A Review on Underwater Friction Stir Welding (UFSW)

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Abstract Underwater Friction Stir Welding (UFSW) is noted as an advanced technique in welding field which is a really new and emerging technology in recent years. In the present paper, a brief explanation on introduction to the Underwater Friction Stir Welding (UFSW) technique along with a review on the latest researches have been made. The review is designed based on joint strength analysis, thermal distribution analysis, microstructural analysis, process modelling and computing techniques, effect of thermal boundary condition in UFSW, effect of process parameters, defects in UFSW and dissimilar welds. The applications of UFSW have also been discussed, along with a detailed description of advantages and limitations of UFSW technique. Lastly, the possible future research exploration has been proposed.

1 Introduction

Friction Stir Welding (FSW) is a comparatively modern, besides unique form of solid-state joining method that applies a non-consumable tool to weld two facing workpieces without melting the workpiece material. This technique is invented and experimentally proven by Wayne Thomas at The Welding Institute (TWI) of United Kingdom (UK) in December 1991. Also, TWI held patents in this operation method which is the first well detailed procedure. At first, the FSW method was observed as a "laboratory" inquisitiveness, however then it was established as a technique which provide virtuous advantages in products fabrication [1, 2]. This technique is rapidly employed as an attractive operation to fabricate lightweight products in area like aerospace, aircraft, marine, automobile, railway and food processing industries for about a decade [3, 4]. It is able to join various types of materials such as metals, ceramics, polymers and etcetera [5, 6]. In the past few years, UFSW has been introduced as a new solid-state welding technique. It takes place at temperatures lower

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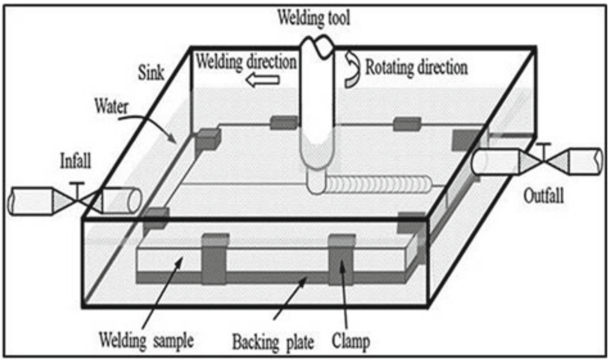

Fig. 1 Schematic diagram of Underwater FSW [5]

than the melting point of the material, where rotating tool shoulder rubs between the alloy surface of workpieces under the water, as illustrated in Fig. 1. It generates enough heat due to friction to melt the workpiece beneath that benefits the tool pin to stir the melted material and cause plastic deformation to produce a weld joint.

Besides believed as one of the innovative welding practices in the present era, UFSW also helps to avoid defects such as shrinkage, cracking, solidification, splatter, cracking, embrittlement and porosity to occur [7]. By the same token, this technique does not involve any shield protective gas or electrodes to produce an arc like some different joining methods during the welding process. It makes this process cheaper and requires less energy. UFSW also produce fine defined differences in grain size between different regions, great quality in weld joint in a short cycle time and improve mechanical properties.

2 Studies on Underwater Friction Stir Welding (UFSW)

2.1 Joint Strength Analysis

Thomas, [8] expounded in detail a research work on underwater welding technique to increase the ultimate tensile strength of friction stir weld using AA6061. Fratini et al. [9] observed a successful in-process heat treatment by water streaming above the AA7075-T6 aluminium alloy plates during FSW. The goal of this paper is to study the possibility to improve the joint performances. Comparably, another two different welded joints were carried out in normal FSW conditions: free air and forced air. Both metallurgical and mechanical examinations were developed on the welded joints. It was proven that substantial enhancement of ultimate tensile strength was obtained in all the high, medium and low level of heat input controlled by welding parameters variation. The water cooling effect significantly reduced the soften zones induced to develop the weld mechanical properties.

Nelson et al. [10] clearly defined a literature review on effective influence of cooling rate from thermal exposure on the weld performance of AA7075-T7351 through FSW technique. The outcome of this paper indicated that 7075-T7351 is a quench sensitive alloy because of more quick natural aging response and enhanced mechanical properties. The natural aging response was evaluated through transverse tensile properties and micro-hardness study. Most importantly, the water cooling conditions approximately increased the tensile properties by 10% above normal FSW.

Zhao et al. [11] also states that tensile strength of Underwater FSW method reached 75% of base metal and the elongation is comparably greater than the normal FSW joint. In this research, ultra-high strength spray formed AA7055 is welded using FSW method in air (normal FSW) and underwater, respectively. This Underwater FSW process was applied to reduce the heat input and increase the joint properties by varying welding temperature history. A better performance of underwater welded joint was illuminated through reduced residual stress and minimum thermal cycle curve. Furthermore, the hardness, tensile strength and plasticity of Underwater FSW joint were improved compared to normal FSW joint properties. The underwater joint also produced microstructure with fine grained characteristic which diminished "S line" type of defect and has clear borderline in the middle of WNZ and TMAZ, while reduced HAZ.

Liu et al. [12] studied Underwater Friction Stir Welding (UFSW) for AA2219-T6 to clarify the enhanced value in tensile strength compared to normal FSW (in air) joint. These joints were cut into three different layers (lower layer, middle layer and upper layer) to investigate the homogeneity of mechanical properties of the joint. Tensile strength of all these three layers of the joint was improved as a result of this UFSW technique. Compared to upper layer, the middle and lower layers were recorded great amount of strength improvement which leading to an increase in joints mechanical properties, along with improvement in minimum hardness value of the joint. This study also verified that the effect of water cooling is the fundamental cause for the UFSW joint to increase the strength. However, this study did not include weld temperature distribution.

2.2 Thermal Distribution Analysis

Liu et al. [13] again focused their research on UFSW of 2219 aluminium alloy to further advance the mechanical properties of the joint by varying welding temperature history. This research is able to discover that external water cooling action in UFSW developed the normal FSW joint tensile value from 324 to 341 MPa. Nevertheless, plasticity of the weld is weakened. It also concluded that UFSW joint have a tendency to fracture in the middle of Thermal Mechanically Affected Zone (TMAZ) and Weld Nugget Zone (WNZ), on the Advancing Side (AS) during tensile test.

Sakurada et al. [14] In their investigation, were the first who used submersion, focused on the high-speed rotating cylindrical sample with different welding conditions in Underwater FSW of 6061 aluminium alloy. The experimental results proved that underwater joint generate less peak temperature compared to normal FSW joint. The softening ratio and the width of softening area were reduced through Underwater FSW process while enhanced the joint efficiency (obtained 86%), in withal.

Hofmann and Vecchio [15] investigated and revealed that additional grain refinement was achieved through Submerged friction stir processing (SFSP) condition because of faster cooling rate. The grain sizes were predicted using boundary migration model along with recorded thermal distribution in the stirred material. Besides, the microstructures were characterized using Transmission Electron Microscopy (TEM).

2.3 Microstructural Analysis

Zhang et al. [16] conducted experimental study to discover the basic justification for the mechanical properties enhancement in the Heat-Affected Zone (HAZ) by UFSW of AA2219-T6. The experimental observations through microstructural analysis exposed that the hardness of the HAZ can be enhanced by UFSW method due to the narrowing of precipitate free zone and the shortening of hardened precipitate level. The variations in welding thermal distribution by the effect of water cooling treatment is the basic cause for differences of mechanical properties and microstructures in the HAZ of UFSW joint.

Hosseini et al. [17] deliberated the effect of Underwater FSW approach on the microstructure and mechanical characterization of the joint, in comparison with normal FSW (in air). This research has an objective to diminish the weakening of joints mechanical properties using Ultra Fine-Grained strain hardenable 1050 Aluminium Alloy. With respect to the normal FSW technique, the evaluated microstructure of the Underwater FSW condition using Transmission electron microscopy and X-ray diffraction examinations exposed smaller final grains and sub-grain sizes in stir zone through slowing in grain growth rate and less softening occurred in stir zone (SZ). Moreover, the Underwater FSW is also resulted tensile and yield strength increment, improved super-plasticity tendency of the material, besides narrowed the HAZ.

Wang et al. [18] studied the metallurgical and mechanical characterization through Underwater FSW joints of spray forming 7055 aluminium alloy (T6). The microstructure of joints was examined through Optical Microscope (OM) and Scanning Electron Microscope (SEM), while Energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), Differential Scanning Calorimetry (DSC) and Transmission Electron Microscopy (TEM) were used to analyse the strengthening phase's developments. It is indicated that the hard-etched area was completely removed (with 'W' shaped distribution of hardness) from microstructure of UFSW joint in cooperation with normal FSW, as shown in Fig. 2. The water cooling treatment of UFSW process enhanced the thermal cycle of welding while influence the strengthening mechanism

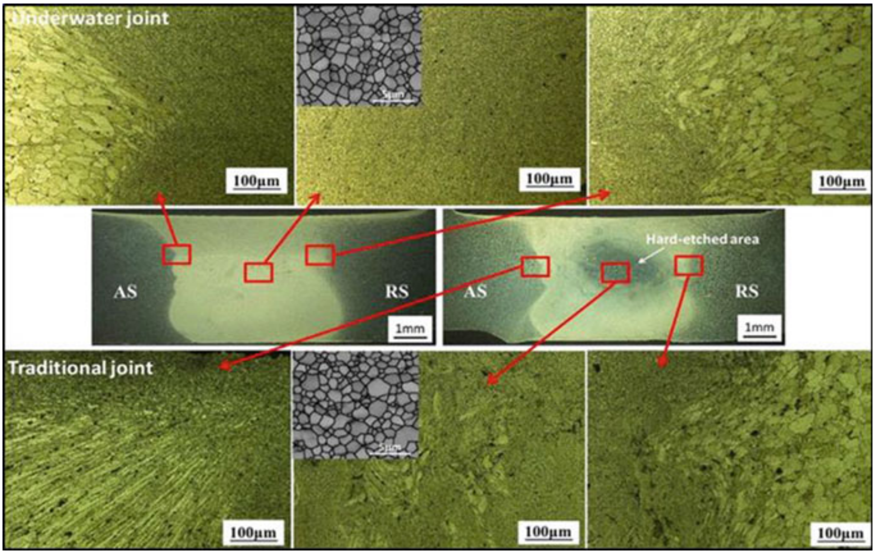

Fig. 2 Microstructure of traditional (FSW) and UFSW joint [18]

and microstructure of the joints. Defect free joint was reported with twice the elongation (1.96%) and enhanced the tensile strength as 406.06 MPa (~30%), compared to normal FSW joint.

Hofmann and Vecchio [19] conducted their research on submerged friction stir processing (FSP-modification of submerged FSW) using Al-6061–T6 material as an alternative and advance practice to produce ultrafine-grained bulk materials in stir zone (SZ) by great plastic deformation, compared to normal FSP (in air). It is attributed to the less extent of thermal distribution to the weld material during the welding operation. Thermocouples and Transmission Electron Microscopy (TEM) results were used to analyse the outcome of this paper.

2.4 Process Modelling and Computing Techniques

Fratini et al. [20] further studied an integrated numerical and experimental exploration by effects of an in-process water cooling action using FSW technique for AA7075-T6 butt joints. The temperature distribution, tensile strength and microstructure of the welded joint were observed, along with an expanded finite element to interpret specimens obtained under various process conditions. Despite the analysed temperature histories, in-process water cooling treatment was increased joint strength, diminished destructive effect on nugget zone, besides reduced the material softening and thermal flow adjacent to the tool.

Zhang et al. [21] represents the 3D thermal modelling as an advanced exploration on temperature histories of Underwater FSW technique by using the mathematical modelling approach based on heat transfer model. Experimental results are also analysed to validate efficiency of the thermal model, while disclosed good agreement with the calculated results. Mathematical model was examined the vaporizing aspect of water to clarify the conditions of boundary, while considering the material's temperature dependent characteristics. It was revealed that welding thermal cycles in different zones and area of high-temperature distributions are significantly reduced via Underwater FSW technique. Compared to normal FSW, the utmost peak temperature of UFSW joint was minimized, even though the shoulder surface heat flux is greater.

Zhang and Liu [22] further examined UFSW and developed a mathematical model using 2219-T6 aluminium alloy to optimize the welding parameters for maximum tensile strength. Highest tensile value of 360 MPa was obtained through UFSW operation and it was comparably 6% greater than the highest tensile value of FSW operation in air. This study concluded that the basic reasons for increment in tensile strength through UFSW were microstructural developments and controlling of temperature histories.

Sree Sabari et al. [23] examined the microstructural appearance and mechanical characteristics of UFSW joint with maximum strength, armour grade 2519-T87 aluminium alloy. For comparison, similar material joints were made by normal FSW (in air). The study composed of tensile test, microstructure examination, micro-hardness, fracture surface analysis and thermal analysis of all joints. A finite element analysis is used to evaluate the width of Thermo-Mechanically Affected Zone (TMAZ) and temperature distribution. The outcomes were compared with results from experimental analysis. It is concluded that Underwater FSW experienced higher peak temperature (547 °C), higher cooling rate and higher temperature gradient compared to normal FSW joint attributed to heat absorption ability of the water cooling system. Additionally, UFSW also reduced the width of TMAZ as the weaker zone and over aging of HAZ which substantially increase the tensile properties of the joint where the joint efficiency was improved by 60%.

2.5 *Effect of Thermal Boundary Condition in UFSW*

Fu et al. [24] conducted their study and then investigated the micro-hardness distribution, weld thermal cycles and tensile strength for UFSW of 7050 aluminium alloy. In this study, produced weld joints under hot and cold water, as well as in air for comparison. The outcomes indicated that maximum temperature was recorded during welding process in normal FSW (in air), after welding process in hot and cold water. It has been discovered that joint's retreated side accounted maximum temperature in contrast to advanced side and it has been recommended that weld joint under hot water is the best compared to other two conditions where it improved the mechanical characteristics of the weld. This results in a ratio of 150% elongation and 92% ultimate tensile strength. The fracture positions were situated in HAZ area (lowest micro-hardness location). Width of minimum hardness zone is changing accordingly with the ambient conditions.

Darras and Kishta [25] In their research, friction stir processing technique using three different conditions: normal FSW (in-air), under-hot-water and underwater-at-room-temperature were effectively compared. This experiment was conducted using AZ31B-O Magnesium alloy. It is analysed and supported that Underwater FSW generated better grain refinement, reduced both time spent on some reference temperature and peak temperature, besides minimized porosity and increased the formability of alloy. Particularly, the formability of this alloy is enhanced by UFSW in hot water.

Upadhyay and Reynolds [26] In their work, theoretically clarified the influence of varying the thermal boundary condition and control variables on friction stir welding process using AA7050-T7 material which were examined in-air (normal FSW), underwater, and under sub-ambient temperature (−25 °C) conditions. From the study, it was possible to conclude that welding underwater compared to normal FSW expressively lessened the size of nugget grain, enhanced amount of cooling in the HAZ, increased the hardness of weld nugget, decreased probe temperature, besides increasing power consumption and torque. The ultimate tensile strength of Underwater FSW in all range of parameters were presented good improvements along with elongation of the joint. Yet, it is also justified that sub-ambient temperature (−25 °C) condition does not contribute a consequential benefit in contrast to the underwater welding at ambient temperature.

2.6 *Effect of Process Parameters*

Liu et al. [27] clarified the influence of speed of welding from 50 to 200 mm/min on the efficiency of underwater friction stir welded joints. This investigation used 2219 aluminium alloy with fixed rotational speed equivalence to 800 rpm. It resulted in the weakening on the precipitate degradation in TMAZ and HAZ with increasing speed of welding. Subsequently, it leads to increase in lowest hardness value and reduced the softening region. The study also stated the joints fracture features are basically reliant on the speed of welding, and increasing the speed of welding increases tensile strength of the defect-free joints. Nevertheless, the temperature range applied in the investigation was restricted less than room temperature.

Zhang et al. [28] additionally explored the impact of rotation speed on mechanical properties of UFSW weld using AA2219-T6 with constant speed of welding. The tensile properties, microstructural characteristics and hardness distributions of the joints were illuminated through this investigation. The joint tensile properties were extremely sensitive to the rotational speed where it was dramatically increased from rotational speed of 600–800 rpm, and later reached a plateau in a large range of rotation speed. Thenceforth, notable reduction in tensile properties was attained due to void defects formations in the SZ. Escalate in dislocation density as well as in grain size of SZ were reported with increasing of rotational speed, which slowly increased the SZ hardness. At higher speed of rotation, the defect-free joints fracture locations changed to the HAZ or Thermal-Mechanically Affected Zone (TMAZ) as the hardness increased in the SZ. Meanwhile, the welded joint was fractured in the SZ at lower speed of rotation.

Kishta and Darras [29] analysed and presented the impact of different parameters of process, namely rotational speed and translational speed, on Underwater FSW of 5083 marine-grade aluminium alloy. The outcomes of UFSW joints were compared with normal FSW (in air) joints, in withal. The void fractions, tensile properties, micro-hardness, thermal histories, and the process power consumption were comprehensively discussed. Investigation concluded that UFSW has produced good quality welds by higher rotational speed due to excellent thermal capacity of water, peak temperature decrement as well as cooling rate increment. The fraction of void-area in the SZ of Underwater FSW joint was decreased significantly nearly one-third of the base material. The maximum micro-hardness value was recorded in the SZ, while the UFSW joint elongation upsurge to almost two times the elongation of the base material.

Abbas et al. [30] examined the effect on weld quality of sample is investigated through the relation between the tool profile, welding speed and angle of tool inclination of Underwater FSW process enveloped for 6061 aluminium plate. After a brief description of operational principal of friction stir welding, the experiment setup is illustrated in detail together with clamping structure, welding tool properties, material properties and process parameters. The weld quality is evaluated through microstructure analysis, tensile strength test and Vickers hardness. Microstructure analysis disclosed that very few amounts of porosity is detected, while a good joining is obtained with no voids and cracks by UFSW technique. The mechanical properties of UFSW is increased approximately 20% compared to FSW. The Taguchi optimization technique has been used to analyse the optimized parameter with Mini Tab 16 software.

2.7 Defects in UFSW

Zhang and Liu [31] expounded in detail the outcomes of an experimental investigation, done on the UFSW of 2219-T6 aluminium alloy. Preceding research studies showed the influence of process parameters: speed of rotation and speed of welding on the quality of UFSW. Hence, the investigation objective is to comprehend the characteristics of welding defects and formation mechanisms of the welding defects in UFSW joints through examining the material flow patterns, as shown in Fig. 3. It is an attractive method to illustrate the results of experiment and it is really beneficial to provide guidance for process optimization. At low and high speed of rotation yield welding flaws during UFSW process. At high rotation speed and low speed of welding, defect formed is influenced by the high amount of extruding reflux of stir zone material on the AS. While at high rotation speed and high speed of welding, a

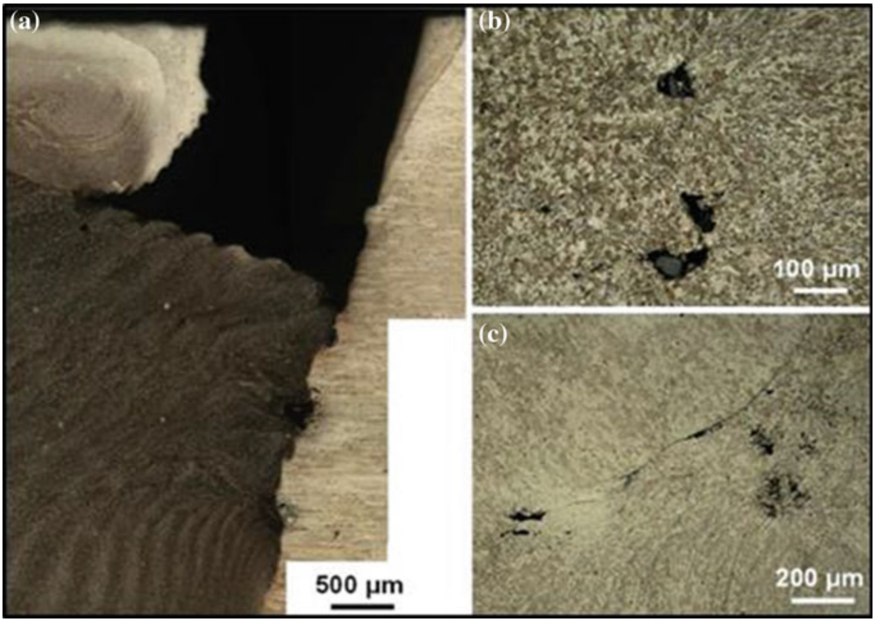

Fig. 3 Welding defects formed under different process parameters: **a** 800 rpm–200 mm/min, **b** 1000 rpm–300 mm/min, **c** 1400 rpm–100 mm/min [31]

great volume of material from TMAZ is pulled into the pin hole reduces the quantity of stir zone material that flows back to AS. Consequently, it formed groove and void type defects in the joints. Also, the low rotational speed flaws are usually found at the TMAZ and SZ boundary on the AS.

2.8 Dissimilar Weld Joints by UFSW

Mofid et al. [32] explored the effect of dissimilar welds in Underwater Friction Stir Welding (UFSW) using 5083 Aluminium alloy and AZ31C–O Magnesium alloy. The outcome revealed that submerged FSW technique enhanced the fine grained welds and lessen the development of intermetallic phases due to lower temperature attained. It impacts the joint mechanical characteristics substantially. Nevertheless, normal FSW (in air) produced great peak temperature in SZ with great amount of joint hardness in the centre, in contrast to UFSW joint.

Mofid et al. [33] discussed the impact of submerged welding using liquid nitrogen and underwater on the grain refinement in dissimilar materials of AA5083 H34 and AZ31 (Mg alloy). For comparison, three different environments: in air, water, and liquid nitrogen using parameters of 400 rpm and 50 mm/min were applied. Results of microstructure, Scanning Electron Microscopy (SEM), Energy-Dispersive

Spectroscopy (EDS), temperature profile, micro-hardness and tensile testing were systematically analysed. It is concluded that, Submerged FSW method suppresses formation of brittle interatomic compounds due to lower peak temperature.

3 Applications, Advantages and Limitations of UFSW

3.1 Applications of UFSW

The most significant applications of Underwater FSW method are building large sized ships beyond the capacity of facilities in existing harbours, maintenance and repairing works of ships, temporary reconstruction works due to unexpected accidents of ships, recover containers sunk in the sea and offshore construction for pipelines [34].

3.2 Advantages of UFSW

The good qualities and advantages of Underwater FSW method are producing great quality and decent joint in limited cycle time, not requires filler metals and does not produce shielding gasses, able to weld most of the common metals, not difficult to operate and good operation flexibility in all positions with simple automated function. Moreover, this UFSW method is also able to weld numerous types of dissimilar materials, generate fine-grained forged joint by eliminate weld inclusions or weld dilution, produce reliable welds while consume less energy during the joining process [5, 34].

3.3 Limitations of UFSW

The disadvantages of Underwater FSW method are the inspection process for welded joints by underwater friction stir welding (UFSW) technique may be harder compared to normal FSW, promising a better quality of UFSW joints much difficult and risk of not detecting the defects properly might occur. Besides, requires quite expensive machines as well as the machine tools [34].

4 Future Scope of UFSW

Preceding substantial researches have been constructed to advance the control strategies and process performance of underwater FSW method. Nevertheless, there are many conflicts to solve where the UFSW exploration should be focusing detailed research on properties of welded material and process optimisation. In addition, research on UFSW must develop the potential usage of robot manipulator for underwater FSW joints of complex geometry to improve the automation of UFSW joining and examination process, aside from developing the application of underwater FSW for large and complex scale of any structures. Furthermore, this technique should explore in detail on thermal management in terms of both closed-loop temperature control and thermal boundary condition modification, while improving the in-process weld quality assurance, increasing the application of UFSW to a wider range of engineering materials and improving the control techniques for continuous welding [34].

5 Conclusions

UFSW is really an innovative and developed technique of joining process in this present era. From the above literature review, it is disclosed that very few investigations are done based on underwater FSW method. It is acknowledged as an advanced welding technique and very little number of studies have applied the optimization technique in the field of UFSW. UFSW is not fully examined yet. By focusing the future research on it, can really enhance and attain good weld joint with economical, environment friendly and safe welding condition.

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