir welding. Proceedings of University of Ruse, volume 60, 2021, 22-28.

Gospodinov, D., Ferdinandov, N., Radev, R., Ilieva, M. (2024). Research on the possibility for temperature determination during friction stir welding using mechanical properties analysis. AIP Conference Proceedings, vol. 2980 (1), 2024, 1-9.

Kosturek, R., Torzewski, J., Wachowski, M., & Śnieżek, L. (2022). Effect of Welding Parameters on Mechanical Properties and Microstructure of Friction Stir Welded AA7075-T651 Aluminum Alloy Butt Joints. Materials, 15, 2022, 5950, 1-15.

Mehri, A., Abdollah-zadeh, A., Entesari, S., Saeid, T., Wang, J. T. (2023). The effects of friction stir welding on microstructure and formability of 7075-T6 sheet. Results in Engineering 18, 2023, 1-9.

Mishra, R.S., & Ma, Z.Y. (2005). Friction stir welding and processing. Materials Science and Engineering R 50, 2005, 1-78.

Pinto, L., Cipriano, G., Braga, D., Vidal, C., Machado, M., Correia, A., & Infante, V. (2024). Mechanical behavior of friction stir butt welded joints under different loading and temperature conditions. Mechanics of Advanced Materials and Structures, 31:7, 2024, 1413-1422.

Rhodes, C., Mahoney, M., Bingel, W., Spurling, R., Bampton, C. (1997). Effects of friction stir welding on microstructure of 7075 aluminum. Scripta Materialia. Vol. 36, No.1, 1997, 69-75.

Sharma, A., Kumar Dwivedi, V., Pal Singh, Y. (2023) The effect of different conditions on the tensile properties of AA7075-T6 during the friction stir welding process. Arch. Metall. Mater. 68, 2023, 813-821.

Silva, A., De Backer, J. & Bolmsjö, G. (2017). Temperature measurements during friction stir welding. Int J Adv Manuf Technol, (2017), 88, 2899–2908.

Singh, P., & Srivastava, M. (2025). A Parametric Study on the Influence of Welding Speed and Axial Force in Friction Stir Welding of High-Strength Aluminum Alloys. International Research Journal of Engineering and Technology, Volume12, Apr 2025, 635-639.

Thakkar, N., & Badheka, V. (2022). Tool Designing for Friction Stir Welding Variants. In book: Advances in Manufacturing Engineering, 2022, 175-193.

Threadgill, P. L., Leonard, A. J., Shercliff, H. R., & Withers, P. J. (2009) Friction stir welding of aluminium alloys. International Materials Reviews, vol.54, no.2, March 2009, 49-93.

Tiwari, S. K., Shukla, D. K., Chandra, R. (2013). Friction Stir Welding of Aluminum Alloys: A Review. International Scholarly and Scientific Research & Innovation 7(12), 2013, 1315-1320.