MECHANICAL PROPERTIES EVALUATION OF WELDED JOINTS MADE OF ALUMINIUM ALLOY AW7075 BY THE FRICTION STIR WELDING

Jozef Bárta[1,*], Jan Urminský[1], Milan Marônek[1], František Jurina[1], Ivan Buranský[1], Katarina Bártová[1], Jana Ptačinová[1]

[1]Faculty of Materials Science and Technology, Slovak university of Technology, J. Bottu 25, 917 24, Trnava, Slovakia

* Corresponding Author. E-mail: jozef.barta@stuba.sk

Abstract

Friction stir welding is still more being used in shipbuilding, aerospace, and automotive industries to develop and produce welded components. This welding technology offers many benefits, including reducing emissions and waste, increasing production possibilities by transforming machining devices into welding devices, and raise the competitiveness of companies. The quality of welded joints is most influenced by main welding parameters. Aluminium alloy AW7075-T651 with a thickness of 3.6 mm was used in the experiment. The main welding parameters were the frequency of tool rotation and welding speed. Macroscopic analysis confirmed the presence of a typical FSW joint areas, weld nugget, thermomechanical affected zone and heat affected zone. Microscopic analysis exposed a fine-grain microstructure in the weld nugget. Mechanical properties of the welded joints were evaluated by microhardness measurement, bend test and tensile strength test.

Keywords: FSW; AW7075, welding; microscopic analysis; mechanical properties

1. Introduction

The friction Stir Welding (FSW) was invented at the UK's 'The Welding Institute' (TWI) in 1991, and is viable process for joining aluminium alloys. During friction stir welding is necessary using a specialized non-consumable cylindrical tool to weld a butt or lap joint. This tool has a small probe and a larger shoulder. The tool is rotated and plunged into the joint line, generating frictional heat that softens the surrounding material, allows the tool to move along the joint line. The depth of penetration is determined by the probe length. When the tool shoulder contacts the metal plates, additional frictional heat is generated and plasticizers a cylindrical metal column around the probe. The rotating tool continually plasticizing and mixing the material it within a narrow zone [1]. The aluminum alloy AW7075-T651 applications are typically where high strength and good corrosion resistance are required. Aircraft structural parts and other high-stress parts from any industry are usually made from this alloy [2]. In previous studies, it has been found, that the friction stir welding process is possible used to joined of 7xxx aluminium alloy. The welded joints from 6 mm thick plates of AW7075-T651 was produced by using the FSW process were free of defects. The best process parameter selection resulted in fully penetrated welds. Direct observation, it was found that the weld joint and the surrounding area can be divided into four zones: stir zone (SZ), thermomechanical affected zone (TMAZ), heat affected zone (HAZ), and base material (BM). Microstructural examination of these zones showed that SZ had very fine and equiaxed grains. Microhardness measurements were carried out on the welded joint and base material. The average hardness of the base material was higher than the hardness of the welded joint. The heat-affected zone had the lowest hardness. The tensile strength of the base material and welded joint were also evaluated, with values of 574 MPa for BM and 278 MPa for welded joint [3, 7, 10]. The yield strength, ultimate tensile strength, and elongation of the base materials AW7075-T6 alloy plates with a thickness of 5 mm were 521 MPa, 578 MPa, and 17%, respectively. Friction stir welding was used to join the plates with a tool rotation rate of 800 RPM and a traverse speed of 100 mm/min. The tool was made of H13 steel, with a concave shoulder diameter of 16 mm and a probe length of 4.7 mm. The diameter of the tapered threaded pin ranged from 3.5 to 5.5 mm. The base material had an average hardness of about 185 HV, with the lowest hardness (111 HV) observed in the heat affected zone. The average hardness of the nugget zone was 129 HV, which was lower than the base material. The base material had elongated grains with an average width of 31 μm. The grains in the heat-affected zone were almost similar in size and shape to those in the base material. The thermo-mechanically affected zone showed elongated grain structures, but they were much finer than in the base material. The average width of the elongated grains in the TMAZ was about 11 μm. Equiaxed grains were observed in the nugget zone, with an average size of 4 μm. The yield strength, ultimate tensile strength, and elongation of the FSW joint were 291 MPa, 408 MPa, and 7.9% [4, 8]. According to Ma et al. [5], AW7075-T651 is a heat-treatable (precipitate-hardened) aluminium alloy, and friction stir welding process leads to softening of the nugget area. Combination of constant rotational speed of 1200 RPM with various translational speeds of 32, 64, 127 and 241 mm/min during the friction stir process is possible affected a behaviour a resulted microhardness. The central region of the nugget zone has a higher microhardness, but it is still softer than the base material. The regions with lower microhardness values, TMAZ or HAZ, surround the central region of welded joint, depending on the local peak temperatures. Microhardness values increase with distance from the centreline of the nugget. The results show that increasing the tool rotational speed leads to a decrease in hardness, while increasing the translational speed results in a hardness increase. These changes are due to the influence of the peak temperatures. The increase in translational speed led to a reduction in grain size in the SZ. Conversely, higher translational speeds of the tool result in less heat generation and changing a grain size [6, 9]. The aim of the paper is to find out whether the standard milling machines are stiff enough to handle friction stir welding and spindle load will not be too high. Another aim was to produce a full penetration butt welded joint made of aluminium alloy AW7075-T651 and compare the mechanical properties with the properties of base material.

2. Materials and Methods

Material used within the experiment was AW 7075 T651 aluminium alloy with thickness of 3.7 mm. Chemical composition and mechanical properties of the AW 7075 T651 are provided in Table 1 and Table 2. Chemical composition was analysed using Bruker Q4 TASMAN advanced benchtop spark - Optical Emission Spectrometer.

Table 1. Measured chemical composition of AW 7075 T651 aluminium alloy [wt. %]

Al	Cr	Cu	Fe	Mg
88.7	0.178	1.740	0.201	2.511
Mn	Si	Ti	Zn	Other
0.059	0.082	0.018	6.440	0,071

Table 2. Typical mechanical properties of AW7075-T651 provided by manufacturer [1]

Hardness, Brinell	150	AA; Typical; 500 g load; 10 mm ball
Hardness, Rockwell B	87	Converted from Brinell Hardness Value
Hardness, Vickers	175	Converted from Brinell Hardness Value
Ultimate Tensile Strength	538 MPa	AA; Typical
Tensile Yield Strength	476 MPa	AA; Typical

Probe used in this experiment was in the shape of a threaded cone cut into a regular four-sided pyramid. Probe was 3.45 mm pulled out from the shoulder. Shoulder had a single helix-shaped groove with 1 mm depth. Material used for production of the 5.5 mm probe in diameter was tungsten carbide, whereas the shoulder with diameter of 14 mm was made of standard tool steel.

Figure 1. Milling machine DMG DMU 85 Monoblock

Welded joints were produced using DMU 85 monoBLOCK- 5-Axis Milling by DMG MORI (Figure 1), which is a standard milling machine. Microhardness was measured using NEOPHOT 21 microscope equipped with Hanneman microhardness extension and Tinius Olsen 300 ST device was used to analyse static tensile strength as well as bend tests. ZEISS Metrotom 1500 was used for X-Ray analysis of welded joints, whereas VG Studio 3.0 software was used to analyse X-Ray scans. Structural analysis was realized using standard procedures. After grinding and polishing, Keller's reagent (95 ml H2O, 2.5 ml HNO3, 1.5 HCl, 1 ml HF) was used for etching to reveal the macrostructure and microstructure of the welded joint.

3. Experimen

Previous experiments showed that penetration of the tool is 3.7 mm so the plates with the 5 mm thickness were reduces to this thickness. Plates to be welded were fixed by clamps in the table of milling machine (Figure 2). After milling the thickness to 3.7 mm, welding took place without moving the plates. Welding parameters were used from previous experiment having best results from X-Ray analysis and weld surface appearance. Revolution frequency of the tool was 1000 RPM and welding speed was 200 mm/min. The weld surface is shown on Figure 3. The surface roughness of the weld joint was measured and average surface roughness (Ra) was 4.657 µm. Samples for mechanical properties and structural analysis were cut out from reduced thickness only.

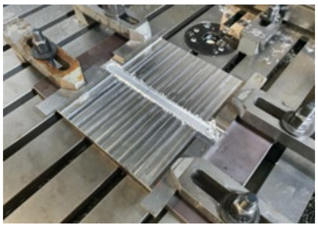

Figure 2. Welding setup and clamping

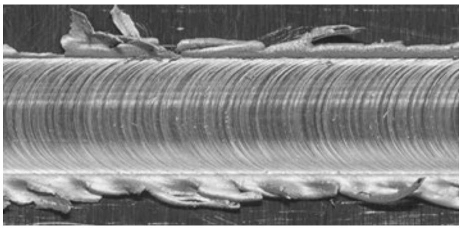

Figure 3. Weld surface appearance with flash

X-Ray analysis of welded joint (Figure 4) did not show any abnormalities or porosity in welded joint, however the porosity of the welded joint may be very small (at the limit of detectability) due to the fine structure and nature of the process. Porosity was later also evaluated during microscopic analysis.

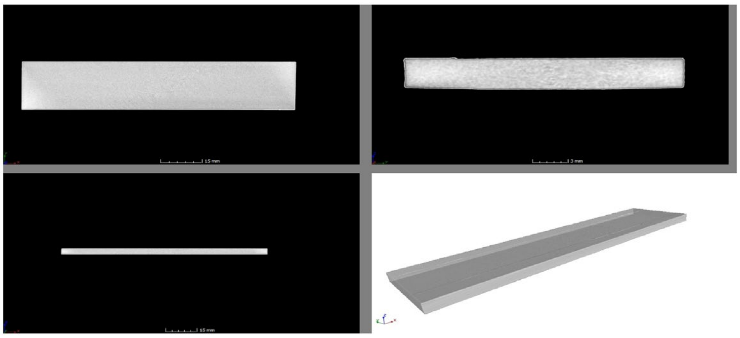

Figure 4. Results of X-Ray analysis of welded joint

Macroscopic analysis (Figure 5) showed full penetration without any abnormalities on the surface of the weld bead and weld root. Figure 5 shows different zones of the welded joint. Stir zone is the middle zone of the welded joint, however the weld nugget was not observed. Transition between stir zone and thermomechanically affected zone (TMAZ) was sharp on the advancing side, but difficult to locate exactly on the retreating side of the welded joint. The precise line between thermomechanically affected zone and heat affected zone (HAZ) is not significant due to fine microstructure. Identification of TMAZ was done based on grain direction changes compared to original direction of rolled based material. Advancing side showed narrow TMAZ but wide HAZ. Wide TMAZ and narrow HAZ were observed on the retreating side.

Figure 5. Macrostructure of Sample 14

Microstructure of welded joint was analysed using scanning electron microscopy on cross-sections. Microstructure of base material is provided on Figure 10. Longitudinal grains, typical for rolling, were observed. Precipitates were observed on grain boundaries inside the grains.

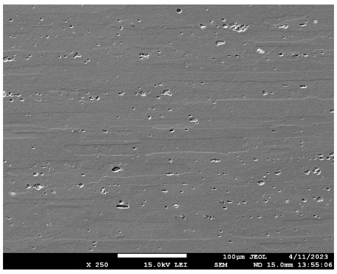

Figure 6. Microstructure of AW7075-T651 (base material)

EDX analysis was used to analyse chemical composition and distribution of particular elements Figure 7. EDX map of base material showed relatively big precipitates rich to Al-Cu-Fe and Al-Cu. Most probably it could be Al_7Cu_2Fe or Al_2Cu phases as it was reported by other researchers [12, 13]. Precipitates rich to Si-O were also observed. In this case it could be SiO_2 phase. Also, particles rich to Cu were observed. TEM or XRD analysis would be required to confirm these phases. Elements like Zn and Mg are evenly distributed in matrix. We assume that fine $MgZn_2$ phase can be found in matrix as well. Measured chemical composition of particular precipitates is provided in Table 3.

Table 3. Chemical composition of precipitates in base material

	Cu	Fe	Al	Si	O	Zn	Mg	Cr	Mn
Al-Cu-Fe	34.0	13.3	44.2	0.3	2.7	3.2	0.8	0.9	0.6
Al-Cu	36.1	0.3	54.2	0.0	2.0	5.6	1.7	0.0	0.0
Al-Si	1.5	0.0	24.2	35.1	35.6	2.6	1.0	0.0	0.0
Cu	88.9	0.0	5.1	0.0	3.4	2.0	0.7	0.0	0.0

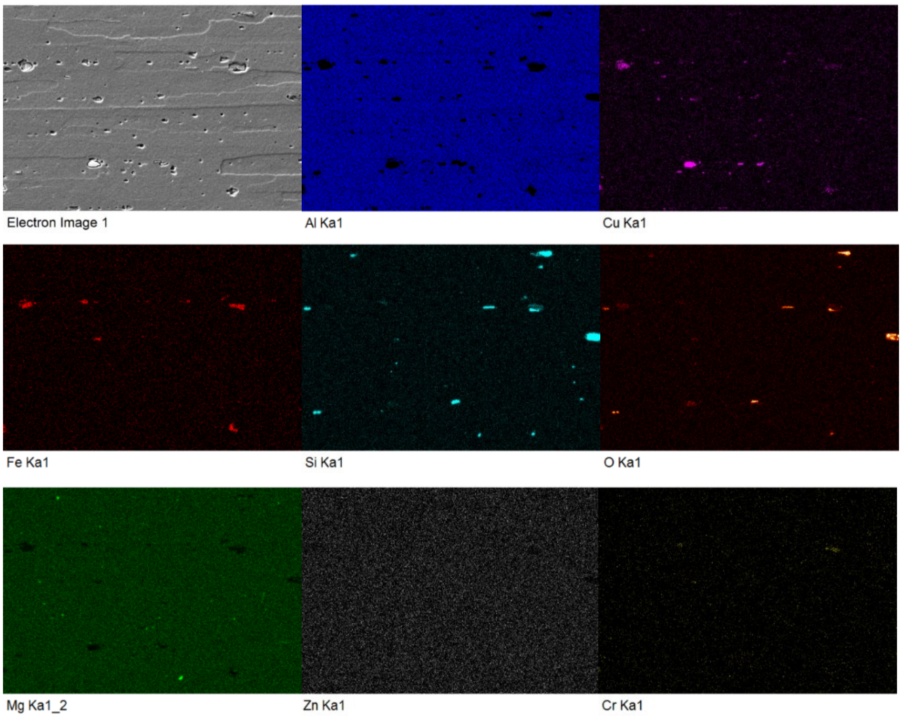

Figure 7. EDX mapping of base material

Transition zones between stir zone (SZ) and thermomechanicaly affected zone (TMA Z) are shown in Figure 8a and Figure 8b. TMAZ showed deformed grains and precipitates were observed again in grains and on their boundaries, similar to base material (Figure 9a). Precipitates rich to AL-Cu-Fe, Al-Cu, Al-Si a Cu were also observed in this transition zone. Beside these precipitates, Al-Cu-Mg based precipitates were observed (60.0%Al, 17.3%Cu, 10.1%Mg). Stir zone was formed by equiaxed grains (Figure 9b). This fine grained structure was achieved by recrystalisation cause by strong deformation. Preciptates rich to Al-Cu-Fe, Al-Cu a Si-O were observed in stir zone.

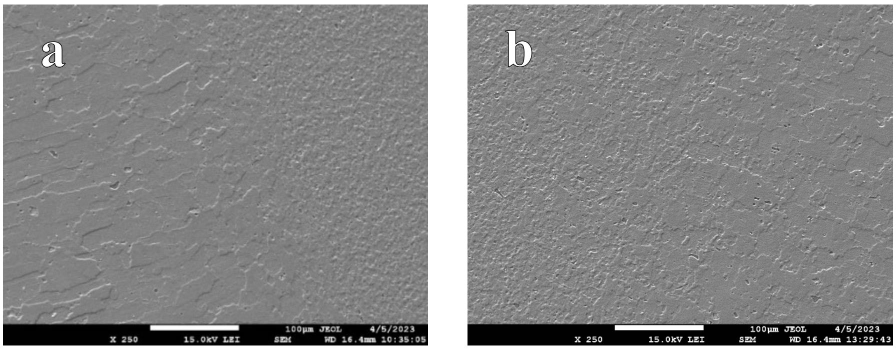

Figure 8. Microstructure of transition zone SZ-TMAZ: a) retreating side, b) advancing side

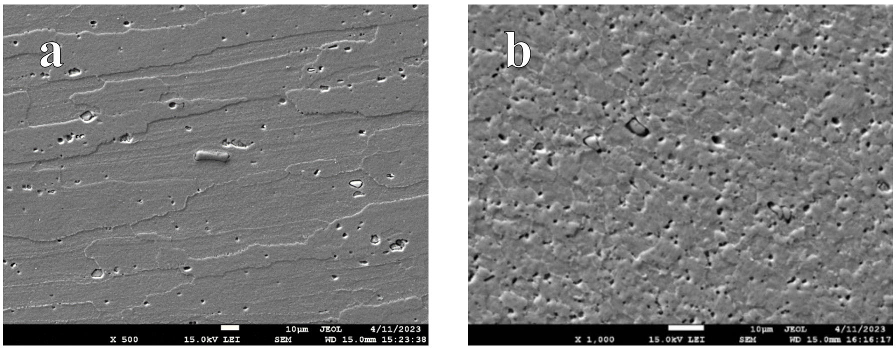

Figure 9. Precipitates in particular areas: (a) TMAZ, (b) SZ

Microhardness was measured across the welded joint (Figure 15) in the middle section. Significant drop of the microhardness was observed in the heat affected zone. Heat affected zone showed microhardness of 134 HV 0.1 what represents 23 % drop compared to value of 175 HV 0.1 measured in the base material. Stir zone showed the highest microhardness in welded joint compared to base material. Microhardness measured in the weld axis of the welded joint from the top to the root section was very uniformed. Average value measured in stir zone was 155.8 HV 0.1 what represents 89 % of value measured in base material.

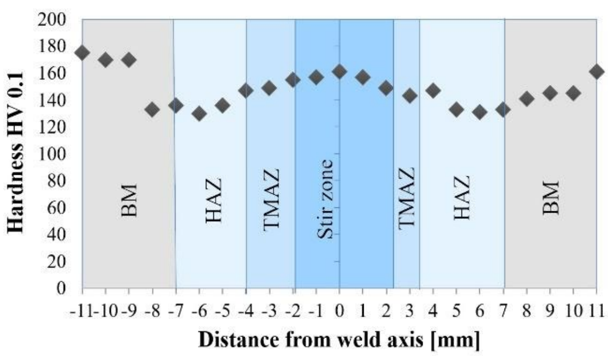

Figure 10. Microhardness measurement across the weld joint

Bend test was realized according to ISO 5173:2009 standard (Destructive tests on welds in metallic materials - Bend tests) Eight samples (Figure 16) were cut out from a welded joint (Figure 4) with 20 mm width. Half of the samples were assigned for a bend test from the root side and the other half from surface side of the welded joint.

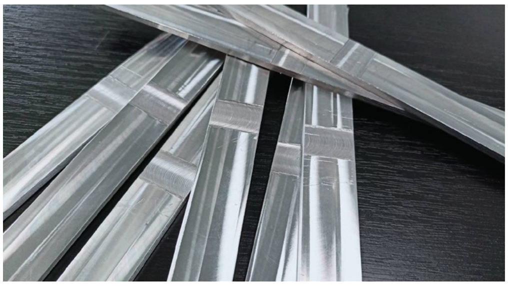

Figure 11. Welded joints before bend test

After the cutting, the flash was removed from the surface completely and both surface and root side of the welded joint by grinding with 600 grit grinding paper in direction perpendicular to the welded joint axis (welding direction). Since the shoulder was pushed into the material, the transition smooth and crack initiation could start at the sharp edges. Finally, the edges were deburred to avoid crack initiation from the sharp edge. Samples after the bend test did not show any crack while bending from both sides (Figure 17, Figure 18).

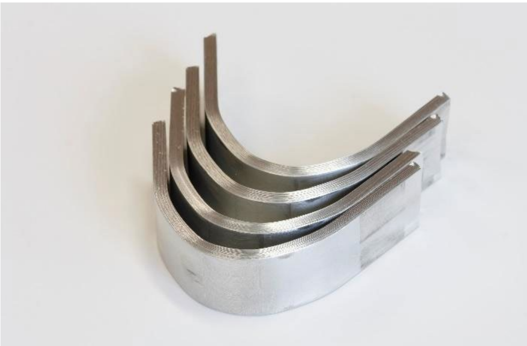

Figure 12. Welded joints after bend test from root part

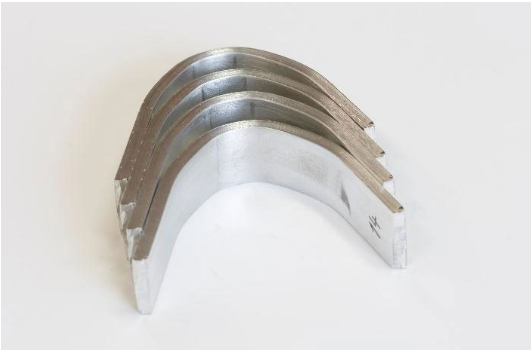

Figure 13. Welded joints after bend test from surface part

Three samples for the tensile test were prepared according to the ISO 4136 standard (Destructive tests on welds in metallic materials - Transverse tensile test). Similar to bend test samples, flash and edges were brushed to prevent early crack initiation. Samples were cut off from the welded joint using electro erosion machining. Samples after the tensile strength test were broken in HAZ.

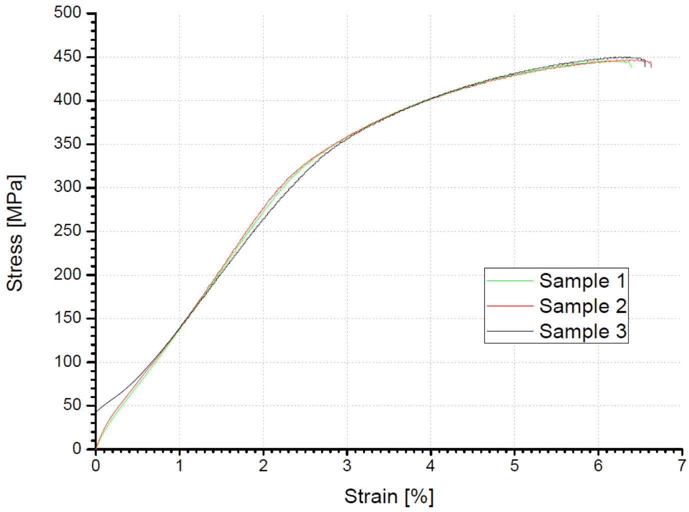

Figure 14. Results of tensile strength test

Average tensile strength of welded joints was 452 MPa, whereas the proved strength was 348 MPa (Figure 19). There is a noticeable difference in sample No.3 which was probably caused by slipping of grippers in the testing device at the very beginning of the test. Therefore, the stress-strain diagram is shifted to the right side at the beginning of the test, however the shape is very similar to the first two measurements. Cracks appeared in heat affected zone in all samples.

6. Conclusions

Based on provided results, following conclusions from this research can be pointed out:

1. High rotational frequency of the welding tool causes irregular formation of welded joint surfaces due to tearing off the material. Moreover, it causes the porosity underneath the weld surface.
2. With low rotational frequency and higher welding speed, porosity in the root section of the welded joint appeared, which may lead to tunnel defect in the root section.
3. Best parameters for welding AW 7075 based on analysis were 1000 RPM rotational frequency and 200 mm/min welding speed. These parameters showed a stable welding process and no internal defects confirmed by X-Ray analysis.
4. Spindle load was only 23% of its maximum, so the milling machine proved to be capable of welding AW7075 aluminium alloy with the thickness of 3.7 mm.
5. Macrostructure of welded joint did not reveal any defects and confirm the presence of standard zone (stir zone, thermomechanically affected zone and heat affected zone).
6. Microstructure showed very fine structure in stir zone and deformed grains in TMAZ. Moreover, it revealed the presence of small precipitates. Chemical analysis of particles was realised however, TEM or XRD analysis would be required to confirm the presence of particular phases observed by other authors.
7. Tensile strength showed 16 % drop compared to values provided by manufacturer.

Microhardness exhibited 89 % of base material value. Bend tests showed no cracks on any sample after the test.

Further research will be focused on material of the tool and its lifetime, as well as confirmation of the phases by advanced material analysis.

7. Acknowledgements

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-21-0111 „Research of friction stir welding of aluminium alloys with regard to spindle load and tool life".

8. References

[1] T. SRINIVASA RAO, G. MADHUSUDHAN REDDY, S.R. KOTESWARA RAO, Microstructure and mechanical properties of friction stir welded AA7075–T651 aluminum alloy thick plates, Transactions of Nonferrous Metals Society of China, Volume 25, Issue 6, 2015, Pages 1770-1778, ISSN 1003-6326, https://doi.org/10.1016/S1003-6326(15)63782-7. URL: https://www.sciencedirect.com/science/article/pii/S1003632615637827, [cited 06.04.2023]

[2] ASM International Handbook Committee., 1990. ASM Handbook, Volume 02 - Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. [S.l.]: ASM International. ISBN 0-87170-378-5

[3] Rakesh Kumar, Shailendra Singh Bhadauria, Varun Sharma, Manoj Kumar, Effect on microstructure and mechanical properties of single pass friction stir welded aluminium alloy AA-7075-T651 joint, Materials Today: Proceedings, 2022, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2022.10.111. URL: https://www.sciencedirect.com/science/article/pii/S221478532206610X, [cited 29.03.2023]

[4] L. Zhang, Y.F. Hou, C.Y. Liu, H.F. Huang, H.M. Sun, Effects of short-time heat treatment on microstructure and mechanical properties of 7075 friction stir welded joint, J. Mater. Eng. Perform., 30 (10) (2021), pp. 7826-7834, 10.1007/s11665-021-05876-0 URL: https://link.springer.com/article/10.1007/s11665-021-05876-0?utm_source=getftr&utm_medium=getftr&utm_campaign=getftr_pilot#citeas [cited 06.04.2023]

[5] Z.Y Ma, R.S Mishra, M.W Mahoney, Superplastic deformation behaviour of friction stir processed 7075Al alloy, Acta Materialia, Volume 50, Issue 17, 2002, Pages 4419-4430, ISSN 1359-6454, https://doi.org/10.1016/S1359-6454(02)00278-1. URL: https://www.sciencedirect.com/science/article/pii/S1359645402002781, [cited 06.04.2023]

[6] R. Abrahams, J. Mikhail, Panahsadat Fasihi, Effect of friction stir process parameters on the mechanical properties of 5005-H34 and 7075-T651 aluminium alloys, Materials Science and Engineering: A, Volume 751, 2019, Pages 363-373, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2019.02.065. URL: https://www.sciencedirect.com/science/article/pii/S0921509319302400, [cited 06.04.2023]

[7] Ali Mehri, Amir Abdollah-zadeh, Sina Entesari, Tohid Saeid, Jing Tao Wang, The effects of friction stir welding on microstructure and formability of 7075-T6 sheet, Results in Engineering, Volume 18, 2023, 101041, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2023.101041. (https://www.sciencedirect.com/science/article/pii/S2590123023001688) [cited 02.04.2023]

[8] J.S. De Lima et al., Influence of welding parameters on the mechanical properties and microstructure of 7075-T651 aluminum alloys welded joints performed by FSW process, 2022. Materials Research. 2022; 25:e20210629 https://doi.org/10.1590/1980-5373-MR-2021-0629 [cited 30. 03.2023]

[9] R. Abrahams, J. Mikhail, Panahsadat Fasihi, Effect of friction stir process parameters on the mechanical properties of 5005-H34 and 7075-T651 aluminium alloys, Materials Science and Engineering: A, Volume 751, 2019, Pages 363-373, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2019.02.065. URL: https://www.sciencedirect.com/science/article/pii/S0921509319302400, [cited 30. 03.2023]

[10] L. Zhang, Y.F. Hou, C.Y. Liu, H.F. Huang, H.M. Sun Effects of short-time heat treatment on microstructure and mechanical properties of 7075 friction stir welded joint J. Mater. Eng. Perform., 30 (10) (2021), pp. 7826-7834, https://doi.org/10.1007/s11665-021-05876-0, URL: https://www.researchgate.net/publication/351725709_Effects_of_Short-Time_Heat_Treatment_on_Microstructure_and_Mechanical_Properties_of_7075_Friction_Stir_Welded_Joint, [cited 02. 04.2023]

[12] Rui Lin, Bo Liu, Junjie Zhang, Shengen Zhang. Microstructure evolution and properties of 7075 aluminum alloy recycled from scrap aircraft aluminum alloys. Journal of Materials Research and Technology; Volume 19; 2022. ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2022.05. 011. URL: https://www.sciencedirect.com/science/article /pii/S2238785422006809, [cited 08. April 2023]

[13] Jia-ying Hu, Peng Liu, Si-yu Sun, Yan-hua Zhao, Yuan-bin Zhang, Yu-shuang Huo. Relation between heat treatment processes and microstructural characteristics of 7075 Al alloy fabricated by SLM. Vacuum; Volume 177; 2020. ISSN 0042-207X, https://doi.org/10.1016/j.vacuum.2020.109404. URL: https://www.sciencedirect.com/science/article/abs/pii /S0042207X20302414, [cited 08. April 2023]