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An experimental investigation of fatigue behavior and deformation of double spot friction welded joints

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ABSTRACT

Fatigue behavior of double spot friction welded joints in aluminum alloy 7075-T6 plates is investigated by conducting monotonic tensile and fatigue tests. The spot friction welding procedures are carried out by a milling machine with a designed fixture at the best preliminary welding parameter set. The fatigue tests are performed in a constant amplitude load control servo-hydraulic fatigue testing machine with a load ratio of ($R = P_{min}/P_{max}$) 0.1 at room temperature. It is observed that the failure mode in cyclic loading (low-cycle and high-cycle) resembles that of the quasi-static loading conditions i.e. pure shearing. Primary fatigue crack is initiated in the vicinity of the original notch tip and then propagated along the circumference of the weld's nugget.

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1. Introduction

Increasing problems in replacing welded joints from conventional iron based sheets with lightweight and high-strength materials have lead to an increasing utilization of new welding techniques. Spot Friction Welding (SFW) is a technology that has recently received considerable attention from modern industries.

SFW is a new solid-state welding process that has been targeted by the automotive and, aerospace industries [1]. It is an advanced type of friction stir welding (FSW), which was first introduced by TWI in 1991 [2] and further developed by Mazda Motor Corporation and Kawasaki Heavy Industries [3] in order to produce hoods and rear doors for the Mazda RX-8 sport model. The SFW technology includes a process similar to FSW except that, instead of moving along the weld seam, the tool only penetrates the sheets. The specimens are joined by the action of frictional heat that is generated in the contact interface of tool and fixed specimens. This is the major cause of material being plasticized around the pin. The resulting weld has an inherited characteristic hole in the middle of the joint left by the probe. Both the FSW and SFW are ecological welding processes, due to their ability to reduce material waste and, prevent pollution and harmful gas emissions which are usually associated with the common fusion welding methods. Other advantages of friction welding that have attracted many researchers in employing this method are good retention of baseline mechanical properties, little distortion, low residual stresses, few weld defects [4], and the ability to join dissimilar materials with good mechanical performance which has been investigated by Chang et al. [5] and Su et al. [6] described the material flow during welding of Al 5754 and Al 6111 sheets. The most important advantage is the ability to join advanced high-strength steels (AHSS) [7], which are very common materials in the automotive and aerospace industries, with over 90% in power saving and 40% in equipment saving compared with resistance spot welding (RSW) Sakano et al. [8].

The main research fields of SFW technology can be categorized as: micromechanical characteristics of the joints, optimization of welding process parameters, welding dissimilar materials, evaluation of the effects of deviations of process parameters on joint strength, and fatigue life and failure mode determination of joints. The following documents a number of investigations on SFW between similar and dissimilar Aluminum alloys.

Smith et al. [9] proposed a review of the advantages of Friction Stir Spot Welding (FSSW) and its applications in the transportation industry. In order to achieve joints with better mechanical performances, Buffa et al. [10] introduced an operational mode of the welding process, where the preloaded tool is subjected to an axial rotation and an orbital motion. Merzoug et al. [11] focused on the experimental approach to determine the optimal parameters of the FSSW process for AL 6065-T5 alloy. Da Silva et al. [12] evaluated the effect of joining parameters on the mechanical properties, microstructural features, and material flow of dissimilar intermixing of FSSW. Rodrigues et al. [13] studied the influence of welding parameters especially the geometry of two different tools, with

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conical and flat shoulders, on microstructure and mechanical characteristics of the joints in order to achieve non-defective welds. Failure modes of SFW joints under quasi-static loading conditions and their fatigue failure are also of great importance and have been widely investigated from strain-life and fracture mechanic points of view.

Lin et al. [14,15] studied the microstructures and failure modes of SFWs in lap-shear specimens of 6111-T4 sheets with concave and flat shoulders. They employed optical micrographs and crack propagation models based on stress intensity factors expressed in terms of local stresses. Wang and Chen [16] predicted fatigue lives of FSSW in AL 6061-T4 lap shear specimens under cyclic loading conditions based on Paris law and local stress intensity factors as functions of the kink length. Lin et al. [17] investigated the failure modes of SFW joints of aluminum 6061-T6 sheets under quasi-static and cyclic cross-tension loading conditions. Fatigue lives were estimated by employing Paris law and accurate values of global and local stress intensity factors which were calculated based on the 3D finite element model. Rash Ahmadi et al. [18] investigated the fatigue life of single FSSWs by employing finite element analysis and strain-based modified Morrow's damage equation. Taking into account hardness-dependence in cyclic material constants and mechanical strength of different welding zones, their results showed good agreement with experimental findings.

Mechanical joints which connect overlapping plates are widely employed in engineering structures especially on aircraft and ship building. As noted above, the majority of the studies addressing the performance of SFW joints on fatigue circumstances which are conducted on a single joints to obtain fundamental information. Although single joints are generally employed in practice, this method is rarely used in double lap configurations. Currently adhesive bonding, riveting and bolting are the most common procedures in producing double lap joints. A number of works have been conducted in this area. Campilho et al. [19] evaluated the stress distributions, residual strength and failure modes of single and double-lap joints under tensile loading based on finite element modeling and experimental tests. Chakherlou et al. [20] investigated the effect of cold expansion on fatigue life enhancement of double shear lap. Abazadeh et al. [21] estimated the fatigue lives of double shear lap joint specimens of Al 2024-T3 with bolt clamped and interference fitted-bolt clamped fastener holes by employing various multi-axial fatigue criteria. In literature there is lack of information dealing with the performance of double friction stir welded joints in different circumstances. For example, Cerri and Leo [22] who evaluated mechanical properties of double-lap FSW joints in 2024-T3 and 7075-T6 aluminum alloys during heat treatments. They investigated the microstructures of welded zones of double lap FSW joints subjected to several post-welding heat treatments at warm and high temperature that were followed by room temperature deformation.

In fact, the applicability of the results obtained in most of the previous studies conducted on single welded joints, can be subject to question for other types of joints. Therefore, in the present research, the performance of welds on fatigue condition is investigated for the case of double shear lap joints as a more practical configuration. This article aims to study the fatigue behavior of double SFWs. The structure under consideration consists of a double spot friction joint which demonstrates the capability of this welding technique in joining more than two metallic sheets and this procedure can lead to having an inexpensive alternative joining method with good level of confidence. To this end, experimental fatigue tests are conducted on Al alloy 7075-T6 in order to afford a detailed analysis of the process and characterize the failure modes and deformations of the specimens.

Table 1
Chemical composition (wt.%) of 7075-T6 aluminum alloy.

Si	0.4
Fe	0.5
Cu	2
Mn	0.3
Mg	2.9
Cr	0.28
Zn	6.1
Ti	0.2
Al	Rem.

2. Experimental program

2.1. Specimen geometry

A popular aluminum grade in aerospace industry 7075-T6 alloy was chosen to produce double SFW specimens. The chemical compositions and tensile properties of the parent material are listed in Tables 1 and 2 [23]. The stress–strain relation for aluminum alloy 7075-T6 was obtained from tensile tests and is shown in Fig. 1.

The main purpose of this study is to investigate the fatigue behavior of double SFW joints. To this end, a series of equally sized samples was fabricated by employing three sheets with 2 mm thicknesses, with a length of 150 mm and a width of 30 mm. The overlap area of the sheets was $30 \times 30\ mm^2$ as shown in Fig. 2.

2.2. Welding parameters and tool geometry

Generally the crucial parameters which affect the quality of SFW joints are tool geometry, rotational speed, holding time and downward force or shoulder plunge depth. Since the proper processing variables are different for each tool, any changes in these parameters could have an influence on the strength of SFW connections. Since the major goal of this study is to investigate the fatigue behavior of double SFW joints, the only parameter requiring modification in the fatigue tests, is the applied load. A special fixture was designed for double SFW of specimens, as shown with the specimen in Fig. 3. The specimen was mounted on a backing plate which was supported by upper sheet with four bolts. High

Table 2
Mechanical properties of Al 7075-T6.

Property	Value
Modulus of elasticity (GPa)	71
Yield strength (MPa)	469
Ultimate tensile strength (MPa)	578
Elongation (%)	33
Poisson's ratio	0.33

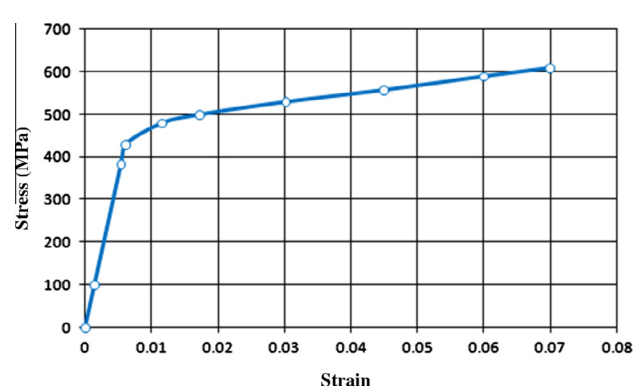

Fig. 1. True stress–strain curve of 7075-T6 Aluminum alloy.

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