Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 28(2018) 193−219
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties

Mohd. Atif WAHID, Zahid A. KHAN, Arshad Noor SIDDIQUEE

Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi, India

Received 5 December 2016; accepted 18 April 2017

Abstract: Friction stir welding (FSW) is a solid-state welding process which is capable of joining materials which are relatively difficult to be welded by fusion welding process. Further, this process is highly energy-efficient and environmental-friendly as compared to the fusion welding. Despite several advantages of FSW over fusion welding, the thermal cycles involved in FSW cause softening in joints generally in heat-treatable aluminum alloys (AAs) due to the dissolution or coarsening of the strengthening precipitates leading to decrease in mechanical properties. Underwater friction stir welding (UFSW) can be a process of choice to overcome these limitations. This process is suitable for alloys that are sensitive to heating during the welding and is widely used for heat-treatable AAs. The purpose of this article is to provide comprehensive literature review on current status and development of UFSW and its importance in comparison to FSW with an aim to discuss and summarize different aspects of UFSW. Specific attention is given to basic principle including material flow, temperature generation, process parameters, microstructure and mechanical properties. From the review, it is concluded that UFSW is an improved method compared with FSW for improving joint strength. Academicians, researchers and practitioners would be benefitted from this article as it compiles significantly important knowledge pertaining to UFSW.

Key words: aluminum; friction stir welding; fusion welding; mechanical properties; microstructure; underwater friction stir welding

1 Introduction

The joining of materials has been an essential issue for several ages. In general, various problems have been found in traditional fusion welding (FW) with regard to welding of different alloys, i.e., aluminum [1] and magnesium [2]. Welding discontinuities such as cracks, voids, porosity and inclusions during FW significantly affect the quality and mechanical properties of the welds. In 1990's, a solid state welding process, friction stir welding (FSW) was developed by The Welding Institute (UK) [3]. This process is competent enough to weld materials which are relatively difficult to be welded or almost unweldable by FW process. The major aspect of this process is that the temperature remains below the solidus temperature, i.e., melting of the material does not take place. As the welding takes place below the solidus temperature, various defects associated with the FW process are not present in FSW, leading to outstanding weld strength and ductility. Further, this process is highly energy-efficient and less prone to environment than existing FW processes. Additionally, distortion in the final products is also reduced due to the decrease in the residual stresses owing to reduced thermal flux [4,5]. FSW was initially developed for aluminum alloys (AA), but subsequently, it was employed to many different materials and alloys. FSW is found extensive application in aerospace, automobile, railway, shipbuilding and offshore construction [6−8].

In FSW, a non-consumable rotating tool with a profiled probe and shoulder is plunged into the substrate as the force is applied vertically downward. The friction between the tool and workpiece increases the temperature in the weld region which softens the materials being welded and the workpiece gets plastically deformed easily. As such, a softening region is created around the pin, leading to the reduction in the resistance to deformation of the base material. The tool is also traversed along the joint line which causes the material movement from advancing side (AS) to retreating side (RS) and the tool shoulder consolidates the material at the back side of the pin leading to a solid joint. As a result of this, a joint is produced in 'solid

Corresponding author: Mohd. Atif WAHID; Tel; +91-8826815309; E-mail: wahidatif89@gmail.com
DOI: 10.1016/S1003-6326(18)64653-9

state' [9−13]. The working principle of FSW is schematically shown in Fig. 1 [9].

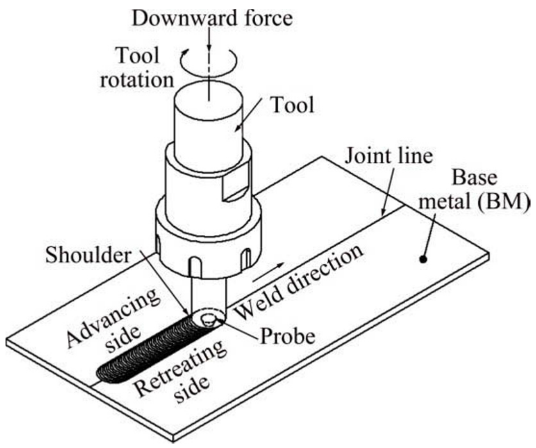

Fig. 1 Schematic diagram of FSW process [9]

FSW leads to fine grain structure in the stir region due to dynamic recrystallization owing to severe plastic deformation, resulting in substantial microstructural evolution [14−17]. Due to this fine microstructure, good mechanical properties are observed in FSW. Even though the heat input in FSW is low as compared to FW, it is high enough to cause softening generally in heat treatable AAs. The softening is due to the dissolution or coarsening of the strengthening precipitates, leading to decreased mechanical performance of the joints [18−20]. In order to resolve these issues, a method that enhances the cooling rate and lowers the peak temperature can be used to improve properties of the joint in FSW. In this regard, external cooling has been employed in several solid state joining processes to improve the joint performances [21−23]. Water cooling method has also been investigated to provide cooling effect on the samples during FSW because of its extensive circulation and exceptional heat absorption capability.

UFSW is a modification of the FSW in which the water as the coolant is employed to normalize the temperature profiles existing in the weld joint [24−26]. Fundamentally, the welding is performed under water, either in a water container or in a state where water continually flows across the surface of the sample, as shown in Fig 2.

During UFSW, the high heat absorption capacity of water manages the transmission of heat to thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). Thus, the low heat existing in the TMAZ and HAZ due to cooling is not adequate for coarsening of the precipitates [27]. Also, the TMAZ and HAZ width is narrowed by restricting the heat input and plastic deformation by UFSW [27,28]. UFSW gives improved mechanical properties by minimizing various welding defects like porosity, shrinkage, and solidification

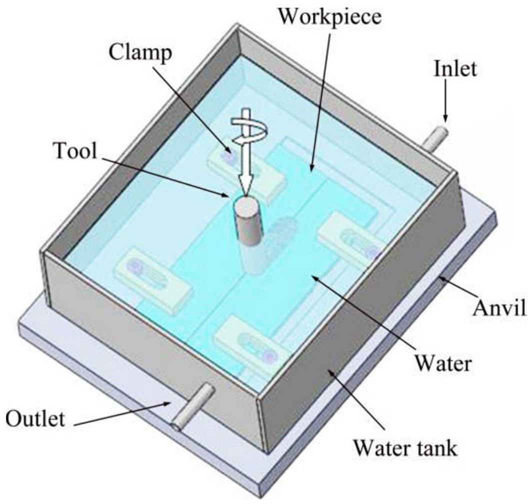

Fig. 2 Schematic diagram of UFSW

cracking. It also provides well-defined variation in grain size in different zones along the joint and therefore, a high quality weld joint is produced. This process is suitable for alloys that are sensitive to overheating during the welding process and it is widely used for AAs [29]. UFSW has diverse marine and offshore applications. It is widely used in shipbuilding, submarines, oil and fuel tanks and various offshore structures involving fabrication and repair. UFSW is gaining importance as a very valuable welding process due to its ability to provide superior mechanical properties over FSW and FW [25−27,30]. Table 1 presents a comparison of UFSW with FSW and FW with respect to various features to demonstrate the advantages and benefits of UFSW.

The benefits of UFSW over FSW are as follows.

1) USFW is suitable for materials and alloys that are sensitive to overheating.

2) Development of peak temperature is lower in UFSW than in FSW, limiting the coarsening and precipitate dissolution.

3) UFSW provides the better mechanical properties of the workpiece materials than FSW.

4) UFSW prevents the oxidation and provides better surface texture than FSW.

5) UFSW offers refined grain structure as compared to FSW.

6) UFSW is more suitable to heat-treatable aluminum alloys as it reduces the softening effect.

7) Less welding defects are observed in UFSW than in FSW.

8) Development of intermetallic compounds is less in UFSW than in FSW.

9) UFSW reduces the residual stresses and creates less distortion than FSW.

UFSW is relatively a new variant of FSW due to which very few investigations pertaining to the UFSW