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Submerged friction stir welding: An overview of results of experiments and possible future works

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Abstract

Conventional Friction Stir Welding (FSW) is performed in an open air environment making use of the heat generated by both friction and plastic deformation of a material. Submerged Friction Stir Welding (SFSW) is a new development from the FSW process in which the welding is performed under liquid medium like water or brine. SFSW process has wide applications in the marine field. This paper reviews the investigations carried out in SFSW and compares them with conventional FSW. Also, it describes the influence of the process parameters like tool rotational speed and tool traversing speed on mechanical and microstructural properties of the joints made in SFSW, compared with FSW. Further, it deals with some of the novel methods of SFSW. Research gaps are identified to suggest future work for deriving more information regarding SFSW.

Keywords: Friction stir welding, Submerged friction stir welding, Tool traversing speed, Tool rotation speed, Mechanical properties

1. Introduction

A solid state welding process known as Friction Stir Welding is gaining importance in field of the welding of lightweight materials. In this process, both the heat produced by the friction between the rotating tool and workpiece surface and heat generated due to the plastic deformation of the material are sufficient to plasticize the workpiece material to be joined and welded. The advantage of using this process is to overcome defects like solidification cracking and distortion, which are common in conventional fusion welding [1]. In the past, many researchers have investigated this process using aluminium [2], magnesium [1], steel [3], composites [4], and polymers[5]. Initially underwater friction stir welding (UFSW) was attempted to reduce excessive heat generation observed in conventional FSW to control the formation of brittle inter-metallic compounds [6].UFSW is also known as Submerged Friction Stir Welding (SFSW) [6]and Immersed Friction Stir Welding (IFSW) [7-9]. Few researchers have tried friction stir processing (FSP) under water and air to investigate the mechanical and microstructure properties of the aluminium Al7075 alloy [10], and magnesium alloys AZ31B and AZ91 [11-12]. Underwater welding technology is of very much importance in the case of construction of structures like platforms for underwater mining of crude oil and natural gas as well as for erection of pipelines which transport gas or liquid under the sea. Also, the erected structures may fail subjected to the various factors like corrosion wear and fatigue, among others. Furthermore, maintenance and service of pipelines require a suitable wet welding technology [13]. Figure 1 shows the conventional FSW and UFSW setup for experimentation [14].

Among the various welding techniques used under water, manual metal arc (MMA) welding with a covered electrode and a dry method in which the welding area is isolated from the surrounding liquid, are commonly used [15]. Recently, researchers investigated various new techniques of underwater welding. Among them is submerged friction stir welding (SFSW). From a literature survey, it was observed that very little work has been carried out in this area and more information needed. This paper describes the research done in the past and advancements in SFSW. It provides information regarding SFSW with respect to welded material, type of welding, design of tools, process parameters and their effects on the properties of the welded joints to open opportunities for researchers to fill knowledge gaps.

2. Materials and types of welded joints

SFSW was carried out using various materials that were both similar and dissimilar to those studied in the past. From the literature survey, it is observed that the majority of the materials under investigation were aluminium alloys

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(Al) [7-9, 14, 16-36] with other work on materials such as steel [37-39]. Studies are very negligible on FSW using other materials. In fabrication of marine structures, AISI 2205 duplex stainless steel material is very extensively used due to its better machinability and weldability characteristics [40]. However, this material has not drawn much attention from researchers investigating FSW under any liquid medium.

Few attempts have been made to study the SFSW of dissimilar materials such as different grades of aluminium alloys [41], Al-Mg alloys [42-44], aluminium alloys with copper [45] and galvanized bolts of grade 8.8 with structural steel (St 37) plates [46]. So, based on this survey, it is clear that limited SFSW research work has been done and this is supported same by Garg et al. [47] and Noor and Awang [48]. Furthermore, a very little study on SFSW of dissimilar materials was done in the past, and therefore, availability of this information is very limited. This was also observed by Wahid et al. [49]. So, more attention is required to explore the welding characteristics of SFSW on similar and dissimilar materials such as stainless steel, high strength low alloy steel (HSLA), Inconel, titanium and composites.

The different types of welded joints made by the researchers in the past are butt joints [6, 9, 14, 22, 24-26, 41-44], lap joints [45], stud welding [46] and stitch welding [38-39]. Within the surveyed literature, it is observed that T-joint, corner joint, edge joint and pipe joint welding has not been investigated or that little work has been done using both dry and wet conditions.

3. Effect of design parameters on the joint formed

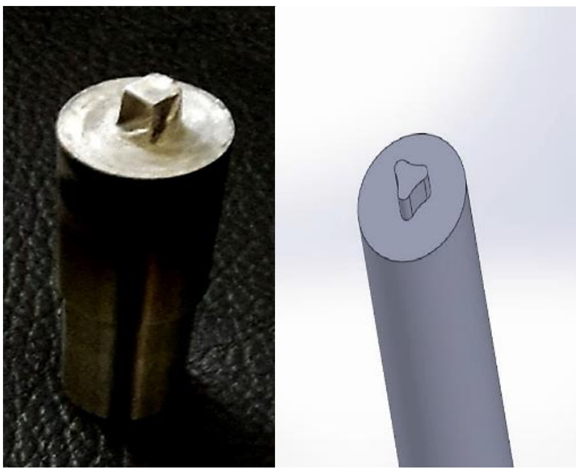
Tool material, tool pin shape and tool pin size are some of the important design parameters under consideration. The majority of the tools are made with the H13 steel [6, 28-30], High Speed Steel (HSS) [7, 23] and Hardened Super HSS [14, 31-32]. Usually, a shouldered tool with a pin is used for the stirring and welding process. The different shapes of pins used in SFSW are cylindrical [6, 19, 26, 28], cylindrical threaded [25, 41, 43] and conical threaded [7-8, 14, 24, 31-32]. Special shapes like triangular [24], tapered square [34] and cam profiles [35] have also been tried by previous researchers due to the pulsating action caused by these pin profiles to get thorough mixing in the weld region. Figure 2 shows the special shaped tool pins used in FSW [34-35]. It is observed from the literature survey that length of the pin was designed to be 0.1 - 0.3 mm less than the thickness of the sheet material under investigation [16, 23, 34, 44].The tool pin diameter (major diameter in the case of a tapered pin) was between t and t+1 mm where 't' is the welded sheet thickness [6, 16, 25, 29, 41].

4. Effect of process parameters on the mechanical properties of the joint formed

From the reviewed literature, it is found that most researchers compared the mechanical properties of the welded joints formed by conventional FSW (in air) and submerged FSW (in water or other liquid medium). Fu et al. [22] performed FSW in air, cold water and hot water. They concluded that regardless of the weld parameters used, the FSW done under hot water conditions was the

(a) (b)

Figure 1 Experimental setup for (a) conventional FSW and (b) UFSW [14]



(a) (b)

Figure 2 Special profiled tool pin shapes (a)tapered square [34], and (b) cam profile [35]

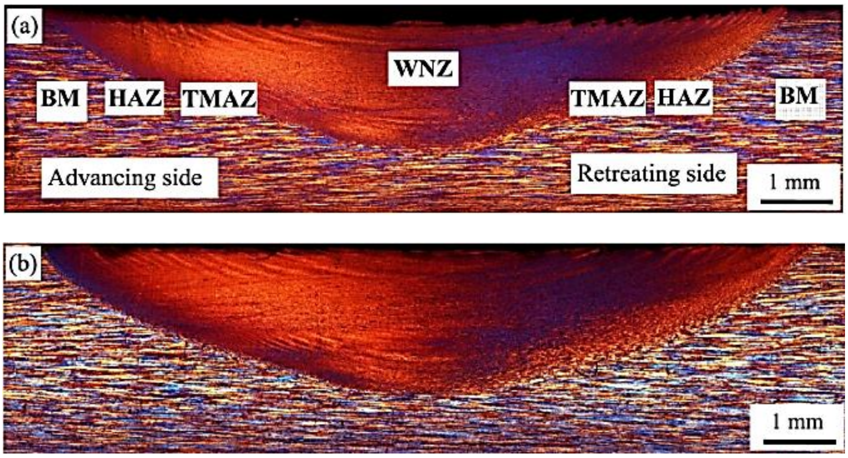


Figure 3 Optical microscopy of various welded joint zones observed in (a) FSW and (b) SFSW [29]

best among the three in improving the welded joint. Sabri et al. [14] found that tensile strength (TS) is higher in a joint made in UFSW and the joint efficiency is about 60% higher than that obtained in FSW. This was attributed to the precipitation behavior. This is the sequence of formation of precipitate and heat available in the thermo-mechanical affected zone (TMAZ) are responsible for the increased tensile strength. In UFSW, the cooling rate is higher than in conventional FSW, so the weld attained brittleness and increased tensile strength, as observed by Papahn et al. [24]. A tensile strength of 152.3 MPa, which is 63.3% of Mg alloy sheet strength, was reported by Zhao et al. [43] in FSW of dissimilar materials, i.e., Al and Mg alloys.

Tool rotational and tool traversing speeds are the major process parameters under investigation in both FSW and SFSW. From the experiments, it was found that the traversing speed of welding plays a predominant role in improving the mechanical properties of the joints made by UFSW [8, 27]. Increased TS was observed when increasing the tool rotational speed and decreasing the tool traversing speed [27]. Finer grains are produced in the welded region at lower rotational speeds and higher traversing speed and hence hardness is increased [41]. In FSW done in air, an increased tool travel speed decreases the heat input, which in turn decreases the dissolution, thereby strengthening precipitate formation and therefore increasing the TS. In the case of UFSW, both lower and higher tool travel speeds decrease TS due to the formation of voids [7]. Also, increasing the traversing speed results in a 20-25% increased efficiency of the welded joint in UFSW [31-32].

5. Effect of process parameters on microstructural properties of the joint formed

Figure 3 shows optical microscopic images of various zones of the welded joints produced in FSW and SFSW using AA3003 aluminium alloy reported by Tan et al.[29]. It was found that the grain size in the weld nugget zone (WNZ) is reduced significantly with SFSW compared with that of conventional FSW.

Since the sizes of the grains are finer due to the stirring action of the rotating tool both in air and water FSW, the highest hardness is obtained in the WNZ and the lowest in heat affected zone (HAZ) [23, 29]. Fracture occurred at the bonding line of the weld due to the high hardness difference between the WNZ and base metal (BM) in both conventional and SFSW [37, 43]. Sabari et al. [31] observed severely deformed grains in the thermo-mechanical affected zone (TMAZ) that move toward the stirred zone. Also, a gradual deformation was observed in the retreating side (RS),whereas it was abrupt on the advancing side (AS) in the case of FSW. In UFSW, both AS and RS showed the same deformation.

6. Advances in SFSW

Mofid et al. [42] performed FSW of dissimilar materials under liquid nitrogen and observed lesser mixing and formation of much smoother interfaces due to the low peak temperature compared with FSW in air. Friction taper plug welding (FTPW) is a combined operation of blind hole drilling and filling of the consumable plug material concentrically in a hole. Zhang et al. [38] tried friction stitch welding of a plug by overlapping five FTPWs where in three FTPWs were done along a predefined path with a definite distance and two more FTPWs are carried out to connect previously made welds. It is concluded that better joint quality was achieved by properly designing the geometry of hole and plug to produce higher heat generation and better plastic flow. Similar work was carried out by Teng et al. [39] to weld a Q345 steel plug in a DH36 steel plate. They arrived at the conclusion that the tensile strength was reduced in the lower part of the weld due to crack development in the overlapping FTPWs. Spray formed aluminium is very sensitive to heat input during welding. A study was done by Wang et al. [27-28] to balance the required heat input to produce better UFSW joints. It was stated that a 30% increase in strength was realized and elongation doubled in comparison with the joints made by a conventional method. Wahid et al. [35] investigated the effects of various cooling media like air, normal water and water with crushed ice on the properties of welded joints. It was found that an increased cooling rate produced no significant improvement in elongation and tensile strength of the joints made in water with crushed ice. The values of these parameters were lower than for FSW and UFSW joint strength.

7. Discussion

From a review of the literature, it is observed that the majority of the researchers used aluminium alloys or aluminium with other materials due to the extensive use of lightweight materials in industry. However, the materials used in marine and other underwater applications have not been well investigated. Previous researchers concentrated more on butt welding and did not investigate on other types of welded joints. Different tool pin shapes are used in FSW for thorough mixing by pulsating action, but only few shapes have been studied in SFSW. The effects of various tool types and tool pin shapes need to be explored. Tensile strength, elongation and hardness of the welded joints were studied by most of the earlier researchers. From the reviewed literature, it is seen that better welded joints are obtained using higher tool rotational speeds and lower tool traversing speeds. These actions generate sufficient heat for plasticizing and welding in both FSW and SFSW. Increased tensile strength, hardness and decreased% elongation were reported by many researchers [14, 28, 31-32] in SFSW over that of FSW due to the higher cooling rate in SFSW. Formation of fine grains due to the stirring action of the rotating tool in the WNZ is another reason for increased hardness. Fractures occurred along the bonding line of the weld due to the higher hardness gradient between the base metal and WNZ.

8. Conclusions and scope for future research work

From the reviewed literature, the following conclusions can be drawn:

1. Extensive work has been carried out in FSW of aluminium alloys. Few researchers have attempted SFSW using the same materials.
2. The tensile strength of joints formed in SFSW is higher than those of FSW [14, 28, 31-32].
3. Tool traversing speed has played a predominant role in improving the mechanical properties of the joints produced by SFSW.
4. Overall joint efficiency of UFSW is a maximum of 60% higher than the FSW [14] in the reviewed literature.
5. The maximum hardness is in the center of the WNZ and minimum in the HAZ.
6. The extent of deformation is the same in both AS and RS in SFSW but it is abrupt in the AS of conventional FSW.
7. Few researchers have investigated the FSW process under water with crushed ice and liquid nitrogen.

In spite of many advantages and applications of SFSW over FSW, only limited information is available at present. The following future research work should be done to study SFSW:

1. SFSW of materials like stainless steel, Inconel, titanium, polymers, and composite should be examined. The outcome of investigation may open a new platform for using SFSW in the offshore oil and gas industry, ship building industry and other marine applications for fabrication and maintenance work.
2. Investigation of the effect of various spin shapes on joint properties should be done.
3. Influence of various tool materials on the joint efficiency needs examination.
4. A study on the effect of various cooling media on the mechanical and microstructure properties is needed.
5. A study of properties such as flexural strength, impact strength, and fatigue strength, among others is needed in addition examination of tensile strength and % elongation.
6. Investigation on inter-metallic compound formation in dissimilar material welding should be done.
7. Behavior of such processes under deep and high pressure environment needs to be examined. This will enable future use of SFSW for maintenance of submarine structures where the pressure is very high.

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