Fatigue Behavior of Friction Stir Welded EN AW 5754 Aluminum Alloy Using Load Increase Procedure

A. B. Chehreh, M. Grätzel, M. Klein, J. P. Bergmann, F. Walther

***Abstract*—**Friction stir welding (FSW) is an advantageous method in the thermal joining processes, featuring the welding of various dissimilar and similar material combinations, joining temperatures below the melting point which prevents irregularities such as pores and hot cracks as well as high strengths mechanical joints near the base material. The FSW process consists of a rotating tool which is made of a shoulder and a probe. The welding process is based on a rotating tool which plunges in the workpiece under axial pressure. As a result, the material is plasticized by frictional heat which leads to a decrease in the flow stress. During the welding procedure, the material is continuously displaced by the tool, creating a firmly bonded weld seam behind the tool. However, the mechanical properties of the weld seam are affected by the design and geometry of the tool. These include in particular microstructural and surface properties which can favor crack initiation. Following investigation compares the dynamic properties of FSW weld seams with conventional and stationary shoulder geometry based on load increase test (LIT). Compared to classical Woehler tests, it is possible to determine the fatigue strength of the specimens after a short amount of time. The investigations were carried out on a robotized welding setup on 2 mm thick EN AW 5754 aluminum alloy sheets. It was shown that an increased tensile and fatigue strength can be achieved by using the stationary shoulder concept. Furthermore, it could be demonstrated that the LIT is a valid method to describe the fatigue behavior of FSW weld seams.

***Keywords*—**Aluminum alloy, fatigue performance, fracture, friction stir welding.

I. Introduction

The requirements for current and upcoming production technologies include equally high demands on the reliability of joining technologies. These demands which concern markets from automotive to aircraft industry are namely lightweight design, manufacturing of complex components and the continuously increasing demands on joint properties. Against this background, FSW, a high-potential solid-state joining technology developed in TWI in 1991 [1], represents a mature and valid joining technique. It can be used for a variety of metallic materials and combinations especially materials with low melting points such as aluminum alloys or materials which are relatively difficult to weld using conventional fusion welding techniques [2], [3]. This welding technique is also characterized by advantages such as the realization of different materials combinations, the absence of process gases and filler material as well as high strengths mechanical joint which make FSW suitable for numerous industrial applications some of which are noted in [4], [5]. During the welding process, a rotating tool plunges into the interface of the joining components and then moves along the defined seam course. The friction between the tool and the base material leads to the heating of the material while the pin deforms the bulk material and fills the cavity during the advancing movement with plasticized material like in an extrusion process [6]. Fig. 1 demonstrates the operating principle of FSW according to DIN EN ISO 25239-1 [7].

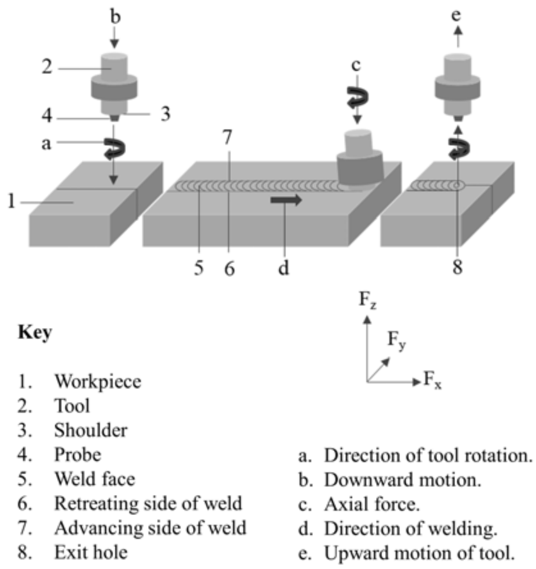

Fig. 1 Operating principle and components of conventional FSW

The operating principle of FSW is established on a welding tool, comprised of a shoulder and a probe. These tools are mainly distinguished in conventional and stationary shoulder FSW whereby, the differences are related to rotation velocity of shoulder and probe. In the case of conventional FSW, shoulder and probe exhibit the same rotational speed and direction. Conventional tools are the most widely used design and are characterised by simple construction and handling.

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Typical for this method is periodic surface structures as a result of a continuous rotational speed which is related to the displacement of the plasticized material. During stationary shoulder FSW, the shoulder is fixed and the frictional heat input is mainly generated by the probe. Due to the decrease of the displaced material, the acting forces can be reduced in comparison to conventional FSW. Furthermore, the stationary shoulder tool glides across the surface and forms a weld seam with significantly reduced surface roughness.

EN AW 5754 aluminum alloy shows outstanding corrosion resistance especially to seawater and industrially polluted atmospheres which makes it suitable for offshore construction applications. It is a relatively famous aluminum alloy which is used by many researchers for FSW investigations [8]-[10]. However, most of the literature investigating the fatigue behavior of EN AW 5754 aluminum alloy are focused on the friction spot welding process (FSSW) and only a few on the FSW process [11]-[15]. In addition, although several researchers used constant amplitude tests to investigate the fatigue properties of the aluminum alloys in FSW process [16], there exists even fewer literature performing the LIT for rapid assessment of the welded specimens. Therefore, the objective of this study is to further increase the knowledge of the fatigue behavior of EN AW 5754 aluminum alloys during the FSW process, to extend its application through optimization and to enhance the time- and cost-efficient LIT procedure.

II. Experimental Procedures

The investigation to determine the fatigue behavior of friction stir welded EN AW 5754 (AlMg3) aluminum alloy was performed on sheets with 2 mm thickness, 600 mm length, and 170 mm width. Table I shows the chemical composition of the material used.

TABLE I
Composition of EN AW 5754 H22 [12]

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
in %	0.4	0.4	0.1	0.5	2.6-3.6	0.3	0.2	0.15	Bal.

The welding experiments were carried out with conventional and stationary shoulder tool sets. The geometry of the conventional tool is depicted in Fig. 2.

The depicted and in-house manufactured conventional tool was fabricated from hot working steel 1.2344 (X40CrMoV5-1) with an aspect ratio of 2.6 between shoulder and probe. The 8 mm shoulder was specifically designed and manufactured with a concavity of 10° to hinder the displacement of the material out the welding zone. As for the probe, it consists of a tapered geometry, a thread and three flanks with an angle of 120° from each other.

The depicted stationary shoulder setup (shoulder and probe) are purchased from Grenzebach Maschinenbau (Fig. 3). The 8 mm shoulder had no concavity and the probe had a tapered and threaded geometry. During the investigations, the rotational velocity and the process force for conventional FSW were 3000 min^{-1} and 3750 N, respectively. For stationary shoulder FSW a rotational velocity of 11500 min^{-1} and an axial force of 3400 N were used. The penetration depth of 95% (i.e. 1.9 mm) of the sheet thickness was used for both designs.

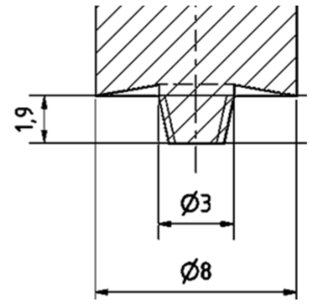

Fig. 2 Convectional FSW tool

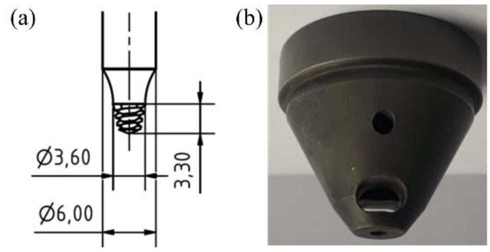

Fig. 3 Stationary shoulder FSW tool with (a) probe and (b) shoulder

A visual inspection according to DIN EN ISO 25239-5 [18] was carried out after the welding in order to characterize the weld seams. The welding experiments were conducted using a robotized FSW setup also purchased from Grenzebach Maschinenbau and connected to a Kuka KR500 heavy-duty robot (Fig. 4).

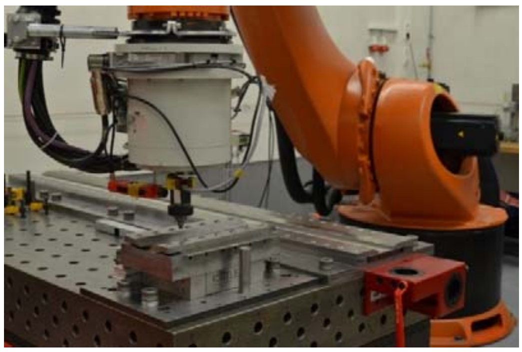

Fig. 4 Robotized FSW setup for stationary shoulder and conventional FSW

The welding configuration (Fig. 4) was force-controlled enabling an axial force up to 10 kN and a maximum rotational velocity of 14000 rpm. Each experiment was performed three times in butt joint configuration, keeping a welding speed of 1000 mm/min and tilt angle of 2°. After welding, the test specimens were prepared using a milling procedure according to DIN 50125 [19], as shown in Fig. 5.

The deformation behavior of EN AW 5754 friction stir welded aluminum sheets were analyzed under quasi-static and cyclic loadings. To characterize the mechanical properties of the specimens, tensile tests were carried out on a Shimadzu AG-X universal testing system with a load cell of 100 kN using the standard ISO 6892-1:2016 [20] at a strain rate of $\dot{\varepsilon}$ = 2.5 × 10^{-4} s^{-1}. The deformation behaviors and the total strain amplitude ε_t of the specimens during the tensile tests were analyzed using an extensometer with a gauge length of 50 mm and a strain measurement range of ± 10%. To ensure the reliability of the results, two tensile tests were performed for each welding procedure.

LIT in combination with constant amplitude tests (CAT) using the appropriate stress levels obtained from LIT, were performed on an Instron 8801 servohydraulic testing system with a load cell of 100 kN. This fatigue behavior characterization technique which is fully explained in [21] has been successfully applied on many classes of material from metal- to polymer-based material systems [22].

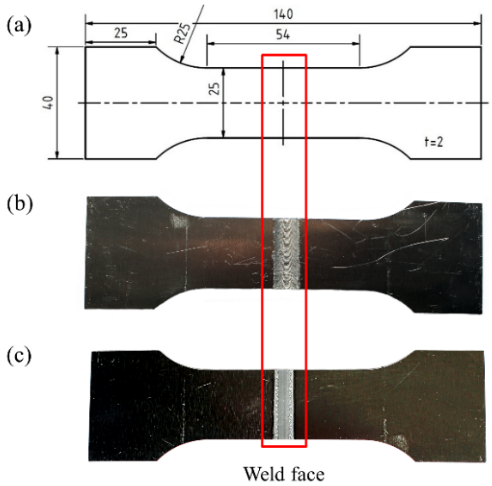

Fig. 5 (a) Specimen geometry and position of weld seam in specimens made by (b) conventional and (c) stationary shoulder tools

σ_a = 20 MPa was chosen as the starting point of the LIT at which the aluminum sheets are supposed to be damage-free. Afterwards, the stress level was continuously increased at a rate of 10 MPa/10^4 cycles until failure with a frequency of 10 Hz and under stress ratio of R = 0.1. An extensometer with a gauge length of 12.5 mm, with a strain measurement range of up to ± 40% was used for measuring the total strain amplitude $\varepsilon_{a,t}$ during the fatigue tests. Three LIT were performed for each welding procedure.

In addition to the tactile extensometer, an optical measurement technique of 3D-digital image correlation (DIC) by Limess was used for full-field image analysis and generation of deformation and strain maps over the entire material surface [23]. DIC system enables a frequency-dependent triggered image acquisition synced with the testing frequency (10 Hz) to visualize the strain distribution across the surface of the specimen and identify the localized damages. Applying the DIC also allows the comparison of its results with standard strain measurements done by the extensometer. Engineering tangential total strains ε_{xx} were computed after the test in the tensile direction.

To further investigate the material response to the cyclic loading, a Gamry Interface 1000A potentiostat was used during the fatigue tests. It is an electrical measuring technique which injects alternating current (AC) into the specimen and measures the current flow between the working and counter electrodes. The changes of the voltage during the fatigue tests allow monitoring the crack initiation and growth. The advantage of a potentiostat compared to normal potential drop techniques is that using potentiostat it is possible to investigate the suitable AC current frequency for the measurement. Using this feature, measuring frequency of 10 Hz was chosen in order to keep the influence of the wire resistance to a minimum.

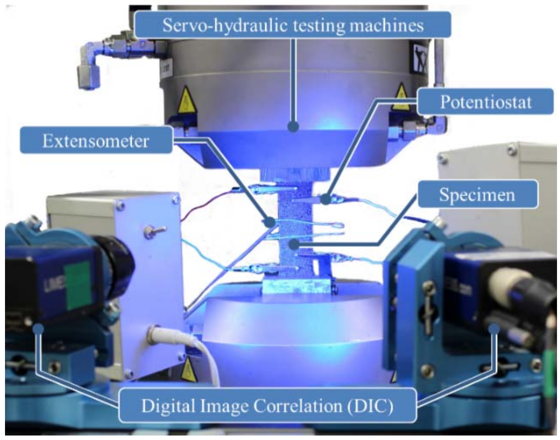

Fig. 6 Experimental setup for fatigue tests of FSW specimens

To cover the high cycle fatigue regime, four stress amplitudes were chosen for the CAT based on LIT results. Two tests were performed for each amplitude using LIT setup.

In this study, load increase and CAT for assessment of the conventional and stationary shoulder friction stir welded EN AW 5754 aluminum sheets were used. After testing, the fracture surfaces were analyzed using light microscopy to investigate the fracture mechanism.

III. Results

A. Quasi-Static Properties

Fig. 7 shows the result of the quasi-static tensile tests of the specimens made by stationary shoulder and conventional FSW. The summarized results are also visible in Table II. The serration in the plastic region of the tensile curves can be related to the Portevin-Le Chatelier (PLC) effect which is typical for EN AW 5754 aluminum alloys [19]. As it can be seen, the yield strength and the ultimate tensile strength of the samples made by the stationary shoulder FSW were about 7% and 10% higher than the conventional FSW samples, respectively. Their corresponding total strain was also slightly improved (5%) as a result of a more homogenous mixture of the materials which led to a more consistent weld structure.

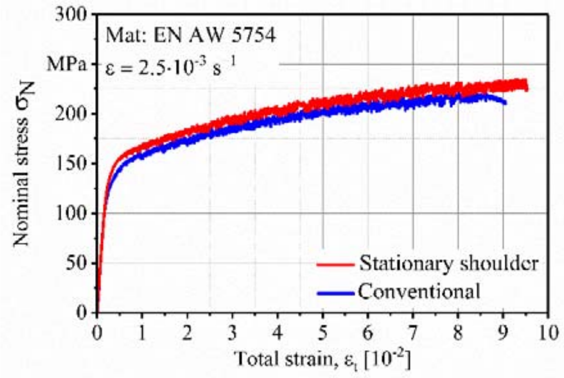

Fig. 7 Quasi-static tensile test results of stationary shoulder and conventionally welded samples

TABLE II
QUASI-STATIC PROPERTIES OF SPECIMENS MADE BY STATIONARY SHOULDER AND CONVENTIONAL SETUP

Welding process	Quasi-static properties		
	$\sigma_{y,\,0.2\%}$ [MPa]	σ_{UTS} [MPa]	$\varepsilon_{t,max}$ [%]
Conventional	109	212.3	9.05
Stationary shoulder	117	234.7	9.5

B. Fatigue Properties

Results of LIT for conventional and stationary shoulder friction welded specimens can be seen in Figs. 8 and 9, respectively. The material response using tactile extensometer, DIC and potentiostat was monitored to identify the onset and propagation of damage inside the material.

Three distinct regions in the material response can be detected in the LIT results. In the first region, material showed a constant response which can be considered as a damage-free zone. The corresponding stress level at the end of this region can be estimated as the fatigue strength of the material for low to high cycle fatigue regime. In the second region, starting approx. at 120 MPa first material response can be detected with the change in the slope of material response which indicates constantly increasing damage within the material with increasing of the stress amplitude. The third region is characterized by the stepwise behavior of the materials starting approx. at 180 MPa, detected by all of the used measurement techniques. The reason for this abrupt behavior needs further investigation. At the end of this region, when the defect size reaches the critical crack size, the fracture occurs. The slight difference in the results of the extensometer and DIC is due to the reason that the extensometer shows the strain between two single points connected to its blades; however, in Fig. 8 DIC depicts average of the strain map over the surface between the blades of the extensometer.

It can be seen from Fig. 9 that the stationary shoulder FSW specimens performed slightly better in LIT. Specimens welded by stationary shoulder setup, having a more homogenous weld zone and better surface quality, broke at stress amplitude of 220 MPa after 2×10^5 cycles and obtained a maximum total strain of 12.2%. On the other hand, conventional FSW specimens failed at stress amplitude of 215 MPa after 1.95×10^5 cycles and reached maximum total strain of 9.3%.

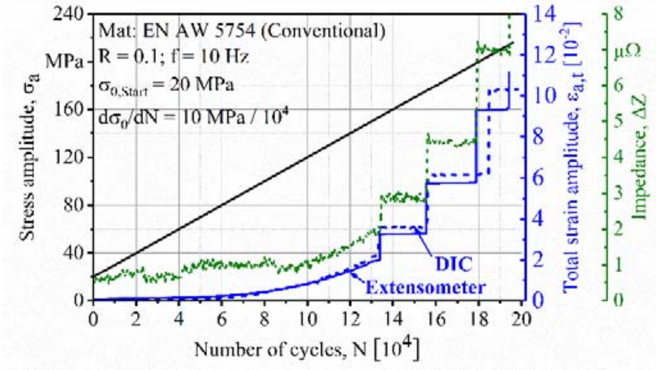

Fig. 8 LIT results for specimens made by conventional FSW

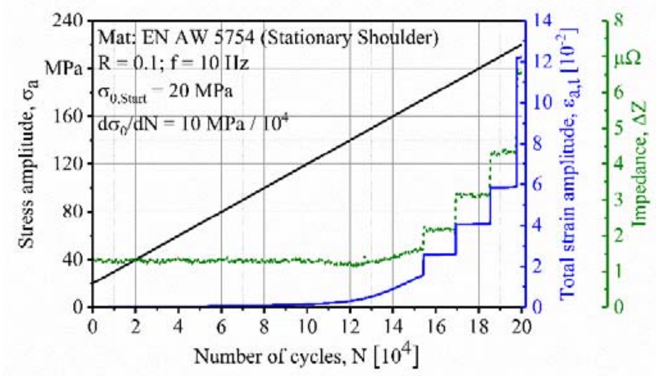

Fig. 9 LIT results for specimens made by stationary shoulder FSW

It is worth mentioning that electrical resistance measurement technique was able to detect an early stage damage within the stationary shoulder specimens approx. at 60 MPa where, neither DIC nor the extensometer showed any significant change in the material response to the increasing load. The first noticeable change in material response detected by the extensometer was at 120 MPa amplitude after 10^5 cycles. However, in the case of conventionally welded specimens, results of the potentiostat were analogous to the other measurement techniques detecting first significant signs of damage at 100 MPa at 8×10^4 cycles.

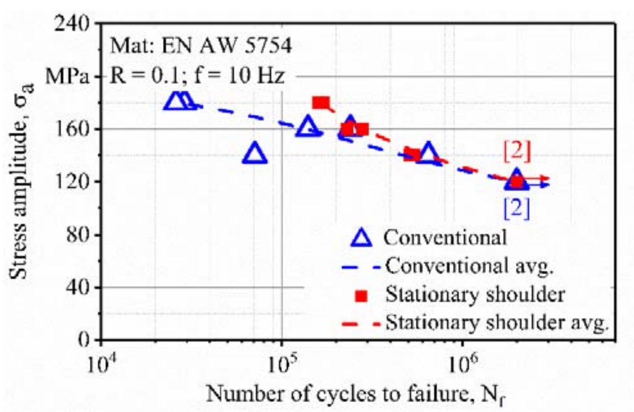

Fig. 10 Woehler curve for fatigue life assessment of welded specimens

The test results help to determine a stress value for the subsequent CAT, initiated with the stress level of 120 MPa for both types of welds where a uniform material behavior is expected. Based on the fatigue life of the material in this stress level, the stress amplitude was lower or increased for the next test.

Fig. 10 shows the CAT results for stress level of 120 MPa to 180 MPa. This range placed both types of welded specimens in the high cycle fatigue regime which is the potential application-relevant regime for the investigated welded specimens.

It can be seen that specimens in stationary shoulder FSW had a relatively lower deviation in the fatigue life compared to the conventional FSW. This high deviation in the fatigue life of the conventional FSW specimens can be attributed to their relatively high surface roughness which acted as crack initiation sites. Also, the smooth surface and homogenous weld zone in stationary shoulder specimens resulted in a significant increase in the fatigue life comparing to the conventionally welded ones.

C. Fracture Behavior

In all fractures, crack initiated in the transition zone between the base material and weld zone and in most of the cases, it continued to propagate on the same plane within the transition zone. In very few cases, fracture occurred when a crack from one transition zone propagated across the weld seam and connected to another crack on the other transition zone. As it can be seen in Fig. 11, the results of the DIC in the LIT also showed the strain concentration in the weld and transition zone as well as the moment of crack initiation in the transition zone. In addition, the existence of several angled strain zones was also visible within the specimen which was also reported by [9] and [24]. These results suggested that the welding zone possess sufficient durability during the fatigue tests.

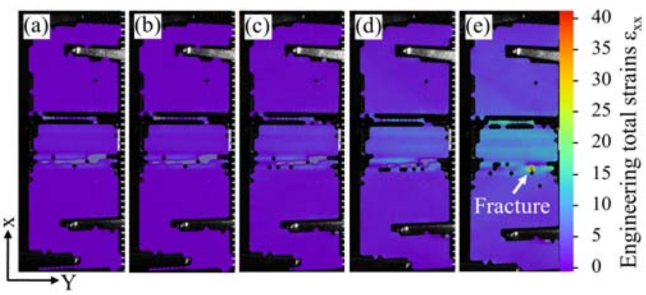

Fig. 11 DIC analysis of specimens during LIT at stress levels of (a) 100 MPa, (b) 170 MPa, (c) 180 MPa, (d) 200 MPa, and (e) 210 MPa

Fracture surfaces of the specimens for each welding procedure were studied to investigate the cause of failure and understand the effect of welding procedure on the fatigue life. Both specimen types suffered crack initiation from the surface and towards the middle of the specimen (Fig. 12).

The surface roughness of the conventional FSW specimens was visibly much higher than the stationary shoulder FSW specimens. That high roughness acted as stress raiser which was the preferred cause of the crack initiation. As it can be seen in Fig. 13, there was one main crack initiation site in the welds made by the stationary shoulder tool while there were multiple crack initiation sites on the fracture surface of the conventional FSW specimen that drastically shortened the fatigue life.

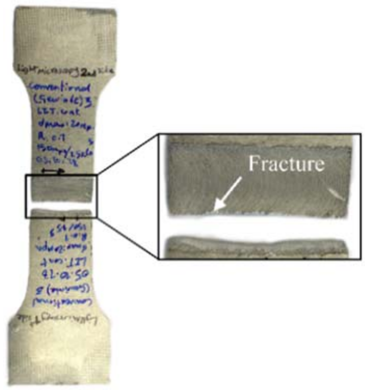

Fig. 12 Example of a fractured specimen at the end of the fatigue tests

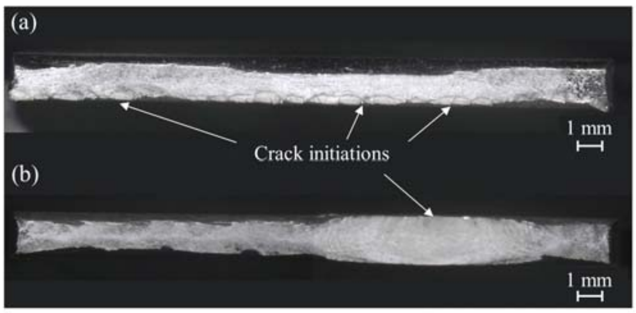

Fig. 13 Light micrograph of the fracture surface of the sample manufactured by (a) conventional and (b) stationary shoulder setup

IV. Conclusions

In this study, mechanical properties of the friction stir welded EN AW 5754 sheets using conventional and stationary shoulder FSW were investigated. It was shown that the stationary shoulder FSW samples possessed 7%, 10%, and 5% higher yield strength, ultimate tensile strength, and elongation, respectively than the samples welded by conventional setup. Fatigue behaviors of welded specimens were reliably monitored using electrical resistance measurement, DIC, and an extensometer. In several cases, the electrical resistance measurement technique was able to detect the damage within the material during the fatigue test in a much earlier stage than the extensometer. LIT and subsequent CAT were used to show the superior fatigue properties of specimens welded by stationary shoulder tool in comparison with the conventionally welded samples. Results of this study will be used in order to be able to choose the best process parameters to investigate the pre-corrosion fatigue properties of friction stir welded EN AW 5754 aluminum alloy.

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