Temperature generation and Traverse force Analysis during Friction Stir Welding in Air and Water

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Abstract
Friction stir welding (FSW) is the newly developed solid-state joining process to join commonly Aluminum alloys (AAs) .This process is environmentally friendly, highly efficient and has wide applications in the shipbuilding aerospace and transportation industries. Underwater Friction Stir Welding (UFSW), a variant of FSW can extend the marine application of the FSW. Since, in FSW/UFSW, the thermal cycles exhibit a significant effect on the weld properties, it generates the need to study the governing process parameters. This paper provides a comparison of the temperature generated by the tool during FSW and UFSW process. Moreover, the effect of cooling media on the transverse force is also discussed. From the study, it is concluded that UFSW resulted in low peak temperature development in comparison to FSW. The results also revealed that traverse force increased significantly in UFSW due to greater heat generated by FSW tool in a water medium.
Keywords: Friction stir welding (FSW), Underwater Friction stir welding (UFSW), Temperature, Traverse Force, Tool.

1 Introduction

FSW is a solid-state non-fusion welding process invented at TWI in 1991 [1]. This process is used for the welding of metal including aluminum, magnesium, copper, etc.[2-4]. Various alloys which found difficulties in the welding by fusion welding process can be easily welded using the FSW [5]. In this process, a non-consumable rotating tool with a profiled pin is inserted into the edge of the plate that is to be joined and is traversed along the line of the joint. The heat generated by friction be- tween the tool and workpiece causes softening of the material leading to plastic de- formation and tool rotation, and traverse speed leads to the movement of the material from one side of the pin to the other side of the pin [6]. The schematic is given in Figure 1. In FSW due to the contact friction b/w the tool and workpiece together with the work hardening of the tool, generation of heat takes place leading to increasing the temperatures. Upon these two phenomena in FSW, heat is transferred by conduction, convection, and radiation depending on the workpiece material [7, 8].

Conduction phenomenon takes place between tool, workpiece and the backing plate and depends upon the thermal conductivity of the material. In convection phenomenon, heat trans- fer takes place from the workpiece to the surroundings. Controlling these phenomena can lead to desired heat transfer. As the tool material, workpiece and the backing plate could not be changed this phenomenon cannot be used for controlling the tempera ture. In contrast, by controlling the convective heat transfer, which is dependent on the coolant material, the transferring heat from the tool shoulder to the other locations of the workpiece can be controlled. Therefore, to control this parameter, water could be employed in FSW. In UFSW water as the cooling media is used to regularize the temperature prevailing in the welded joint [9-10].

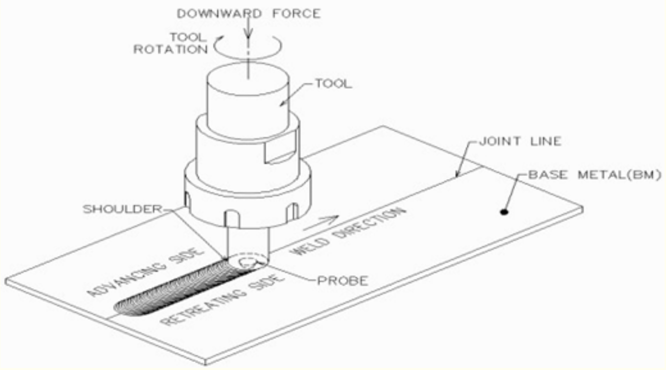

Fig.1. Schematic representation of FSW [6]

It is revealed from the available literature that the temperature generation, the mechanical properties, and microstructure of the welded joint have been studied by some researchers. Sharma et al. [11] studied the effect of three different coolants including the compressed air, liquid nitrogen, and water during FSW of AA 7039.It was obtained that the tensile strength and elongation of the cooled specimens were decreased as compared to those specimens cooled by air. In another study done by Liu et al. [12] on UFSW of the AA2219 tensile strength of the top, middle, and bottom layers were studied. The results revealed fine grains in UFSW as compared to FSW, and the tensile strengths of all the layers were improved during UFSW. Great variation in temperature has been observed by Xue et al. [13] for pure copper in air and water media. Some researchers have also studied the forces developed on the tool during FSW. Rai et al. [14] established the various forces on FSW tool with increasing plate thickness and strength of workpiece. Arora et al. [15] addressed tool probe as the operationally feeblest unit that could fail due to high temperature and stresses during welding. Sorensen and Stahl [16] observed a substantial improvement in tool traverse force with increase in thickness of the plate in FSW of AA6061. Trimble et al. [17] reported a significant increase in tool traverse force with increase in welding speed during FSW of 5 mm thick AA2024. Leitãoa et al. [18] noted a substantial increase in tool torque with an increase in both plate thickness and welding speed. Forces occurring on the tool are also affected by the heat generation and accordingly the temperature distribution in UFSW/FSW [19]. Axial and translational forces improved significantly in UFSW of AA 7075-T6 due to the reduction in peak temperature. Thus from the reviewed literature, it is interpreted that the temperature profiles can have a significant effect on the mechanical properties and forces encountered during FSW/UFSW.

Although a lot of researches are based on acquiring the effect of the temperature field on the mechanical properties during UFSW, negligible information exist on the measurement of forces during UFSW. Hence in the present study, a comparison of thetemperature generated by the tool during FSW and UFSW process is investigated. Moreover, the effect of cooling media on the transverse force is also discussed. For simplicity in understanding FSW in the air is denoted as FSW and FSW in water is denoted as UFSW.

2. Experimental Procedures

FSW/UFSW is performed on AA 5754 H 22 having dimensions of 200 mm x 50 mm x 3 mm. The AA 5754 is chosen in this research work because this alloy has good workability, very good corrosion resistance, light weight, moderate strength and good electrical conductivity.The chemical composition and mechanical properties are given in Table 1 and Table 2 respectively. In the present study tool made of H 13 steel with the triangular pin having shoulder diameter 20 mm and pin of 6 mm as shown in Figure 3 is used to weld plate of AA 5754 using vertical milling machine (shown in Figure 2) retrofitted to perform FSW. The experiment is performed with a constant tool rotation speed of 900 revolutions per minute (rpm) and with tooltravel speed of 50 mm/minin both the air and water, i.e., FSW and UFSW. The welding direction was parallel to the plate rolling direction, and the tool rotation axis was normal to the plane of the plate.

Table 1. Chemical Composition of AA 5754 H22

Eleme nt	Al	Mg	Cr	Mn	Fe	Si	Ti	Zn	Others
AA22 19	94.96	3.1	0.2 8	0.39	0.2 7	0.25	0.1 0	0.20	< 0.40

Table 2. Mechanical and thermal properties of AA5754 H22

Aluminium alloy	UTS (MPa)	SpecificHeat Ca- pacity (J/g °C)	Thermal conduc- tivity (W/mK)	Incipient mmelting-liquidoustemperat ure (°C)
AA5754 H 22	228	0.853	147	553-610

During the welding process, six K type of thermocouples were used for the measurement of the transverse distribution of the weld temperature both on advancing side (AS) and retreating side (RS).The locations of the thermocouple are illustrated in Figure 4.

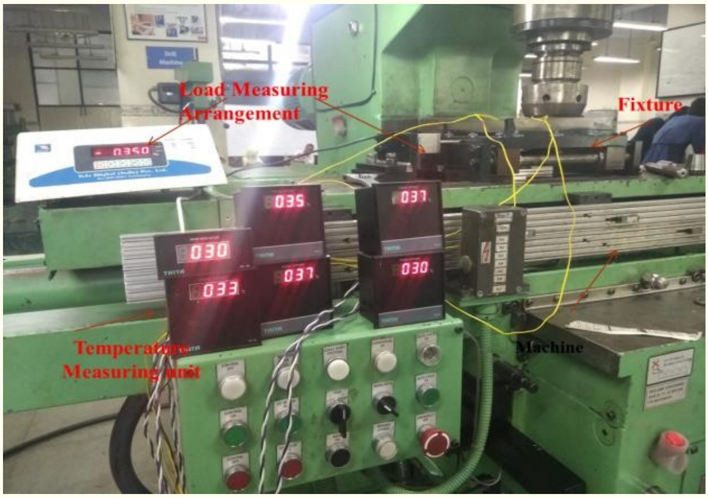

Figure 2. FSW arrangement with temperature and load cell measuring unit

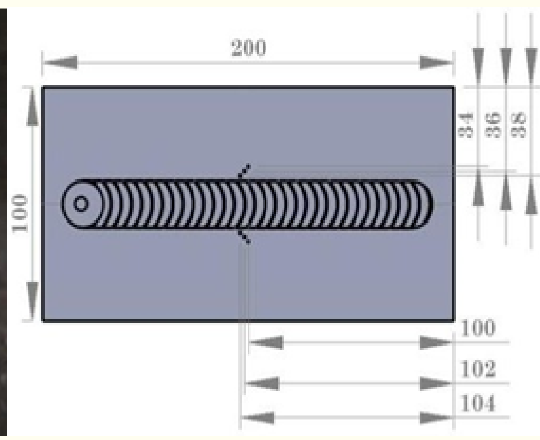

Figure 3. Tool used in the study **Figure 4**. Thermocouple location

For measuring the traverse forces met during FSW/UFSW a load cell having a capacity of 10kN was used. The traverse force experienced by the tool was measured as a function of distance during each experiment using a calibrated digital load cell attached to the fixture. As FSW/UFSW progresses the traverse force is exerted by the traversing tool on the fixture unit, and thus the force gets transmitted to the load cell through plunger attached to the fixture (Figure 2). The calibrated load cell senses this force and generates emf. This emf is converted into the suitable unit (kg/N) and is displayed on calibrated data display system.

3. Result and Discussion

3.1 Temperature distribution in different cooling media

For thoughtful investigation of FSW process, comprehensive information of the heat generation and temperature distribution across the different zones of the FSW is very important. The force encountered and the mechanical properties of the welds are closely associated with the temperature. The extent of the modification in microstructure during FSW process is also governed by the temperature history which in turn is dependent on welding parameters used, and the thermal boundary conditions evolved during the welding.

The transverse distribution of the temperature under water and air cooling is shown below in Figure 5. The distribution of temperature during FSW and UFSW showedsimilar variation with distance away from the weld center. Low peak temperature was observed during UFSW due to the high cooling rate of water leading to shorter dwell time above a given temperature. The maximum temperature measured during UFSW was 1180C which was 1820C less than the FSWed sample due to the high absorbing capacity of water. Further, very large variation in temperature on AS and RS and the large thermal gradient is observed during FSW when compared to UFSW. It is vastly believed that this reduction in temperature and thermal gradient generally limit the coarsening of precipitates and cause improvement in mechanical properties [20, 21].Moreover, the highest temperature was observed at the AS in FSW and RS in UFSW near the weld center. The AS suffers greater deformation than RS in FSW leading to greater temperature on AS. In UFSW, the heated water nearing weld on AS is moved forward opposing the cold water neighboring the weld and cool down rapidly and mandatorily whereas RS obtains the hot water coming from AS thus UFSWed joint shows high temperature on RS.

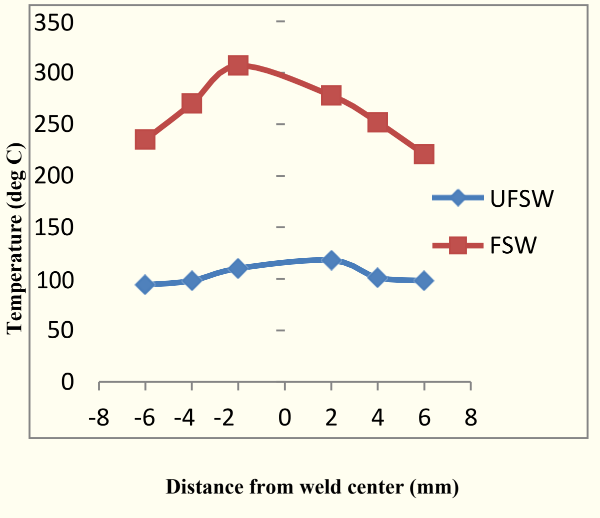

Figure 5. Distribution of temperature at AS and RS for different cooling media

3.3 Effect of cooling media on traverse force distribution

The distribution of traverse force directly affects the amount of pre-heat and heat required during the process. The amount of heating and preheating causes change in the material flow stress of the welded joint. Figure 6 shows the comparison of the tool traverse force during FSW and UFSW of 3 mm thick AA5754 H 22 alloy plates as a function of time in second. For welding speed of 900 rpm and the tool travels speed of 50 mm/min the traverse force were analyzed. Traverse force graph showed the precise variation along the length of tool travel. At first, a tool with a desired rotational speed in a short span of time is plunged into the workpiece (plunging period) in which there is no translational movement, and hence there is no traverse force initially. The region OA denoted in the plot is when the pin penetrates the workpiece surface and the re- gion AB represents the shoulder plunge, i.e., region OAB represents the plunging zone. There is dwell given in between the region AB. The region BCD represents the FSW tool traversing along the joint line. As the region BC which represents period after the shoulder plunge, when feed is applied the process is slightly unstable be- cause of the variation of the traverse force and after some time the traverse force reaches the stable state. When shoulder touches the workpiece due to frictional heat of the tool the material beneath the tool gets soften and consequently causing plastic deformation. Contrary the tool rotation speed causes strain hardening of the plasti- cized material. This competition between the heat generation and work hardening continues until a balance sate is reached (dwell period). The unstable period starts as translational movement of the tool is started. This is basically due to the colder mate- rial ahead of the tool which is not properly stirred at the stating of the tool traverse. Further movement of the tool stabilizes the curve and increase in traverse force is observed due to the adequate stirring of the cold material.

It can be observed from Figure 6 that to perform the UFSW, one might need a longer time in the dwell period. As we see that in UFSW when the pin gets plunged the value of traverse force obtained is slightly greater than the FSW process because there is involvement of water in UFSW which require slightly more traverse force. For FSW and UFSW, the unstable periods are generally equal for translational forces.Furthermore, the applied forces need a longer time to reach a stable condition as the tool starts to move in UFSW as compared to FSW. The traverse force depends on the flow strength of the material which is directly related to the temperature produced during the welding. With the increase in temperature flow strength decreases and vice versa. The applied traverse force is greater in UFSW because of the higher flow strength of the material due to the corresponding lower temperature involved during UFSW [19].

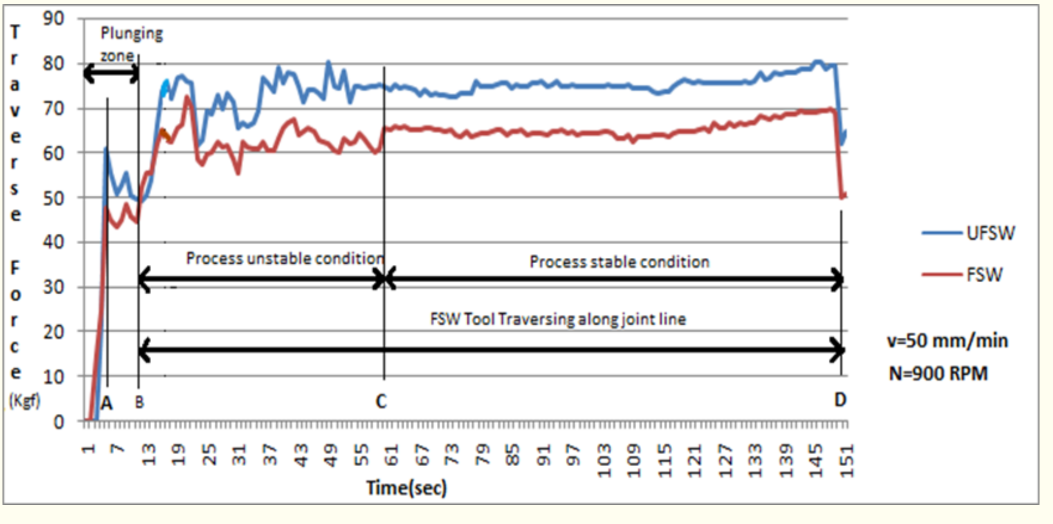

Figure 6. Traverse force applied by FSW tool

4. Conclusion

For the butt joint of AA5754 under welding speed of 900 rpm and the tool travels speed of 50 mm/min, the temperature generated and traverse force were analyzed. The following conclusions are drawn from the present study.

1. The distribution of temperature during FSW and UFSW showed similar vari- ation with distance away from the weld center.
2. Low peak temperature was observed during UFSW due to the high cooling rate of water leading to shorter dwell time above a given temperature.
3. Very large variation in temperature on AS and RS and the large thermal gra- dient is observed during FSW when compared to UFSW.
4. The highest temperature was observed at the AS in FSW and RS in UFSW near the weld center.
5. From force measurement, it is obtained that to perform the UFSW, one might need a longer dwelling time during plunging for obtaining good quality weld.
6. The traverse forces are found to be greater in UFSW when compared to FSW.

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