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The Effect of Water Cooling on the Mechanical Properties of FSW Butt Joints Made of Aluminium Alloy AA7075-T651

Abstract: The article presents test results concerning the mechanical properties of friction stir welded joints (FSW) and underwater friction stir welded joints (UWFSW) made of aluminium alloy AA7075-T651. The analysis of microhardness distribution revealed two positive effects of water cooling, i.e. the reduction of the heat affected zone (HAZ) and an increase in the microhardness of the low hardness zone by approximately 15 HV0.1. Static tensile test results revealed that water cooling led to an increase in the yield point of the FSW joint by approximately 18 % (58 MPa) and tensile strength by approximately 9 % (43 MPa). Under low-cycle fatigue conditions, the UWFSW joints were characterised by higher stress amplitude, lower plastic strain amplitude and a lower number of cycles preceding the failure (of the UWFSW joints) than that preceding the failure of the "classical" FSW joints.

Key words: aluminium, friction stir welding (FSW), mechanical properties, fatigue strength

DOI: 10.32730/mswt.2024.68.5.4

1. Introduction

The use of friction stir welding (FSW) has made it possible to reduce and, in some cases, even eliminate numerous problems accompanying the fabrication of permanent joints of aluminium alloys such as hot cracking or porosity [1]. The FSW technique is particularly effective when joining high-strength aluminium alloys of the 2XXX and 7XXX series, which, because of their high content of alloying components, are considered difficult to weld using conventional joining methods [2]. In spite of the numerous advantages of the FSW technique, the fabrication of precipitation-hardened joints of aluminium alloys is inevitably connected with the noticeable deterioration of their strength properties. The joining of such materials in the hardened state leads to unfavourable transformations of the hardening phases resulting from the effect of heat generated during the joining process [3]. Recent years have seen many articles concerning the strength of FSW joints of precipitation-hardened aluminium alloys indicating its potential improvement through, among other things, post-weld heat treatment, surface post-processing or additional cooling [4–6].

Particular attention should be paid to the FSW variant performed in a watery environment i.e. the so-called underwater friction stir welding (UWFSW) [7]. It was found that the use of the UWFSW technique in the welding of precipitation-hardened alloys of the 2XXX series enabled the significant improvement of their, both static and fatigue, strength-related parameters, [8–10]. The materials subjected to tests were high-strength alloys, such as AA2519-T87 or AA2219-T62 [8, 11]. At the same time, there are very few research works concerned with the subject of UWFSW joints made of alloys of the 7XXX series, which, when subjected to the FSW joining process, are generally characterised by even lower strength than those obtained in alloys of the 2XXX series [2].

The research work discussed in the article aimed to identify the effect of water cooling on the strength-related properties of FSW joints made of aluminium alloy AA7075-T651.

2. Materials and methods

The material used in the test was aluminium alloy AA7075-T651 in the form of 5 mm thick plates. The mechanical properties and chemical composition of the alloy are presented in Tables 1 and 2.

Table 1. Mechanical properties of aluminium alloy AA7075-T651

Yield point $R_{0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation at rupture A [%]
547.5 ± 1.3	583.5 ± 1	14.4 ± 0.6

Table 2. Chemical composition of aluminium alloy AA7075-T651 (wt %)

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	bal.

The plates were cut into strips having dimensions of 90 mm × 500 mm in order to obtain a welded plate having dimensions of 180 mm × 500 mm. Before joining, the side surfaces were subjected to milling, grinding and rinsed with isopropyl alcohol. The FSW joints were made perpendicular to the direction of rolling. The joining process itself was performed using a Legio 4UT machine (ESAB). The tests involved the making of two types of joints, i.e. without water cooling (FSW) and with additional water cooling (UWFSW). In both cases, the same welding process parameters were used, i.e. a tool rotational rate of 400 rpm, a tool travel rate (welding rate) of 100 mm/min, a tool penetration depth of 4.8 mm and a tool inclination angle of 2 °. The process was performed using a tool provided by the ESAB company (catalogue number 0810134-001). The process parameters were adjusted on the basis of previous tests performed by the Authors [12]. The process is presented in Figure 1.

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The determination of the effect of water cooling on the properties of the joints entailed the performance of macrostructural observations, microhardness tests and tests of mechanical properties. The specimens were included in resin and subjected to standard metallographic preparation involving the use of abrasive papers of gradations 320, 500, 800, 1000, 1200, 2400 and 4000 and 3 µm diamond paste. A 15-second-long etching process was performed using Keller's reagent composed of 20 mL H_2O, 5 mL 63 % HNO_3, 1 mL 40 % HF and one drop of 36 % HCl. Macroscopic observations were performed using a LEXT OLS 4100 confocal microscope (Olympus). Microhardness tests were performed using a DURA SCAN 70 hardness tester (Struers) under a load of 0.98 N. Static tensile tests were performed using an Instron® 8802 MTL testing machine and an extensometer with a measurement base of 50 mm. The comparison of the behaviour of test joints under variable load conditions necessitated the performance of low-cycle fatigue tests at total strain levels $\varepsilon_{ac} = 0.35$ % and $\varepsilon_{ac} = 0.6$ % in relation to stress ratio $R = 0.1$.

3. Results and discussion

The first stage of tests involved macrostructural observations aimed to verify if the additional cooling of the material subjected to joining had led to the formation of imperfections in the stir zone. The macrostructural images of the test joints are presented in Figure 2.

The analysis of the macrostructural images revealed the formation of the weld nugget zone, characteristic of the FSW process, characterised by the presence of fine-grained microstructure. At the same time, neither the FSW (Fig. 2a) nor the UWFSW joints (Fig. 2b) contained any structural imperfections. The very shape of the weld nugget was also similar, which justified the conclusion that it was not strongly dependent on the use of additional cooling. The joints were subjected to further analysis, including microhardness distribution (Fig. 3).

The distribution of microhardness revealed a decrease in microhardness in the joint in relation to that of the base material. The analysis of the distribution in the classical FSW joint of aluminium alloy AA7075-T651 revealed that the value of microhardness in the central part of the joint (weld nugget) amounted to approximately 150 HV0.1. The foregoing was the resultant of two effects, i.e. the overageing of phase η' and the refinement of the granular structure [13]. As a result, a decrease in the fraction of the hardening phase was indirectly compensated by the hardening of the boundaries of newly formed dynamically recrystallised grains. An important value, in terms of the load-carrying capacity of the joints, was microhardness in the so-called low-hardness zone (LHZ) [14]. As regards the FSW joint subjected to analysis, the above-named area was located between the heat affected zone (HAZ) and the thermoplastic zone, at a distance of approximately 10 mm from the centre of the joint. The zone was characterised by a relatively low microhardness of slightly more than 110 HV0.1. The referring of the aforesaid observation results to the microhardness distribution of the UWFSW joint revealed the existence of many significant differences between the two test specimens. First of all, the UWFSW joint was characterised by a significantly smaller area of microhardness reduction, which already at a distance of 8 mm from the centre of the joint reached the value corresponding to that of the base material. In addition, the low-hardness zone was located closer to the weld nugget and was characterised by the lowest value recorded, amounting to approximately 125 HV0.1. The above-presented positive effects resulted directly from the additional discharge of heat from aluminium alloy AA7075-T651, which significantly limited the unfavourable thermally initiated transformations of the hardening phase [13]. At the same time, the microhardness value in the weld nugget of the UWFSW specimen, amounting to approximately 140 HV0.1, was noticeably lower than that of the weld nugget in the classical FSW joint (150 HV0.1). The narrowing of the heat-affected zone and an increase in the microhardness of the low-hardness zone had a favourable effect on the load-carrying capacity of the joint, which was reflected in related static tensile strength curves (Fig. 4).

Regardless of the joint variant, the FSW process itself was responsible for a decrease in the tensile strength, yield point and ductility of aluminium alloy AA7075-T651. In terms of the FSW joint, the recorded tensile strength amounting to 449 MPa corresponded to a joint efficiency of nearly 77 %. Additional water cooling made it possible to increase the above-named value to $R_m = 493$ MPa, which translated into a joint efficiency of nearly 85 %. It was also possible to observe a significant increase in the yield point of the UWFSW joint (by approximately 18 %, i.e. 58 MPa) if compared to that of the classical FSW joint and a slight decrease in joint ductility. The effect of additional cooling on the mechanical properties of the FSW joints made of aluminium alloy AA7075-T651 proved highly positive (despite the slight deterioration of joint ductility). The use of the cooling variant for structures operating under variable load conditions necessitates the assessment of the fatigue properties of the joints. Presented below are changes in stress and plastic strain amplitudes as a function of the number of cycles in relation to $\varepsilon_{ac} = 0.35$ % (Fig. 5).

The analysis of the curves justified the conclusion that the behaviour of the FSW and UWFSW joints of aluminium alloy AA7075-T651 was quite similar in relation to the low values of total strain amplitudes. Both joint variants were characterised by susceptibility to slight cyclic hardening. Presented below are changes in stress and plastic strain amplitudes as a function of the number of cycles in relation to $\varepsilon_{ac} = 0.6$ % (Fig. 6).

In relation to higher values of total strain amplitudes, the differences between the specimens were noticeable. It was found that the UWFSW joint was characterised by higher values of stress amplitudes and lower plastic strain amplitude. At the same time, both specimens revealed greater susceptibility to cyclic hardening at $\varepsilon_{ac} = 0.6$ %. It was also observed that the UWFSW joints were generally characterised by a lower number of cycles preceding failure than the classical FSW joints made of aluminium alloy AA7075-T651.

4. Summary

The above-presented tests and results justified the formulation of the following presented below.

1. The microhardness distribution test results revealed two positive effects of water cooling, i.e. the reduction of the heat affected zone (HAZ) and an increase in the microhardness of the low-hardness zone by approximately 15 HV0.1.
2. The static tensile test results indicated an increase in the yield point of the FSW joint by approximately 18 %

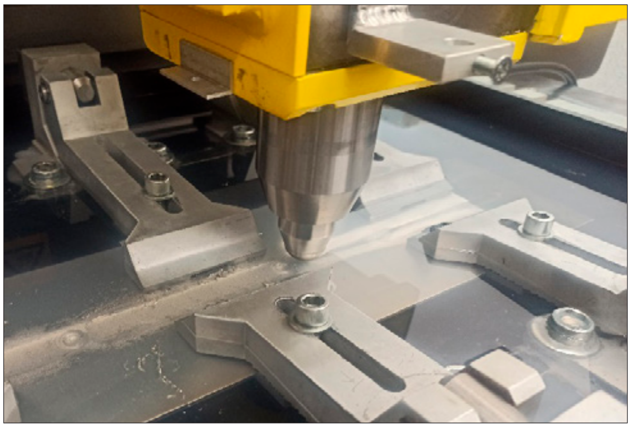

Fig. 1. Underwater friction stir welded joint of aluminium alloy AA7075-T651

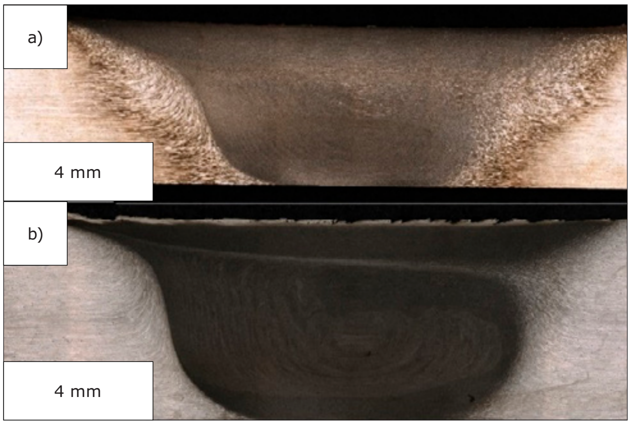

Fig. 2. Macrostructural images of the FSW (a) and UWFSW (b) joints made of aluminium alloy AA7075-T651

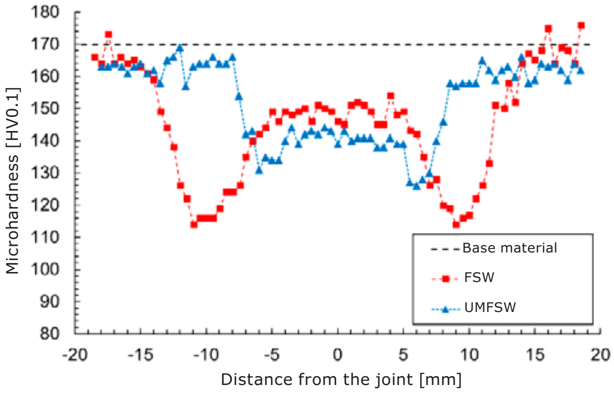

Fig. 3. Microhardness distribution in the cross-section of the test joints

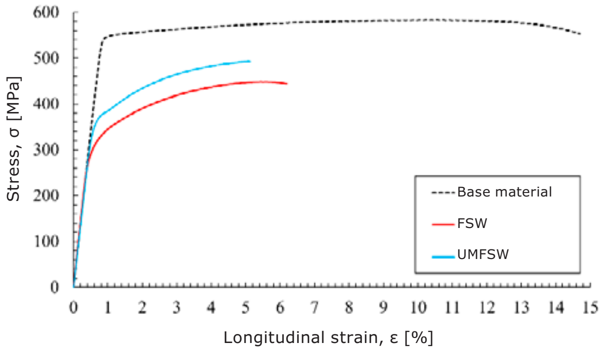

Fig. 4. Stress-strain curves of the base material and test joints

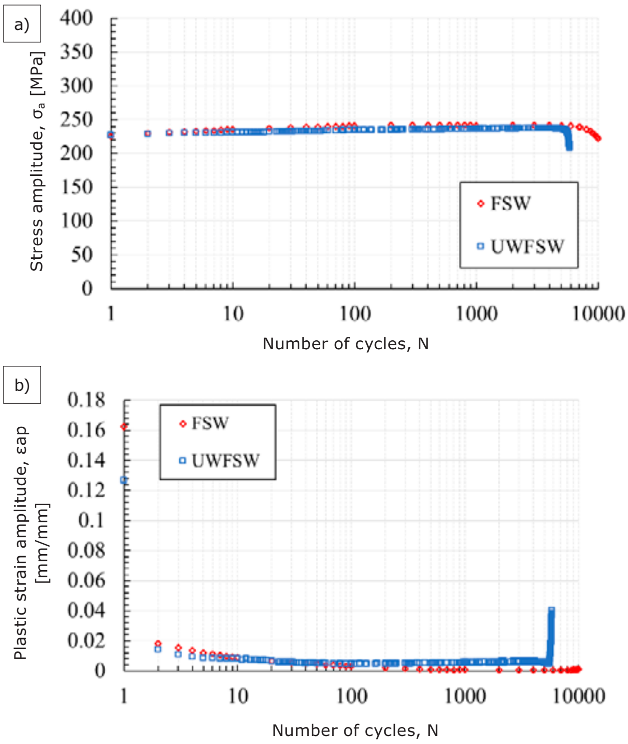

Fig. 5. Comparison of changes in stress (a) and plastic strain (b) amplitudes as a function of the number of cycles of test joints in relation to $\varepsilon_{ac} = 0.35$ %

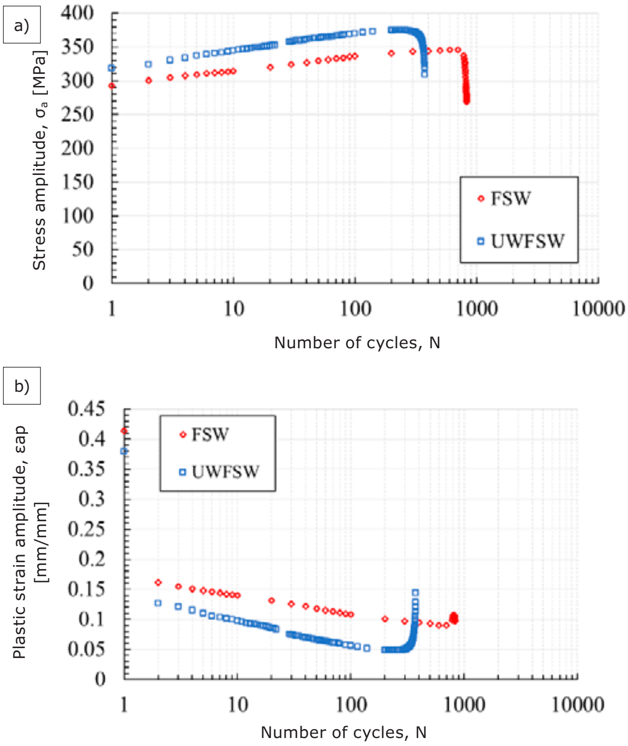

Fig. 6. Comparison of changes in stress (a) and plastic strain (b) amplitudes as a function of the number of cycles of test joints in relation to $\varepsilon_{ac} = 0.6$ %

(58 MPa) and tensile strength by approximately 9 % (43 MPa), as a result of water cooling.

3. Under low cycle fatigue conditions, the UWFSW joints were characterised by higher stress amplitude, lower plastic strain amplitude and lower number of cycles preceding failure than was the case with the FSW joints.

The research was funded by the Military University of Technology within Project UGB 708/2024.

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