APPLICATION OF SELECTIVE HEATING IN AL-STEEL DISSIMILAR JOINING

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Abstract— Al-steel dissimilar joining has the advantages of both the materials in a single unit. This combination of materials has high industrial applicability. There is a large difference in physical, thermal and metallurgical properties of both the materials, which makes it difficult to join combination. In present work, the solid state joining of commercially pure aluminum and steel was performed. A number of attempts have been reported in the literature regarding preheating of steel to achieve better weld amalgamation. Earlier approaches were not much effective due to wide-spreading of heat in both plates. Thus, in this work, selective heating of steel side was performed using an induction heating equipment to avoid the heating of the aluminum side. Further, weld joints made by conventional friction stir welding (FSW) and newly developed induction heat-assisted FSW (IHAFSW) were compared using tensile testing and micrograph analysis. It was found that the elongation is improved up to 35% in hybrid welding which was a major concern in FSW. Detached debris of steel was alleviated and bonding surface area was increased in selective preheating which suggest higher ductility and in a sound weld joint.

Index Terms— Deformation, Friction stir welding(FSW), Hybrid joining, Induction heating, Intermetallic, solid welding, Unconventional.

I. INTRODUCTION

Multi-material design of materials is a concept of combining two or more differently equipped material systems to take advantage of the properties of both. An example of such a combination can be Al-steel joint. Steel and aluminum are the most exploited materials in today's industrial world. They have affable availability in nature and perform suitably in almost every application. The area of application of both the metals is very vast. Their combination has also many applications in automobile, marine, shipbuilding, cryogenics and in aerospace industries. Steel has high strength and rigidity whereas aluminum has a high strength to weight ratio and good corrosion resistance. All of these properties are essential for the automotive industry. A combination of these two metals in a single unit provides good strength as well as weight saving, which in turn saves a lot of energy in the automotive industry. Honda in their fabrication of subframe (used in Honda accord) used Al-steel joint and compared its properties with conventionally formed frame and attained a 50% power saving as shown in Fig. 1.

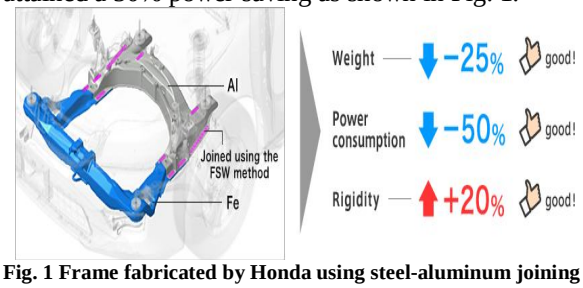


Fig. 1 Frame fabricated by Honda using steel-aluminum joining [1]

Regardless of its high applicability, this combination of metals is rarely used in industries due to various difficulties encountered during joining of these materials. The main issues related to the joining of steel with aluminum alloys are inferior strength and ductility of joint and a narrow process window. The predominant reason for lack of strength and ductility in case of fusion welding is insolubility of both the metal systems. There is an enormous difference in their physical and metallurgical properties. The properties associated mainly with welding of Al-steel are melting temperature, the coefficient of thermal expansion, thermal conductivity and strength. There is a huge difference in properties of these two material systems as shown in Table I. This difference in properties causes problems like non-uniform solidification, different thermal cycle, complex stresses, and differential expansion and contraction in case of fusion welding.

Non-fusion welding processes have an advantage over fusion welding processes in joining of Al-steel due to the elimination of fusion and solidification. The main concern in this metal combination is its insolubility in the molten state which is shunned in solid joining.

Table I Difference in physical properties of steel and aluminum [2]

Properties	Steel	Aluminum
Melting temperature (°C)	1425-1540	463-671
Coefficient of thermal expansion (10^{-6} (°C)$^{-1}$)	11.3-12.3	21.5-23.8
Conduction coefficient (W/m K)	45	235
Tensile strength (MPa)	247	90

In solid-state joining techniques, various factors like heat generated by means of friction and plastic deformation, intermetallic compound formation and process parameters are to be critically balanced in order to get a sound joint. In friction stir joining of

these metals, the most important property is the plastic behavior of the metals under high temperature. Thus, to bring both metals on the same level of strength and plasticity, the steel is heated and brought to a lower strength. Upon heating steel turns soft and its plasticity comes in comparison to that of aluminum. Stirring becomes easier, and both materials mix up in a better way. Therefore, to bring down the steel to a lower strength, heat-assisted friction stir welding is examined by researchers. GTAW assisted hybrid FSW was used to join Al6061-T6 and STS304 stainless steel of 3 mm sheet by [3]. A sound joint was reported with the hybrid process and the strength of the joint was found to be higher than normal FSW joint. An electric current assisted friction stir welding setup was developed by [4] and joined steel and Al-Mg alloys. In his investigation, a variable current was applied and its effect on grain size was compiled. On increasing electric current in the circuit, the grain size in the weld zone was found to be increasing. A setup of electrically assisted friction stir welding was established by [5]. Al6061 alloy was welded with TRIP 780 steel. In his study, the tool of FSW was kept outside the circuit and various configurations of heating were tried. The combination of electro-plastic effect and joule effect aided in plunging and reduced the axial welding force. It was concluded that micro-interlocking can be seen in electric aided FSW at the Al-steel interface. This can inhibit the crack initiation and propagation of the intermetallic layer.
In solid state joining of Al-steel, steel side is not actively taking part in joining. Thus to have an active stirring of steel plate without too much disintegration and fragment formation, selective preheating of steel plate is a viable approach. Therefore, researchers have shifted their attention towards hybrid processes in recent years.

II. EXPERIMENTAL METHODOLOGY

Commercially pure aluminum and mild steel plates of dimension 150 mm × 50 mm and thickness 3 mm were placed in square butt configuration for pilot experiments. The tool made of tungsten carbide (WC) was used for FSW. The dimensions of the tool are specified in Table II.

After initial trials, the sound joint was obtained on welding process parameters of 708 RPM and weld scanning speed of 40 mm/min. For selective preheating trials, an induction heater (15KW) of the medium frequency range (30-100 KHz) is employed. A schematic of the system is shown in Fig. 2.

Table II Dimensions of tool used for welding

Tool shoulder diameter	Pin diameter	Pin length	Pin taper angle	Tool tilt angle
25 mm	6-8 mm	2.8 mm	20°	1°

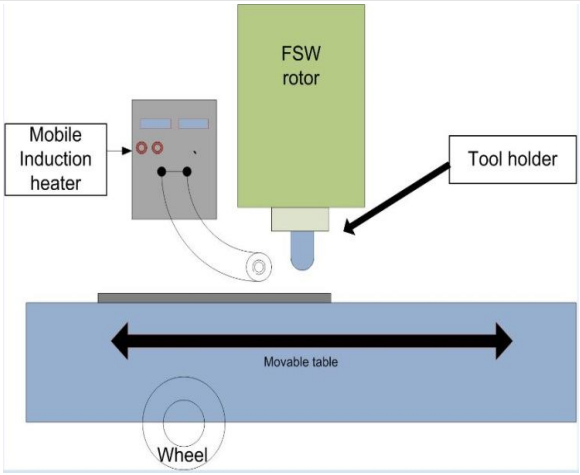


Fig. 2 Schematic view of IHAFSW Setup

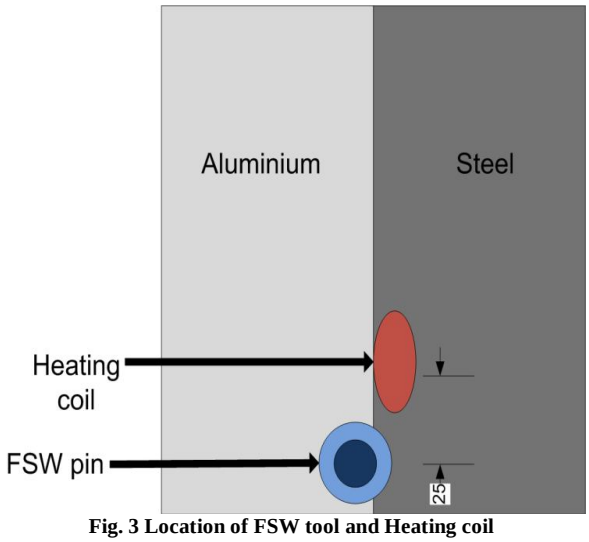


Fig. 3 Location of FSW tool and Heating coil

The coil of the Induction heater is placed over the steel plate at a distance of 25 mm ahead of the FSW tool as shown in Fig. 3. The distance between the coil and tool was kept constant during welding,
The temperature was measured using k-type thermocouples placed in steel and aluminum plates during normal friction stir welding. The temperature of plates was measured by a Digital LCD IR pyrometer during induction heating process. The tensile specimen was prepared according to ASTM E8 standard. Tensile testing was performed on the universal tensile testing machine (Instron USA; model - 5980) at a cross-head speed of 1 mm/min. Samples were machined and polished using standard metallographic practices for microstructure study. Field emission scanning electron microscopy (FESEM) was used for microanalysis of the interface.

III. RESULTS AND DISCUSSION

FSW is fundamentally a process of deformation on the application of a high strain rate. Additionally, thermal softening of the material takes place due to frictional heating. Material near around tool pin flows

plastically. The flow stress of any material depends largely on its temperature. Thus, the temperature is a major factor in dissimilar friction stir welding.

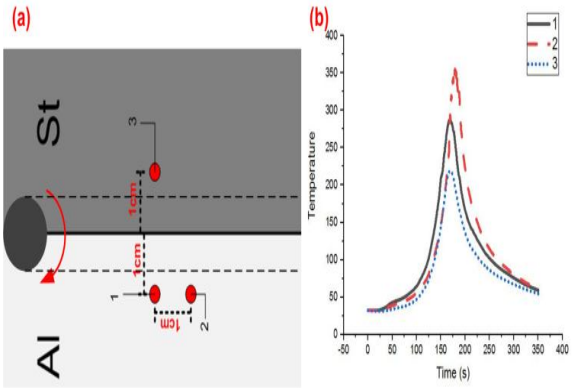


Fig. 4 (a) Placement of thermocouples, and (b) Temperature vs time graph

The temperature of the steel and aluminum plate was measured during welding using three k-type thermocouples. Thermocouples were placed in both the plates at a distance of 1 cm away from the centerline as shown in Fig. 4(a). Temperature vs time relationship during FSW is shown in Fig. 4(b). Peak temperature attained in steel plate during Friction stir welding was 219°C.

It has been shown in the weld thermal cycle that the peak was obtained at around 170 seconds after the starting of the tool rotation. The peak temperature achieved for the aluminum plate was 288°C at location 1 and 356°C for location 2. Thermocouple 2 was placed away from the initial weld start point. Thermocouple 1 and 3 attained peak temperature at the same time whereas 2 attains its peak temperature after 180 seconds. Heat is conducted in the whole Al plate very fast because of the high conductivity of aluminum. Therefore, thermocouple 2 showed the highest temperature because of the accumulation of heat of friction stirring and conduction.

The melting point of steel is around 1425°C - 1540°C. steel tends to get soften at a higher temperature and its strength becomes half of the original strength at 500°C [6]. Strength of steel decreases drastically and ductility is increased on the application of heat and the same is also confirmed by [7] as shown in Fig. 5. As discussed above, the temperature achieved during normal FSW was around 220°C for steel plate. This temperature is not sufficient for easy flowability of steel.

Thus to bring steel to an easily deformable state, we need to assist the FSW by some additional source of heating. There are a number of ways to preheat the steel sheet, for example:- TIG, Laser, Gas torch, induction heating, and electrical resistance heating. Selective heating of the plate can only be realized by induction heating. Therefore, to preheat the limited area of steel plate, Induction heating was selected.

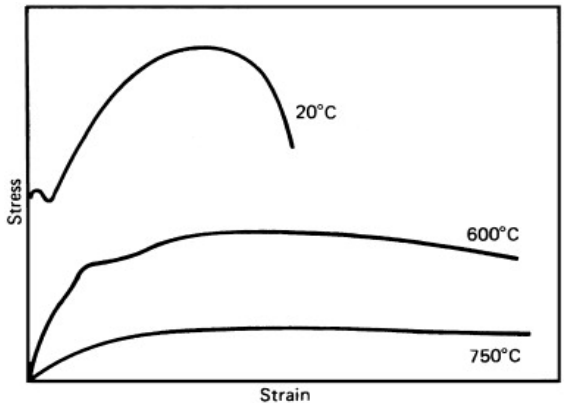


Fig. 5 Stress-strain curve of mild steel at various temperatures [7]

Induction heater works on the principle of eddy current and magnetic hysteresis loss, which only occurs in magnetic materials. Thus on induction heating, only steel plate gets heated and aluminum plate remains unaffected. Although some amount of heat was conducted towards the aluminum side, that was not sufficient to cause melting. Upon induction preheating, the temperature attained during welding was maintained around 600°C. Steel became soft and started flowing plastically during stirring action of FSW tool instead of breaking as a fragment. Macrographs of welds obtained from two different joining processes are shown in Fig. 6. In normal FSW joint, serrated steel fragments were observed. These fragments were detached from the parent steel plate and came in the aluminum matrix. In IHAFSW; the problem of detachment was avoided and extended finger like strand was present. Presence of an elongated fiber indicated the improvement of ductility of steel plate in IHAFSW. The bonding surface area was visibly increased in IHAFSW and it avoided the stress concentration and void formation associated with the detached fragment.

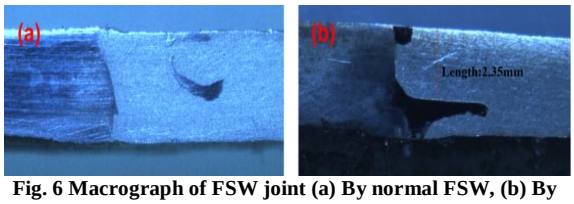


Fig. 6 Macrograph of FSW joint (a) By normal FSW, (b) By Induction Heating Assisted FSW

Scanning electron microscope images of normal Al-Steel FSW joint (A1-A3) and IHAFSW joint (B1-B3) are shown in Fig. 7. On analyzing interface micrographs obtained at high magnification SEM, a continuous bonding surface was apparent without the presence of an intermetallic layer. Further high magnification showed intermittent microcracks along the joint line, which is an intrinsic attribute of a dissimilar weld joint. Even though microcracks are present in both the cases, the joint performed using IHAFSW has a lesser number of crack sites as compared to normal FSW joint interface. This indicated a relatively better bonding in IHAFSW.

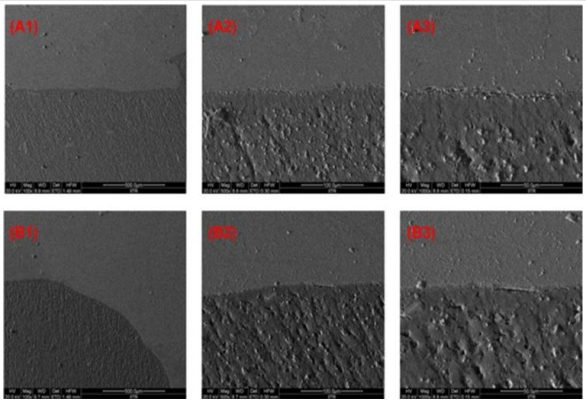


Fig. 7 (A) SEM micrograph of the interface of normal FSW joint at different magnification, (B) SEM micrograph of the interface of IHAFSW joint at different magnification

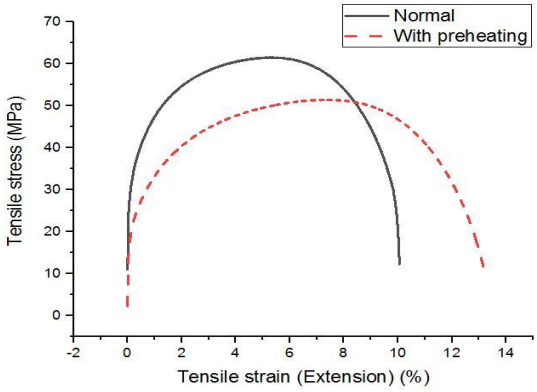


Fig. 8 Tensile test graph of normal FSW joint and Induction preheated FSW joint

The results of the tensile test of normal FSW joint and induction heat-assisted FSW joint are plotted in Fig. 8. It was perceived from the tensile test that the elongation of IHAFSW joint was superior to the normal FSW joint. Tensile strain in IHAFSW joint was found to be around 13.5%. It showed an improvement of 35% over normal FSW joint extension. Although the strength of IHAFSW joint was somewhat inferior to the normal FSW joint which indicated softening of the joint.

CONCLUSION

On the basis of experiments performed for joining of Al-steel dissimilar combination, following conclusive points are drawn:

- Steel has higher flow stress and hardness than the aluminum, therefore for achieving better stirring action during Friction stir welding, flow stress of steel is to be brought in comparison to aluminum by using some external heating source.
- Induction heating process prior to friction stir welding is a suitable alternative for performing selective preheating because of its capability to heat only magnetic (steel) plate.
- Around 35% improvement in the ductility of FSW joint was obtained on the application of selective induction preheating of steel plate.

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