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# Selected Problems in Friction Stir Welding of Titanium and Aluminum Armor Grade Alloys

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**Abstract:**

*In this paper, authors reported selected problems in friction stir welding (FSW) of 5 mm-thick AA7075-T651 and 3 mm-thick Ti6Al4V. The investigation involved macro and micro-structure analysis and mechanical testing. The welded joints of Ti6Al4V were characterized by the presence of backing plate steel fragments and tungsten particles in the bottom part of the stir zone (SZ) and thermo-mechanically affected zone (TMAZ), which resulted in a relatively low value of joint efficiency (60 %). The investigation on AA7075-T651 was concerned with high-speed FSW (HSFSW) using the MX Triflute tool. In all cases, defective welded joints have been obtained (incomplete root penetration, voids in the SZ) with the best result of joint efficiency of about 59 %.*

**Keywords:**

*friction stir welding, mechanical properties, weld defects, aluminum, titanium*

## 1 Introduction

Friction stir welding (FSW) allows to obtain high-quality joints of most aluminum alloys used in the industry. By local plasticization and stirring of workpieces to be welded, a joint with a fine-grained microstructure is formed [1]. Despite numerous advantages of this joining technique, when it comes to titanium alloys and high-strength aluminum alloys, obtaining high load-carrying capabilities of joints become an important factor. Titanium alloys are difficult to weld via FSW, due to the high temperature of the plasticization which requires the application of expensive tools dedicated to operating in the condition of high temperature and wear (e.g. tungsten, boron nitride) [2]. In terms of high-strength aluminum alloys, the crucial problem is the influence of the process temperature, which leads to the overaging of strengthening phases [3]. For this reason, a lot of attention is paid to the underwater FSW (UWFSW) and high-speed FSW (HSFSW) [4, 5]. The increasing welding velocity generally gives

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positive effects in the form of greater mechanical performance and a decrease in welding time [6]. This paper aims to investigate the origin of problems, which authors have faced during the study on the FSW of Ti6Al4V alloy and HSFSW of AA7075-T651 alloy.

## 2 Materials and Methods

The materials used in this study were 3 mm-thick Ti6Al4V alloy and 5 mm-thick AA7075-T651 alloy with the chemical composition presented in Tab. 1.

*Tab. 1 Chemical composition of the alloys to be welded*

| Ti6Al4V | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| N | C | H | Fe | O | Al | V | Ti | |
| 0.009 | 0.021 | 0.001 | 0.120 | 0.110 | 6.10 | 3.98 | Rest | |
| AA7075-T651 | | | | | | | | |
| Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
| 0.071 | 0.122 | 1.610 | 0.025 | 2.596 | 0.197 | 5.689 | 0.041 | Base |

The basic mechanical properties have been established in the tensile test and set in Tab. 2.

*Tab. 2 Mechanical properties of the alloys to be welded*

| Ti6Al4V | | |
|---|---|---|
| Yield Strength, $R_{0,2}$ | Tensile Strength, $R_{\mathrm{m}}$ | Elongation, $A$ |
| 998 MPa | 1031 MPa | 16.5 % |
| AA7075-T651 | | |
| Yield Strength, $R_{0,2}$ | Tensile Strength, $R_{\mathrm{m}}$ | Elongation, $A$ |
| 496 MPa | 570 MPa | 12.2 % |

The materials have been cut into pieces with dimensions of 80×500 mm with their edges precisely machined by milling. The welding process has been conducted on ESAB FSW Legio 4UT. In terms of Ti6Al4V, the tool was made of tungsten lanthanum alloy with a taper cylindrical pin. The applied process parameters were 300 rev/min tool rotation speed and 75 mm/min tool traverse velocity. The pin length was 2.9 mm and its depth during the process was −2.9 mm. HSFSW attempts for 5 mm-thick AA7075-T651 using the MX Triflute tool have been conducted in the range parameters of 1 000 rev/min, 1 250 rev/min, and 1 500 rev/min tool rotation speed and 0.5 m/min, 0.75 m/min, and 1 m/min tool traverse velocity. The photos of used welding tools are presented in Fig. 1.

The investigation involved macrostructural and SEM observations and mechanical testing. The microhardness testing has been performed on Struers DuraScan 70 microhardness tester using 0.98 N load. The microhardness distribution on the joint cross-sections has been established at the distances 0.6, 1.5, and 2.4 mm from the weld face. The tensile test has been conducted in accordance with the ASTM E8/E8M standard on Instron 8802 MTL. The geometry of used tensile sample is presented in Fig. 2.

*Fig. 1 Welding tools: MX Triflute for joining aluminum (left) and W-La tool for joining titanium (right)*

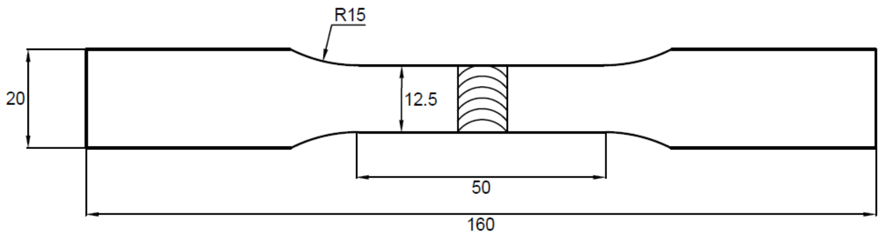


*Fig. 2 Scheme of the tensile sample*

The fractured, tensile samples have also been subjected to the SEM observations in order to establish the fracture character.

## 3 Results and Discussion

### *3.1 Friction Stir Welding of Ti6Al4V*

The observations of the Ti6Al4V FSW joint revealed the presence of impurities in the bottom part of the stir zone (Fig. 3). Despite this imperfection, no other defects have been reported.

The fragments of the stirred impurities have been subjected to SEM observation (Fig. 4) and the chemical composition analysis (Tab. 3).


*Fig. 3 Macrostructural image of Ti6Al4V FSW joint*

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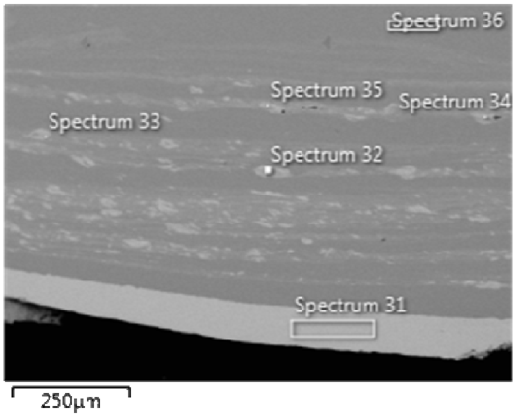


*Fig. 4 SEM image of steel fragments in the FSW joint*

*Tab. 3 Chemical composition (weight %) of point and areas marked in Fig. 4*

| Spectrum | Al | Ti | Fe | W |
|---|---|---|---|---|
| 31 | — | — | 100.0 % | — |
| 32 | 2.9 % | 44.9 % | 51.0 % | 1.2 % |
| 33 | 2.8 % | 44.2 % | 53.0 % | — |
| 34 | 2.8 % | 41.4 % | 55.8 % | — |
| 35 | 2.1 % | 36.8 % | 61.1 % | — |
| 36 | 6.1 % | 93.9 % | — | — |

The obtained results show that the material stirred into the nugget zone is the steel backing plate used as an element of welding equipment. Additionally, the presence of tungsten (1.2 wt.%) has been revealed which indicates heavy wear of the used W-La tool during the joining process. The stirred particles have also an impact on the microhardness distribution of the joint cross-section, presented in Fig. 5.

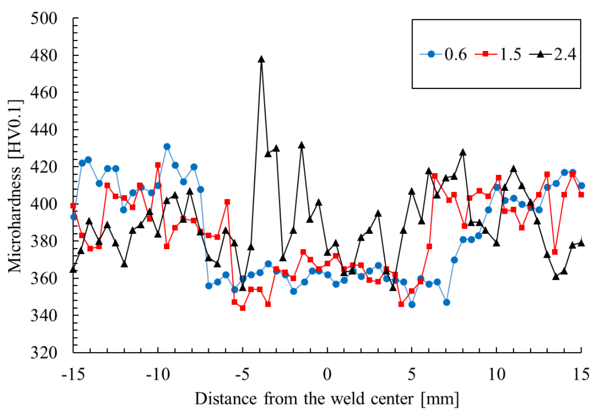


*Fig. 5 Microhardness distribution in Ti6Al4V FSW joint at the distances of* 0.6, 1.5, *and* 2.4 mm *from the weld face*

It can be observed that the width of the stir zone is about 14 mm and it is characterized by a decrease in microhardness, most visibly for 0.6 and 1.5 lines. The FSW process affects the microhardness of Ti6Al4V alloy, reducing its value from about 410 HV0.1 (base material) to 360 HV0.1 (stir zone). Analyzing the curve corresponding to the bottom part of the weld (line "2.4" in Fig. 5), a fluctuation in microhardness value can be observed. The highest reported values of microhardness are the peaks of 2.4 mm line corresponding to 480-440 HV0.1, whose distance from the weld center overlaps with the region rich with stirred steel and tungsten particles. Unintentional enrichment of the stir zone with tungsten alloy particles (having above 500 HV0.1) significantly contributed to the local increase of the microhardness values. The mechanical properties of the joints have been evaluated in the tensile test on six tensile samples taken from the obtained welded joint (Fig. 6).

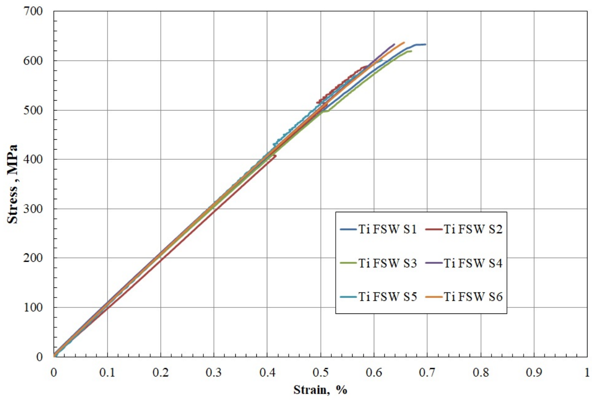


*Fig. 6 Tensile curves of Ti6Al4V FSW joint samples*

The performed mechanical testing of the obtained joint allowed to establish the value of tensile strength equal to (622.37 ± 18.99) MPa which corresponds to 60.4 % joint efficiency. The reported elongation at break does not exceed 0.7 % and the failure occurs in the SZ, which proves the low quality of the produced joint. The decohesion of the joint takes place in the region with stirred steel particles, which is possible to observe in the SEM image of fractured samples (Fig. 7).

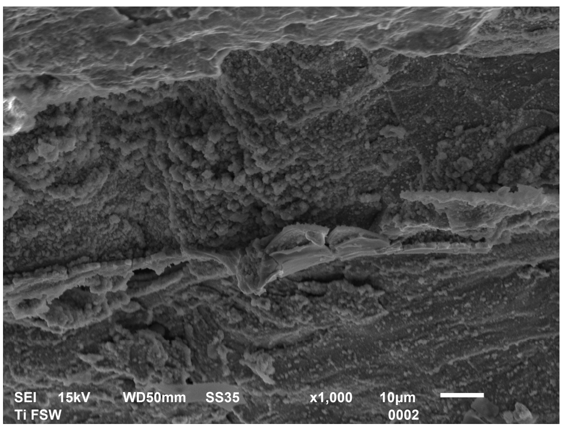


*Fig. 7 SEM image of bottom part of fractured sample*

It is worth mentioning that the tool depth (−2.9 mm) did not allow the complete penetration of the welded workpieces (3 mm), so the tool has no direct contact with the steel backing plate. The potential explanation for the introduction of steel fragments into the stirred region is the in-situ welding of plasticized titanium and the surface layer of the steel backing plate, which is also visible in Fig. 4. Steel fragments underwent further fragmentation in the stir zone, which led to high abrasive wear of W-La tool. The backing plate was made of S355 structural steel. In order to prevent such a phenomenon, the backing plate should be made of a material which does not easily weld itself to the titanium workpieces during the welding (e.g. ceramics).

### *3.2 High-Speed Friction Stir Welding of AA7075-T651*

The performed investigation on HSFSW of AA7075-T651 via MX Triflute tool did not give positive results. The best outcome has been achieved for the sample obtained with 1 000 rev/min tool rotation speed and 0.5 m/min tool traverse speed. The remaining HSFSW joints had a significant participation of voids due to insufficient amount of heat for material plasticization. These highly defected joints were considered for further investigation. The macrostructure of the sample welded with 1 000 rev/min and 0.5 m/min process parameters is presented below (Fig. 8).

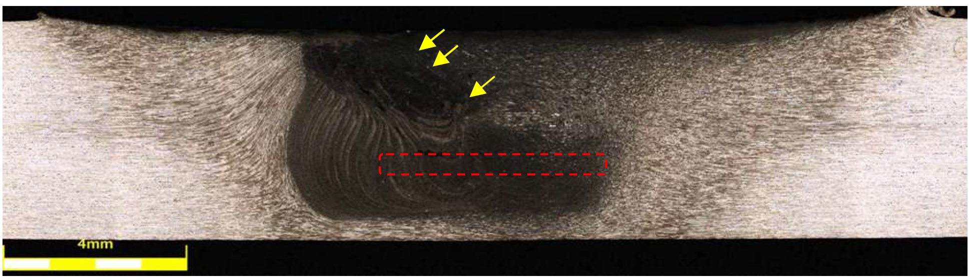


*Fig. 8 Macrostructural image of AA7075-T651 HSFSW joint*

The obtained joint contains two types of defects. First, the incomplete root penetration is directly connected with an insufficient amount of heat in the bottom part of the weld during the process which does not allow for the material to plasticize (red dashed line in Fig. 8). The second defect is voids localized in the upper and central part of the SZ (marked with yellow arrows in Fig. 8), which often form when a difference between temperatures on the joint cross-section is too high, disturbing the plastic flow of the material [3]. Although the participation of defects is not overwhelming, it has serious consequences for the joint mechanical properties (Fig. 9).

The comparison shows that the tensile strength of the defective HSFSW joint is about 335 MPa, which corresponds to 59 % joint efficiency. It has to be mentioned that a defect-free conventional FSW joint can provide about 76 % [1]. Considering a relatively wide matrix of welding parameters it can be stated that MX Triflute is not the appropriate tool for high-speed FSW of 5 mm-thick elements made of AA7075-T651 alloy. The incomplete root penetration is below 1 mm (Fig. 8), so for thinner sheets, complete penetration should be possible. In most research on HSFSW, the thickness of welded workpieces is 2-3 mm [5, 6]. The defects in the produced joints entail rather poor mechanical properties and the failure occurs in the SZ with its character strongly affected by the discussed imperfections (Fig. 10).

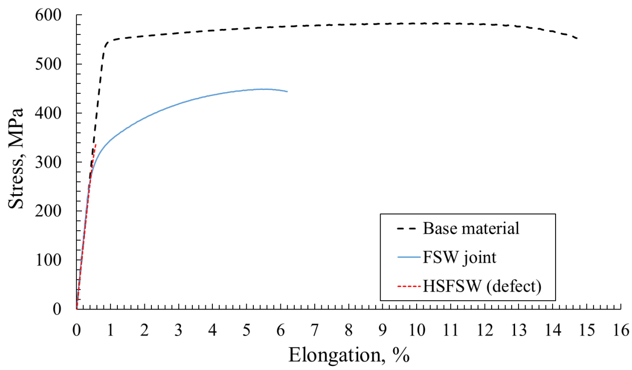


*Fig. 9 Comparison of tensile curves for AA7075-T651: base material, FSW joint, defected HSFSW joint*

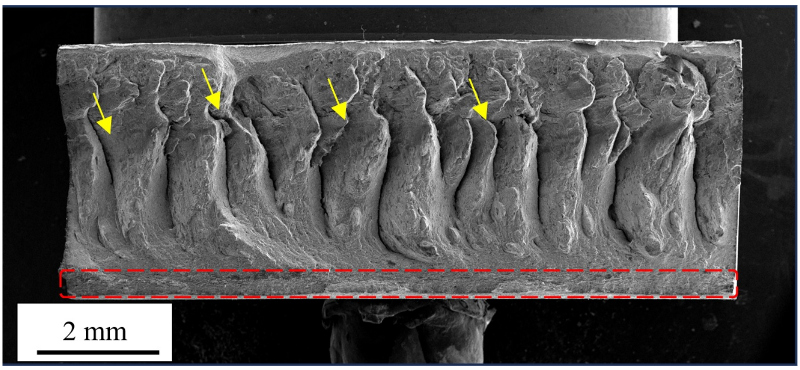


*Fig. 10 SEM image of fractured sample*

The observations of the fractured surface allow to notice the typical “bands” (marked with yellow arrows) for void-defected FSW joints [3]. The bottom part of the fractured surface (red, dashed line) has the character of fracture corresponding to the base material, which is the effect of incomplete root penetration.

## 4 Conclusions

The following conclusions can be drawn from this research:

- The performed mechanical testing of the obtained Ti6Al4V joint allowed to establish the value of tensile strength equal to (622.37 ± 18.99) MPa which corresponds to 60.4 % joint efficiency. The reported elongation at break does not exceed 0.7 % and the failure occurs in the SZ, which proves the low quality of the produced joint.
- The obtained results show that the material stirred into the nugget zone is the steel backing plate used as an element of welding equipment. Additionally, the presence of tungsten (1.1 %) has been revealed which indicates heavy wear of the used W-La tool during the joining process. Further development involves replacing the backing plate in the welding of Ti6Al4V with a ceramic-based one.

- HSFSW attempts for 5 mm-thick AA7075-T651 using the MX Triflute tool have been conducted in the range parameters of 1 000, 1 250, and 1 500 rev/min tool rotation speed and 0.5, 0.75, and 1 m/min tool traverse velocity. Within this range of welding parameters, no defect-free joints were produced.
- The obtained AA7075-T651 HSFSW joint contains two types of defects: incomplete root penetration and voids localized in the upper and central part of the SZ. The joint efficiency of defected HSFSW is about 59 %. Obtaining a high-quality HSFSW (0.5 m/min) joint using a common, commercially available tool is difficult and for future development, more effort will be put into minimalizing heat by a cooling medium (water).

## Acknowledgement

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## References

[1] KOSTUREK, R., J. TORZEWSKI, M. WACHOWSKI and L. ŚNIEŻEK. Effect of Welding Parameters on Mechanical Properties and Microstructure of Friction Stir Welded AA7075-T651 Aluminum Alloy Butt Joints. *Materials,* 2022, **15**(17), 5950. DOI 10.3390/ma15175950.

[2] LI, J., F. CAO and Y. SHEN. Effect of Welding Parameters on Friction Stir Welded Ti–6Al–4V Joints: Temperature, Microstructure and Mechanical Properties. *Metals*, 2020, **10**(7), 940. DOI 10.3390/met10070940.

[3] KOSTUREK, R., L. ŚNIEŻEK, J. TORZEWSKI and M. WACHOWSKI. The Influence of Welding Parameters on Macrostructure and Mechanical Properties of Sc-Modified AA2519-T62 FSW Joints. *Manufacturing Review*, 2020, **7**(28), 8. DOI 10.1051/mfreview/2020025.

[4] SREE SABARI, S., S. MALARVIZHI and V. BALASUBRAMANIAN. Characteristics of FSW and UWFSW Joints of AA2519-T87 Aluminium alloy: Effect of Tool Rotation Speed. *Journal of Manufacturing Processes*, 2016, **22**, pp. 278-289. DOI 10.1016/j.jmapro.2016.03.014.

[5] ZHANG, J., P. UPADHYAY, Y. HOVANSKI and D.P. FIELD. High-Speed Friction Stir Welding of AA7075-T6 Sheet: Microstructure, Mechanical Properties, Micro-texture, and Thermal History. *Metallurgical and Materials Transactions A*, 2018, **49**, pp. 210-222. DOI 10.1007/s11661-017-4411-4.

[6] PATEL, V., J. DE BACKER, H. HINDSEFELT, M. IGESTRAND, S. AZIMI, J. ANDERSSON and J. SÄLL. High-Speed Friction Stir Welding in Light Weight Battery Trays for the EV Industry. *Science and Technology of Welding and Joining*, 2022, **27**(4), pp. 250-255. DOI 10.1080/13621718.2022.2045121.