Backing plate effect on temperature controlled FSW process

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Abstract. Friction stir welding (FSW) has become an important application in modern industries. Friction stir welding is a widely used solid state joining process for soft materials such as aluminum alloys as it avoids/minimizes common problems of fusion welding processes, i.e. distortion, porosity, solidification and liquation cracking etc. Improper selection of parameters such as welding speed, rotational speed, forge force, back plate material etc. affects the weld quality. Thermal boundary condition at the bottom of the work pieces to be joined is important in determining the result of weld quality and its properties, for a given alloy type, tool geometry and selected process parameters (welding speed, rotational speed etc), These thermal boundary conditions are governed by the back plate material used. By using backing plates made out of materials with widely varying thermal diffusivity this work seeks to elucidate the effects of the root side thermal boundary condition on weld process variables and resulting joint properties. Welds were made in 5-mm-thick AMr5 (AA 5056) using siliceous coating, stainless steel, mild steel, and aluminum as backing plate (BP) material. Effects of backing plate material on the tensile strength and elongation were obtained for a particular case.

1 Introduction

Friction stir welding (FSW) is a relatively new solid state joining process. Friction stir welding process was invented at The Welding Institute (TWI) U.K in 1991 [1]. The method is suitable for a wide variety of materials which are hard to weld by conventional welding process. The solid-state nature of FSW process avoids problems of hot cracking, porosity, element loss, etc., which are common to aluminum fusion welding processes. Furthermore, absence of ultraviolet or electromagnetic hazards, high penetration depths, reduced energy requirements, absence of shielding gas, elimination of consumables such as rods and grinding pastes are some of the key additional benefits of the process over traditional fusion welding techniques. FSW is suitable for joining of aluminum alloys, steels, titanium alloys, magnesium alloys and copper alloys. This method in conceptually permit to join aluminum alloys to other metals, including aluminum to magnesium, aluminum to steels, aluminum to copper. Since it was invented in the UK, the friction stir welding process has been applied in the following industrial fields: shipbuilding and offshore, aerospace, automotive, rolling

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stock for railways, general fabrication, robotics, and computers. In essence, FSW is very simple. The fundamentals of this joining method are plunging and stirring a non-consumable rotating tool with a specially designed shoulder and probe or pin into the abutting materials to be welded (Fig. 1).The workpieces are joined together through heating, material movement, and forging. Heating is created both by the friction between the rotating tool and the workpiece and by severe plastic deformation of the workpieces. Materials around the probe are softened due to localized heating and move from front to back during tool rotation and stirring. Consequently, the hole in the tool wake is filled,the welding joint being produced. The shoulder restricts the plasticized materials from flowing out and applies forging pressure to consolidate the materials right behind the moving pin.

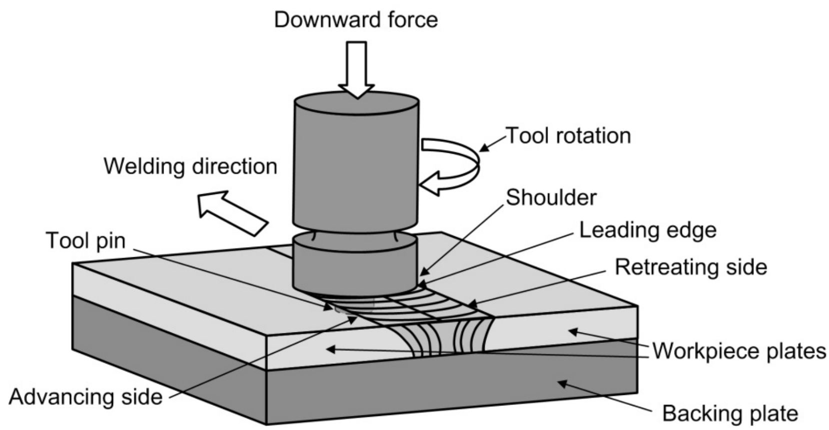

Fig. 1. Schematic of the friction stir welding process.

Friction stir welds have several important process parameters such as tool rotational speed, welding speed, forge force, back plate diffusivity, tool shoulder diameter etc. Reducing the heat input during the FSW process by decreasing the tool rotation rate and/or increasing the work piece travel speed is one of the methods used for increasing the join strength. Since the temperature must be kept high enough to soften the materials around the welding pin tool to stir, this method requires inspection of the optimal welding speeds, which are varied according to the joint configuration (butt or lap) and material types and dimensions. For this reason, there is a limited range of tool rotation rate and travel speeds that could be controlled. Higher tool rotational speed generates high heat causing slow cooling rate that allows reprecipitation of strengthening phases and leads to formation of coarse grains in stir zone which results in lower mechanical properties in the stir zone. Lower welding speed results in higher heat input, which is associated with a higher temperature and slower cooling rate that causes grain growth and weakens the mechanical properties of the joint. As the application of friction stir welding widens, it will be important to understand the behavior of process variables like stir zone temperature and resulting weld properties with the change in thermal boundary condition. Thermal boundary condition at the bottom of the work piece is important in determining the weld process response and resulting weld properties. The rate of heat flux through the bottom of the work piece mostly depends on the backing plate (BP) diffusivity and hence, as it has been pointed out in literature, the most important thermal boundary condition for the process is the thermal condition at the BP. Back plate material diffusivity is a critical factor to the success of friction stir welding. Thermal diffusivity is the ability of material to transfer heat from hot portion to cold portion. Different materials can be used as a back plate such as pure copper, medium carbon steel, granite, ceramic floor tile, aluminum alloys, mild steel, stainless steel, asbestos, tool steels etc. Pure copper, aluminum alloys have higher thermal diffusivity, which results in increased heat extraction rate. While granite, ceramic floor tile, asbestos have lower thermal diffusivity which results in lower heat transfer rate. In spite of significant number of publications devoted to the effect of thermal management at the bottom of work pieces, this phenomenonis poorly understood at present [2-9 et. al.]. Further work is needed for improvement to understand in terms of effect of other materials as a back plate, their effect on corrosion resistance of welds and thereby improvement in the quality of welds.

The main aim of this work is to investigate experimentally the effect of backing plate material on friction stir butt welds. To this end, temperature measurements, macrostructural, and mechanical characterization are carried out for welds obtained with different backing plates.

2 Experimental procedure

The rolled plates of AMг5 (AA5056) aluminum alloy were cut and machined to 1000mm×150mm×5mm by power hacksaw cutting and grinding. Conventional milling machine with appropriate fixture developed for FSW has been utilized for present experimental investigation. Fig. 2 shows FSW setup.

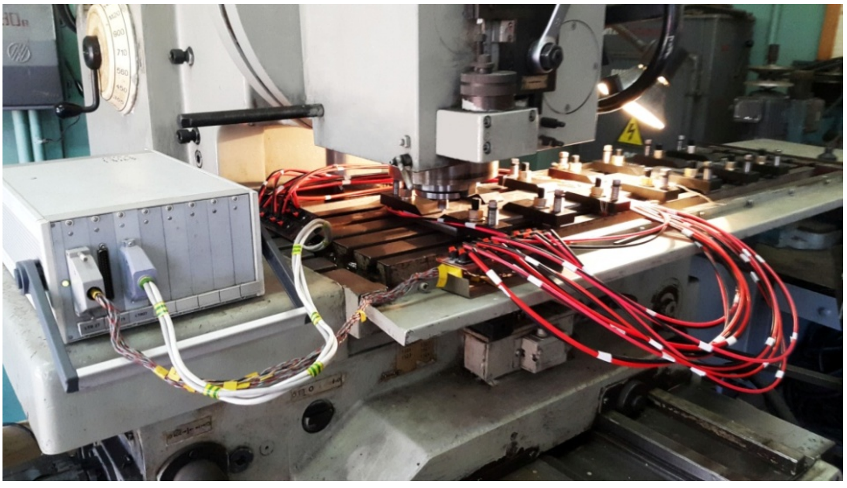

Fig. 2. Friction stir welding set up.

Aluminum plates are located by a slotted base plate of fixture. It constrains the movement of aluminum plates against the tool rotation, accurate and unique position ofthe plates being provided each time. Aluminum plates should be fully constrained at all times to prevent any movement. Clamps provide locking forces to hold the aluminum plates in place, once they are located. A totally restrained aluminum plates are able to remain in static equilibrium to withstand all possible processing forces or disturbance.

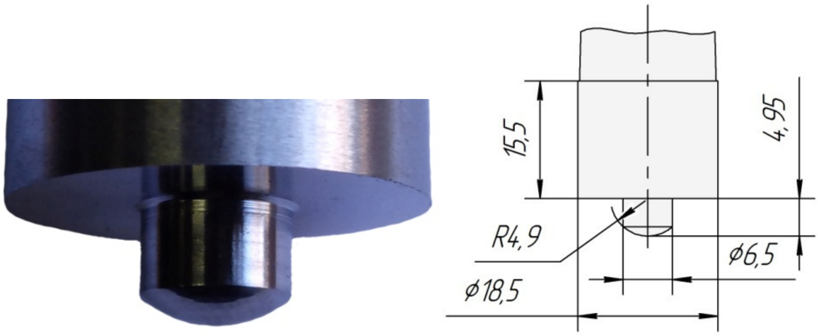

Fig. 3. FSW pin geometry and dimensions.

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed. Tool shoulder was designed to produce heat to the surface and subsurface religion of the work piece. The shoulder also produces the downward forging action necessary for weld consolidation. The pin was designed to disrupt the faying, or contacting surface of the workpiece, shear material in front of the tool, and move material behind the tool. Tool pin length is determined by the workpiece thickness (5 mm for present study) and the desired clearance between end of the pin and backing plate. Pin diameter needs to be large enough not to fracture due to transverse load but small enough to allow consolidation of workpiece material behind the tool before the material cools. Figure 3 shows tool pin geometry and tool dimensions. Excessive tool wear changes the tool shape, thus changing the weld quality and increasing the probability of weld defects. Non-consumable tool, made of high carbon, high chromium steel, **4Х5МФ1С**(H-13**)** was used to fabricate the joints. Tool material was purchased under annealing condition and machined as per tool design and finally heat treated to get required hardness. Tool has been heated at 1020 ºC for 30 minute and then oil tempered at 550 ºC for 2 hour. The initial hardness was 17 HRC, being changed after heat treatment to 52 HRC. The chemical composition and mechanical properties of base metal are presented in Table 1 and 2.

Table 1. Chemical composition of AMr5 (AA 5056)aluminum alloy

Fe	Si	Mn	Ti	Al	Cu	Be	Mg	Zn
Max 0.5	Max 0.5	0.3 - 0.8	0.02 - 0.1	91.9 - 94.68	Max 0.1	0.0002 - 0.005	4.8 - 5.8	Max 0.2

Table 2. Properties of AMr5 (AA 5056) aluminum alloy

Tensile strength MPa	Density Kg/m^3	Thermal conductivity W/m·k	Melting point °C	Hardness HRB
275	2650	126	650	65

The rolled plates of 5 mm thickness AMr5 (AA 5056) aluminum alloy, were cut into the required size (1000 mm x 150 mm) by power hacksaw cutting and milling. Square butt joint configuration (1000 mm x 300 mm) was prepared to fabricate FSW joints. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was followed to fabricate the joints. Trial experiments were conducted to determine the working range of the parameters. Feasible limits of the parameters were chosen in so that the friction stir welded joints be free from any visible external defects.

The important factors influencing the tensile properties of FSW joints and their working ranges are given in Table 3. Equal rotation/welding speed ratio (≈14) was selected for both welding condition sets.

Table 3. Process parameters used in this work

Set	Tool pin profile	Rotational speed (rpm)	Welding speed (mm/min)	Pin height (mm)	Plunge depth (mm)	Tool tilt angle (◦)
1	Cylinder	710	50	4.8	0.1…0.2	1,5…3
2	(without thread)	1120	80	4.8	0.1…0.2	1,5…3

Preliminary welds were made using four different backing plates with widely varying thermal diffusivity values. Welding was performed using four backing plate materials: aluminum alloy, mild steel, stainless steel, and plate with siliceous coating. Thermophysical properties of different backing plate materials are given in Table4.

Table 4. Thermophysical properties of baking plate materials

Properties	Aluminum alloy	Mild steel	Stainless steal	Siliceous coating
Density (g/cm^3)	2.65	7.85	8.0	500 (g/m^2)
Thermal conductivity (W/mK)	126	54	16.2	2.5
Specific heat (J/gK)	0.922	0.62	0.53	0.024

For test welds, temperatures in weld vicinity were measured using K-type thermocouples inserted in 1 mm deep, 1.5 mm diameter blind holes drilled from top and from bottom, respectively and located as shown in Fig. 4. Peak temperatures were measured by the thermocouples in thermo mechanically affected zone (TMAZ) along the weld line. There would be regions within the TMAZ that experience lower as well as higher peak temperatures than that measured by the thermocouples. Separately, thermocouples in TMAZs are placed close to welding nugget zone (WNZ) and gradient in temperature field in this zone is relatively moderate. Thus, peak temperatures measured by thermocouples in TMAZs can be thought of as peak temperatures in these zones.

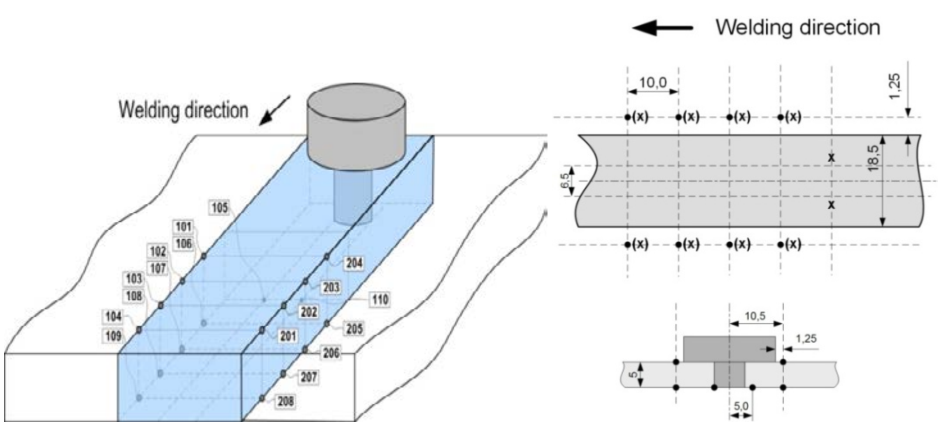

Fig. 4. Schematic arrangement of thermocouples.

The welded joints were sliced using a power hacksaw and then machined to the required dimensions as shown in Fig. 5. Three tensile specimens were fabricated to evaluate the tensile strength of the joints. Tensile strength of the FSW joints was evaluated using universal testing machine type QUASAR 25.

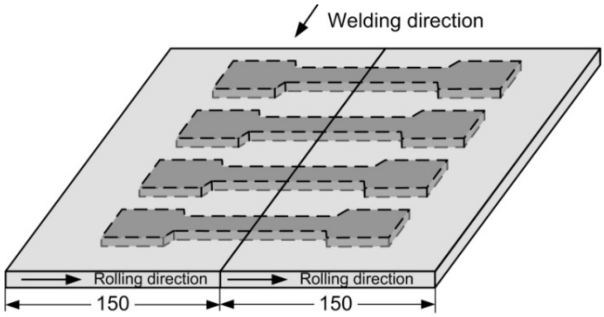

Fig. 5. Scheme of welding with respect to rolling direction and extraction of tensile.

3 Results and discussion

Cross-sectional macrographs of butt welds for 5 mm sheets obtained for four different backing plates are shown in Fig 6. The shape and size of the weld nugget for all cases are similar, however, there are some differences especially at the root region. There are void and lack of tool penetration (LOP) in the weld root in case of stainless BP and siliceous coating BP, respectively. The results in sections clearly show that heat insulation may lead to unwanted effects. It is to be noted that the LOP defects in situation like this may be avoided by increasing the pin length slightly or reducing the welding speed thus facilitating material flow underneath the probe. Owing to limited time and resources further experiments were not conducted to mitigate LOP defects.

Stainless BP Mild steel BP Aluminum BP
Siliceous BP

Fig. 6. Transverse etched cross-section of welded samples.

Temperature peaks in thermo mechanically affected zone (TMAZ) for two set of welding parameters are shown in Fig. 7 and 8.

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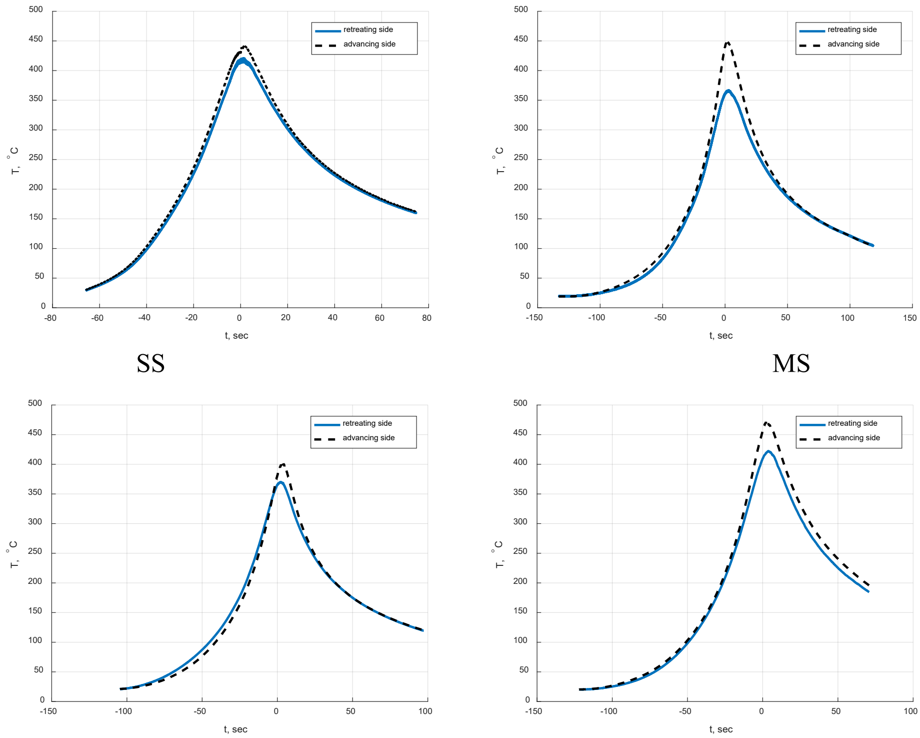

SS MS AA SC

Fig. 7. Peak temperatures at thermocouple locations in TMAZ of AS and RS for four different backing plate materials:stainless steel (SS), mild steel (MS),aluminum alloy (AA), and siliceous coating (SC). Note that tool rotational speed is 710rpm, welding speed is 50 mm/min.

For all welded samples the heat flux in the advancing side (AS) is exceeded heat flux in the retreating side (RS).The maximum THAZ temperature peak take place for the siliceous coating backing plate. This fact is explained by the less diffusivity of siliceous plate material. While the maximum difference between advancing and retreating temperatures is in the case of the mild steel backing plate. This phenomenon appears to depend of the heat flux in backing plate as well as heat flux between advancing and retreating sides. Mutual proportional increasing both rotational and welding speeds cause significant decreasing of TMAZ heat time. In all cases, maximum temperature values in TMAZs are exceeded 400^{o}C.

Defect free welds were obtained with three type baking plate materials: mild steel, aluminum alloy, stainless steel. A total of three samples were extracted for these welds (except for samples welded at siliceous coating backing plate). Magnitudes of yield strength, and percentage elongation (at load maximum) of welds in transverse loadings are shown in Fig. 9. Note that the ultimate tensile strength and percentage elongation at load maximum for base metal are 332 MPa and 22 %, respectively. Considering both diagrams it is clear that BP diffusivity has a significant effect on tensile strength and elongation of the welded joints. There is a 5 pct increase in the ultimate tensile strength of the joint with the use of steel instead of aluminum as BP material.

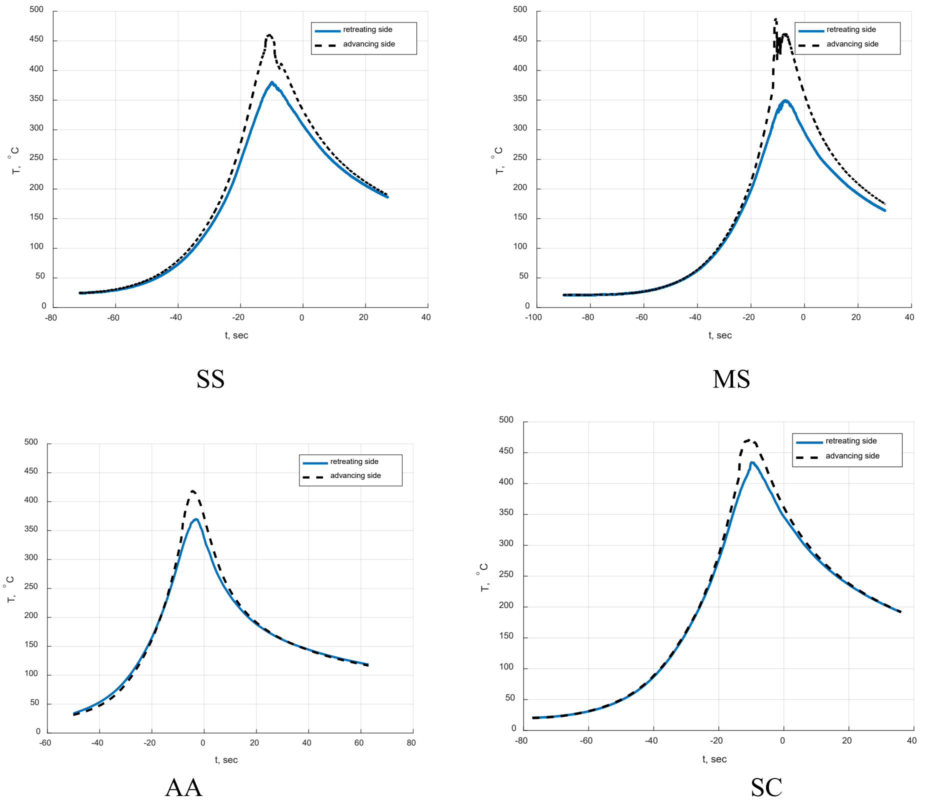

Fig. 8. Peak temperatures at thermocouple locations in TMAZ of AS and RS for four different backing plate materials: stainless steel (SS), mild steel (MS),aluminum alloy (AA), and siliceous coating (SC). Note that tool rotational speed is 1120rpm, welding speed is 80 mm/min.

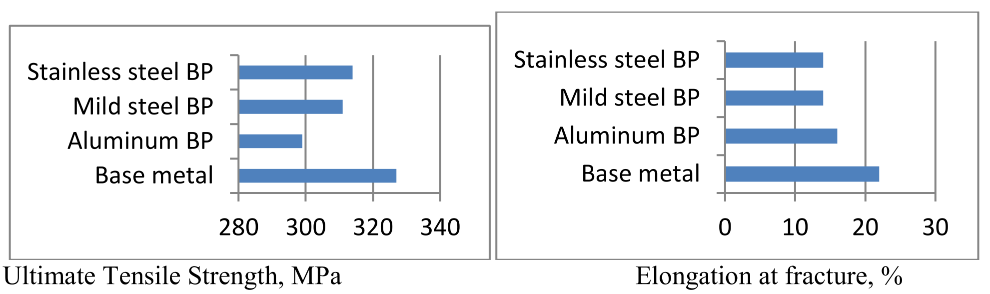

Fig. 9. Ultimate tensile strength and percentage elongation.

4 Conclusions

The effects of BP thermal property on the resulting process response and mechanical properties were evaluated for friction stir welds made with 5-mm-thick AMг5 (FF5056). The following are evident from the results.

1. Back plate material diffusivity is a critical factor for the success of FSW process.
2. In nearly all cases, ultimate strengthis achieved for samples obtained with base metal.

3. Percentage uniform elongation of transverse weld specimen is significantly lower (about 55% or smaller) than that for corresponding base metal specimen. It may be noted that loss of ductility is occurs due to non-uniform weld zone properties.
4. For 5 mm sheets welded at steel backing plate gives the best tensile strength and percentage uniform elongation compared to two other types of BP.

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