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Friction Stir Welding of Dissimilar Metal: A Review

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Abstract: Friction Stir Welding (FSW) is a solid state welding process which produces welds due to the compressive force contact of work pieces which are either rotating or moving relative to each other. The heat required to join different specimens is generated by heating due to friction at the interface. Application of Friction Stir Welding in aerospace industries is very broad. Rolls-Royce now uses friction welding processes for its modern Trent aero engines that drive the Airbus A380 and the Boeing 787.In this paper, Friction Stir Welding of various dissimilar metals are reviewed. The microstructure, hardness and flow characteristics are also reviewed.
Keywords: Friction Stir Welding; Dissimilar Metals; Binary Phase Diagram; Flow Characterisitcs

I. INTRODUCTION

In recent times, focus has been on developing fast, efficient processes that are environment friendly to join two dissimilar materials. The spotlight has been turned on Friction stir welding as a joining technology capable of providing welds that do not have defects normally associated with fusion welding processes. Friction stir welding (FSW) is a fairly recent technique that utilizes a non - consumable rotating welding tool to generate frictional heat and plastic deformation at the welding location, thereby affecting the formation of a joint while the material is in the solid state. Figure.1 shows the schematic drawing of friction stir welding representing all the relevant parameters of the process [1]. A rotating tool is pressed against the surface of two abutting or overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the 'advancing side'; the other side, where tool rotation opposes the traversing direction, is known as the 'retreating side'.

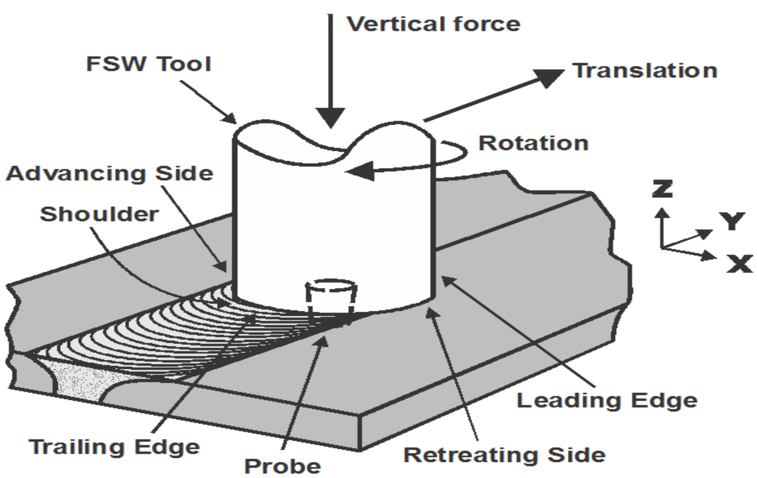


Figure 1: Schematic Illustration of Friction Stir Welding Process

The design of fixture plays an important role in Friction Stir Welding process (FSW). Proper designing of fixture is the one of the major solution to the problems arising during FSW process. FSW of aluminium alloys require a careful designing of both fixture and welding tool. The fixture should be designed and fabricated in such a way that it is able to bear the high magnitude forces and high temperature during welding process [2]. Welding speed significantly affected the microstructure and mechanical properties of the joining [3]. Heat generation during Friction Stir Processing is due to the mechanical loads. No external heat sources are used. As the temperature increases, the material softens and the coefficient of friction decreases. A temperature-dependent coefficient of friction (0.4 to 0.2) helps to prevent the maximum temperature from exceeding the material melting point. The observed temperature rise in the model shows that heat generation during the second and third load steps is due to friction between the tool shoulder and work piece, as well as plastic deformation of the work piece material [4]. Welded dissimilar metals have wide applications in industries. We will rarely find a manufactured product, especially in heavy industrial settings, that is made from solely one component, part or material. This is because of each component, part or material offers its own set of unique qualities or benefits, and this rings true of metals too. While it would, of course, be easier if just one metal could be used, manufacturers look to use different metals to enhance their products in different ways. For example, steel offers a great deal of strength, while aluminium is lighter and has better corrosion-resistant properties. By combining these, you can have a strong, yet resistant and lighter, final product. But the main issue with joining of dissimilar metals are the differences in the chemistry of the materials, their melting points, coefficient of thermal expansion, thermal conductivity etc. which offers a serious challenge in procuring high-quality joints. Welding can be performed by either Fusion Welding process or by a Solid-state joining process. If we perform Fusion welding process to join dissimilar metals, the metal or alloy with low melting point evaporates away which leads to compositional change and thus weld with inferior quality is obtained.

II. PROBLEMS WITH DISSIMILAR METAL WELDING

A major challenge offered for obtaining sound joints between dissimilar metals are their differences in the chemistry of the materials, their melting points, thermal conductivity, coefficient of thermal expansion etc. The chemistry of the resulting weld is taken into account when filler material is used during fusion welding processes. While in Friction Stir Welding process which is a solid state joining process, no filler material is taken into account. The main challenge in Friction Stir Processing of Dissimilar Metal is the prevention of formation of brittle intermetallic phases. Compatibility of materials under considerations for dissimilar welding can be better observed by a phase diagram.

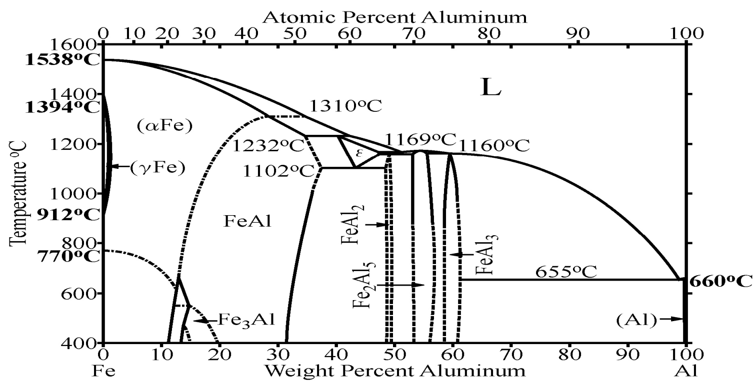


Figure 2: Fe – Al binary phase diagram

In Figure 2, it is obseved that Fe and Al are immiscible in each other and tend to form intermetallic compounds such as $FeAl_3$ and Fe_3Al. Low melting point alloy gets initially melted during fusion welding of materials with different melting points. A compositional changes occur due to evaporation of low melting point alloy which causes unsound weld. On other hand, in Friction Stir Processing, melting is not an a big deal. Friction Stir Welding between materials of different melting points may lead to melting of low melting point material. Differing material softening characterisitcs possess its own set of challenges. Softening characteristics is generally defined as drop of flow strength with temperature. Insufficient material mixing which results undesirable welds occurs due to differences in softening characteristics. Figure 3 shows the variation of Tensile strength of Steel with temperature. It is obseved that at a particular temperature the material possess different strength which will lead to differences in flow characteristics during Friction Stir Welding.

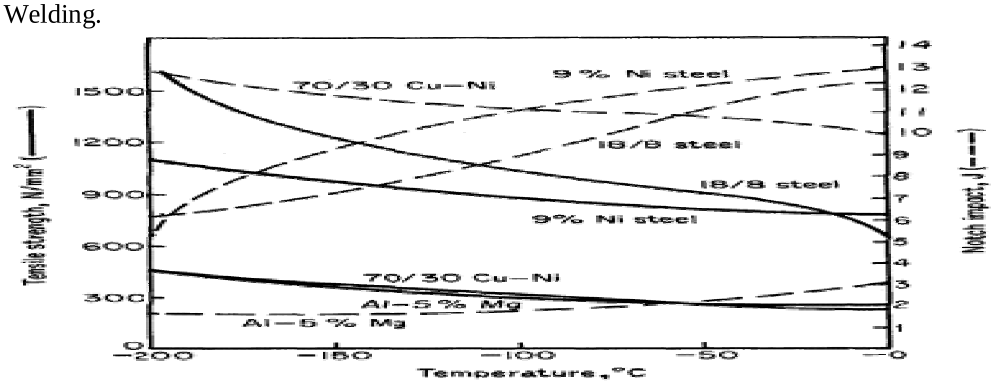


Figure 3: Variation of Tensile strength of Steel with temperature

III. CLASSIFICATIONS IN FRICTION STIR WELDING OF DISSIMILAR METALS

Friction Stir Welding which is a solid-state joining process provides good insight in joining dissimilar metals. There are three broad categories of joining dissimilar metal using Friction Stir Welding:

A. Friction Stir Welding of Dissimilar Alloys Having Widely Different Melting Point

In this case we will discuss about the dissimilar metal welding where the base metal of the alloy differ from each other entirely and have wide difference in their melting point. The welding of Al/Mg alloys to Cu/Ti/ferrous alloys are some examples which fall in this category. But in this section dissimilar welding of Cu – Al alloy will be discussed.For the experimental measurements there were used tin alloy Al - EN-AW-1050A with a thickness of 2 mm and Cu99 sheet with a thickness of 2 mm, joined by FSW weld overlay [5]. The pin was positioned 90% on Al, and the rotation of the pin was clockwise. The parameters used to obtain the joint were rotation speed 1400 [rev / min] and speed of 50 [mm / min]. Joint microstructure and chemical composition in zones (sites) marked in Figure 4 are presented in Figures 5. It can be observed the presence of the two base metals of materials used in the joining process, copper and aluminium, as well as the mixing area. Analysis of figures and spectra presented in these tables highlight the following issues: a) the joining area has an irregular shape (the outline of the joint area is approximately shown in Figure 5 and many "gap" type defects have an acceptable quality of the joining process; b) pieces of Copper are ripped and brought to the site of Al and in the zone where should have been the nugget.

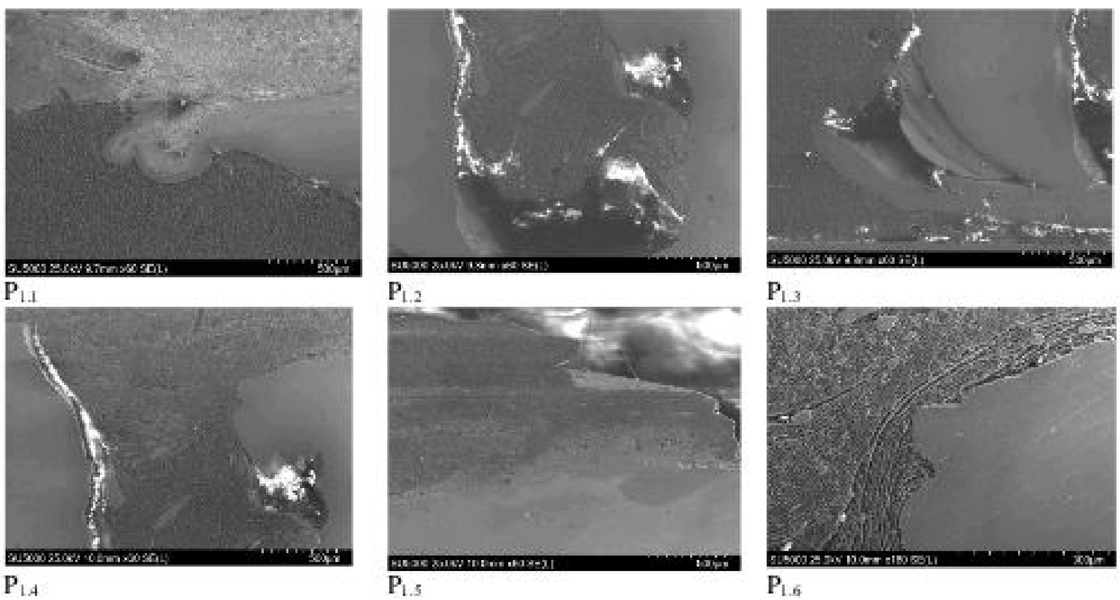
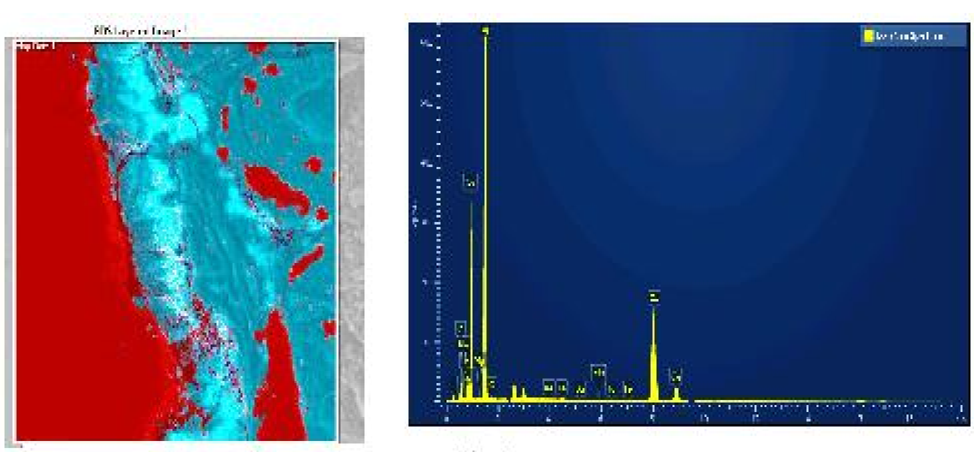


Figure 4: Morphology of Joint zone



Site 1

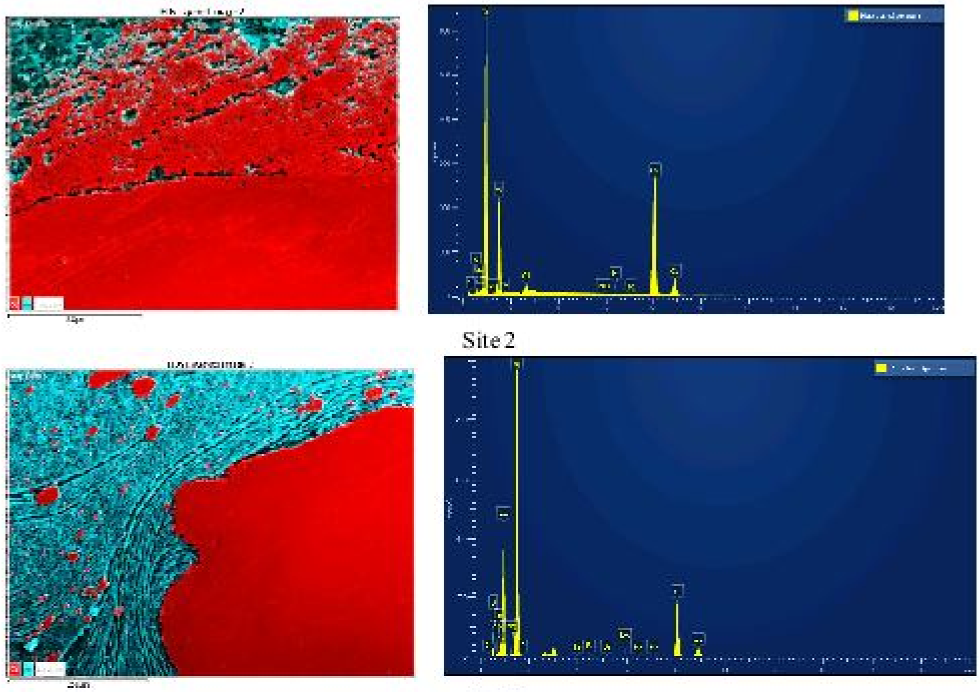
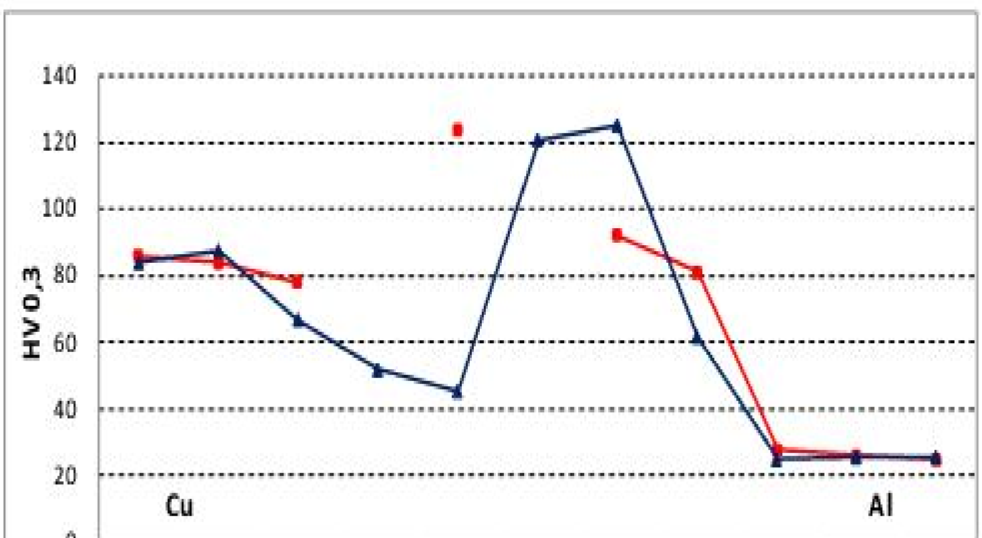


Figure 5: Microstructure and Chemical Composition

It was noted that in the joint zone there was an increase of microhardness values in relation to the values of microhardness of the base materials (86 HV0.3 for Cu, respectively, 26 HV0.3 for Al). Thus, the maximum values of microhardness in the joint zone are over 120 HV0.3, which highlight significant increases of microhardness. These are over more than 50% compared to the "toughest" base material (Cu) and over 360% compared to the "softest" base material (Al). By correlating hardness with the mechanical properties and mechanical strength it can be concluded that tensile strength of the joint zone is greater than the tensile strength of any of the materials joined.



	1	2	3	4	5	6	7	8	9	10	11
F1	86	84,1	78,2		123,8		92,3	81,4	28	26,4	25
F2	84	87,6	67	52	45,6	120,8	125,1	61,9	25,3	25,9	26

Figure 6: Value for microhardness of P1

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B. Friction Stir Welding of Dissimilar Alloys With Similar Base Metals And Melting Point

Various type of combinations which fall under this category are: Al – Al alloys, Mg – Mg alloys and Ferrous – Ferrous alloys where the base materials remains same and they differ only in terms of major alloying elements and their concentrations. In this section, we will discuss about the Friction Stir Welding of Al 5052 with Al 6061 alloys [6]. The dimensions of the work- pieces used were 300mm × 50mm × 5mm material, and fine particles left after the machining process. A commercial high speed steel (HSS) tool, having a cylindrical geometry with 4.8mm pin length and 6mm pin diameter and having 25mm shoulder diameter was used. The tool tilt was kept constant at 3◦ for all welding trials. Several FSW trials were carried out at1120and1400rpm and for various traverse speeds ranging from 60mm/min, 80mm/min and 100mm/min. Depending on the combination of tool rotation speed and tool traverse speed used, the specimens were assigned identities according to the nomenclature (R “tool rotation speed ” F “ tool traverse speed” where R “tool rotation speed” refers to the tool rotation speed in rpm and F “tool traverse speed” refers to the feed or the tool travel rate in mm/min; e.g., the process parameter combination of 1120rpm and 100mm/min is designated as R1120F100.

From the friction stir welding experiments for dissimilar combination of AA5052 and AA6061, it was noticed that the normal load experienced by the tool varied in the range 3.5–7kN a rotational speedof1120rpm.Whereas at a higher rotation speed of 1400rpm, the normal load was found to decrease and was in the range 3.5–6kN. It was found that during FSW AA5052-AA6061 trials, the normal load was less at higher rotation speed of 1400rpm. However no conclusive statement can be made for the normal load at rotation speed of 1120rpm. The traverse load was in the range 0.6–1.2kN and 0.7–1.3kN for rotation speeds of 1120 and 1400rpm, respectively. The spindle torque decreases with an increase in the rotation speed. Spindle torque values in the traversing phase were in the range of 33–38 Nm at 1120rpm and 25–30 Nm at 1400rpm. Further, it was observed that for a particular rotation speed, the spindle torque was not affected with the variation in traverse speeds (60, 80, and 100mm/min).

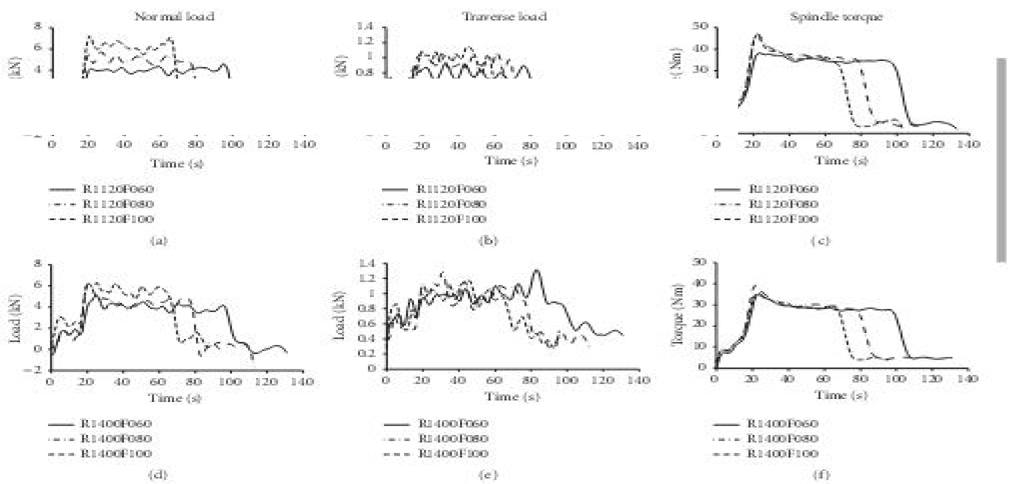

Figure 7: Variationof normalload, traverse load, andspindle torquewithrespect totime during friction stir welding of AA6061and AA5052 experiments at various combinations of process parameters.

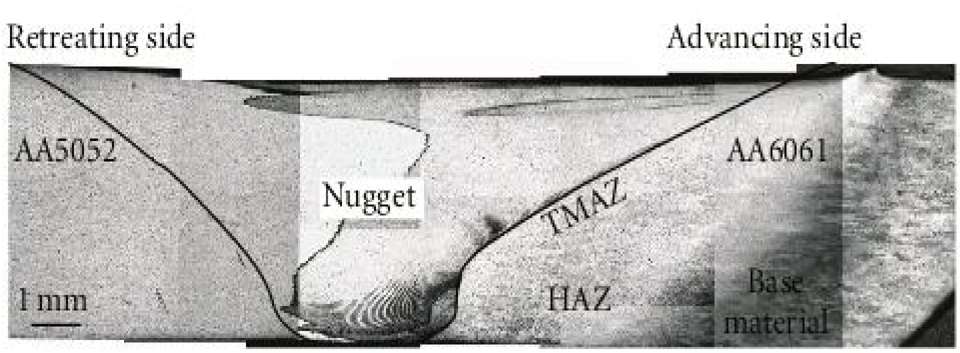

Figure 8: Motif of optical images of the transverse cross-section of FSW AA5052-AA6061 R1400F080 specimen showing the various regions.

Figure 8 shows a motif of the optical images of the cross-section of a FSW AA5052- AA6061 R1400F080 specimen. The different regions of the dissimilar friction stir weld are marked in the figure. It can be noticed that the interface between AA5052 and AA6061, which initially was linear prior to welding, now has a non- linear, wavy, and distorted appearance. The interface appears to be serrated throughout the thickness of the weld. This interface can be considered to be an imperfection and was termed as "joint-line remnant". Several researchers have studied the formation of complex intercala- tion structures consisting of swirl-like features and intermingled dissimilar lamellae during the intermixing occurring in FSW of dissimilar materials.

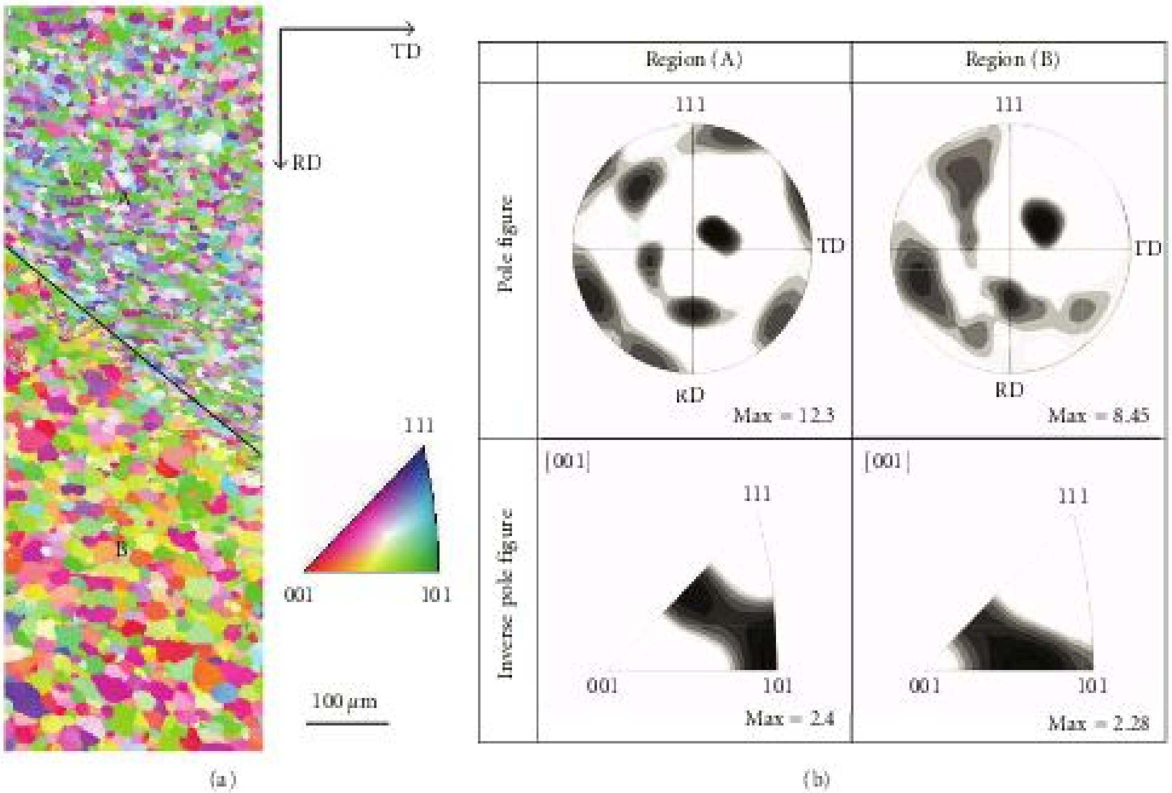

Figure 9: (a) Inverse pole figure map of the region across the interface of AA5052 and AA6061 in the nugget of FSW AA5052-AA6061 specimen. (b) Chart showing the pole figure and inverse pole figures for the various regions marked in (a).

Figure 9(a) shows the inverse pole figure map of a region at the interface of AA5052 and AA6061 in the nugget of FSW AA5052-AA6061R1400F080specimen.Theregionshowsre- fined grains in the nugget for both the aluminium alloys. This region shown was partitioned into two regions A and B. Region A comprised of fine grains of AA6061 while region B comprised of a refined microstructure of AA5052. The average grain diameters for regions A and B were 11 and 20μm, respectively. From the chart of the{111}pole figures of these regions shown in Figure 9(b), it could be seen that the orientation distribution was similar for both the aluminium alloys. Most of the {111} poles were aligned in the ND direction (i.e., parallel to the welding direction).Figure 10 shows the variation of micro- hardness across the transverse cross-section of FSW AA5052- AA6061 R1400F080 specimen in the midthickness region along line AB (. In the figure, the filled and unfilled symbols denote the microhardness values cor- responding to the regions/domains of AA5052 and AA6061 alloys, respectively. An abrupt transition across the AA5052- AA6061 interface in the nugget was observed as one proceeds from the AA5052 towards AA6061. It must be noted that the microindentation in the nugget was performed at intervals of 250μm. Hence any possible smooth change (transition) in the microhardness was not observed using the microindentation technique. The microhardness values remained nearly constant in the nugget and the adjoining HAZ for both the aluminium alloys (56–61 VHN in AA5052 and 86–91 VHN in AA6061). Beyond the HAZ into the base material region, there was a smooth transition of the micro- hardness to the parent material microhardness values— decreasing from the higher hardness in the nugget at the AA6061 side and increasing from lower hardness in the nug- get at the AA5052 side. the welding direction.

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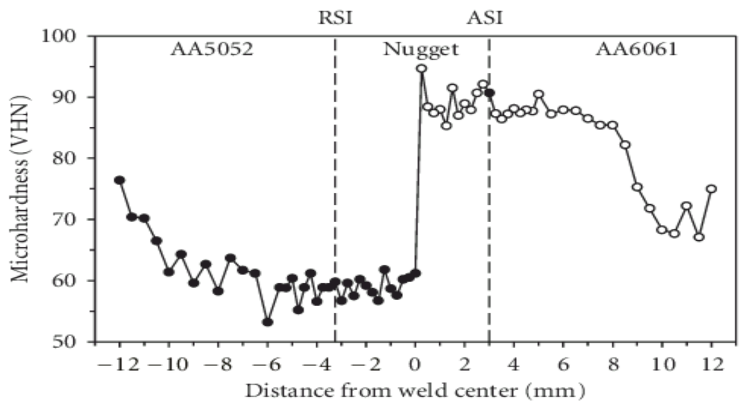

Figure 10: Microindentation hardness distribution across the trans- verse cross-section of FSW AA5052-AA6061 R1400F080 specimen.

C. Friction Stir Welding of Different Alloys Having Dissimilar Base Metals and Similar Melting Point

Magnesium alloys are weaker than Aluminium alloys in terms of their average strength. Thus, welding of dissimilar magnesium alloys in itself offers little or no challenge. So, the tools used for welding aluminium alloys can be used for magnesium alloys without worrying about tool wear. The different chemistry of both alloys offers a real challenge in joining them. To understand, let's have a look at Al-Mg binary phase diagram.

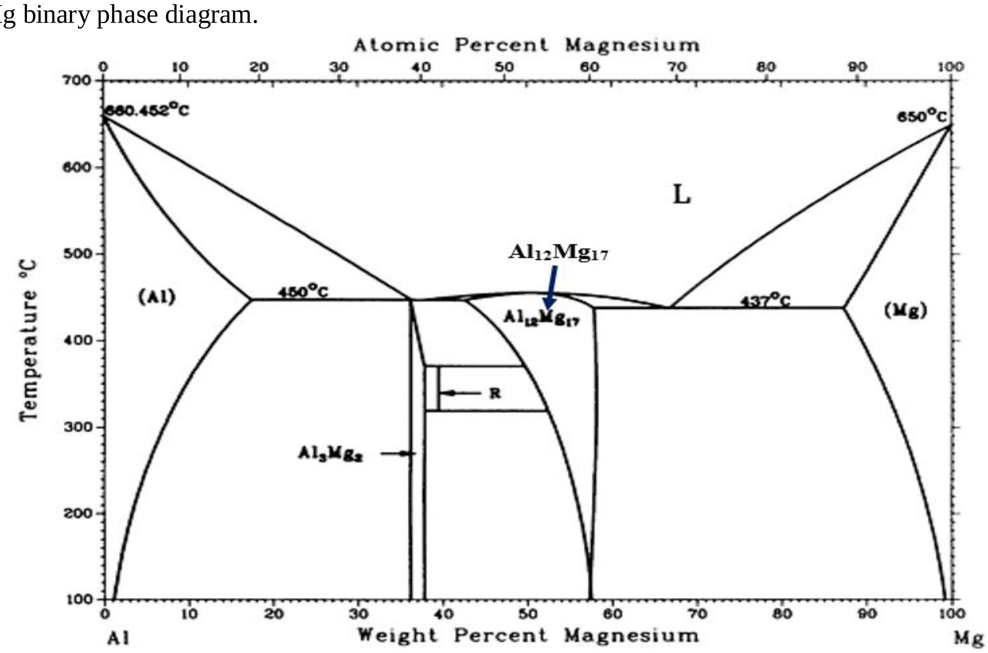

Figure 11: Al – Mg binary phase diagram

The equilibrium diagram indicates five different phases- two terminal solid solutions i.e. Al(Mg) and Mg(Al), and three intermetallic compounds, Al_3Mg_2, R and $Al_{12}Mg_{17}$. If we weld pure Al and Mg together and if an equal proportion of both the materials (weight%) are present in the weld nugget, this will lead to the formation of Al_3Mg_2 and $Al_{12}Mg_{17}$ phases at room temperature. But in reality, during friction stir welding of dissimilar metal, the material flow is quite complex and a non-equilibrium condition exists during processing. Thus, the presence of intermetallics compounds results poor weld quality. To overcome these difficulties, one needs to choose the appropriate welding parameters such as positioning of the materials, tool rotation rate, tool traverse speed and position of the tool from weld interface. In this section, we will discuss about Friction Stir Welding of AZ31B Magnesium Alloys and AA5052 Aluminium alloys [7]. The materials used for butt joints were extruded AZ31B magnesium alloy and A5052-H aluminum alloy plate. The plate thickness was nominally 3 [mm]. These materials were put on the table of high-powered FSW machine that the tool advancing side was Al plate and retreating side was Mg plate. The rotational tool was inserted along the center of butt line. The material of FSW tool was JIS SKD61 tool steel. The tool has shoulder with 12 [mm] in diameter, and has probe with 4 [mm] in diameter and 2.9 [mm] in length. The inclination angle used was 3 degree. Tool load was 10 [kN]. The FSW conditions tool rotational speed, Rt, and welding speed, V were changed from 800 to 1600 [per min] and from 100 to 400 [mm/min], respectively.

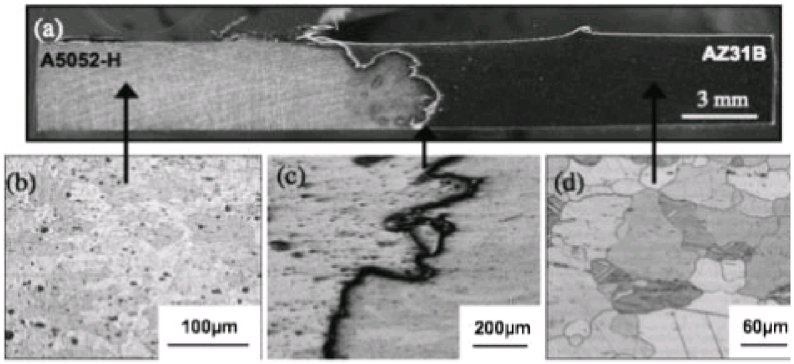

Figure 12: Macroscopic (a) and microscopic image (b)–(d) of the cross section welded at 1000 [per min] and 200 [mm/min].

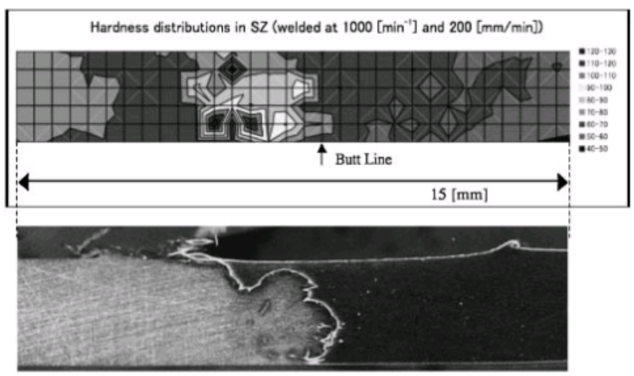

Figure 13: Cross Sectional Hardness Distributions of the joint welded at 1000 [per min] and 200 [mm/min].

As-received A5052-H alloy had 2030 [mm] of the grain diameter. After FSW, the grain size was refined to c.a. 10 [mm] by dynamic recrystallization. FSW-ed A5052-H alloy has 70HV in base material region and 60HV in SZ. This is because the base alloy was H tempered plate and frictional heating made softening as heat treatment. On the other hand, in A5052-H and AZ31B dissimilar FSW welding, crosssectional macroscopic image of the conditions that 1000 [per min] of the tool rotational speed and 200 [mm/min] of the welding speed was shown in Figure 12 and 13.

IV. CONCLUSIONS

The benefits of FSW are large in the field of the welding process. FSW does not require joint preparation between two plates only degreasing is needed. It offers the high quality of welding with increased tensile strength, outstanding fatigue properties and corrosion resistance from the oxidation and chemical action. It is an economical method of welding with low operation cost, which has no consumable with less energy cost unlike consumption of electrode in arc welding process. Friction stir welding has no post heat treatment with low distortion and shrinkage of material. By correlating hardness with the mechanical properties and mechanical strength it can be concluded that tensile strength of the joint zone is greater than the tensile strength of any of the materials joined. The mechanical properties of dissimilar Al and Mg alloy plate joints depend on the distributions of Al-Mg intermetallic compounds. For improvement of the joint efficiency, it must be not only suppressed precipitates of compounds, but also finely dispersed.On the other hand, less intermetallic compound phase is in FSW, and the hardness can be controlled by FSW condition. Lower the ratio of rotational speed to welding speed made less intermetallic compounds in SZ.

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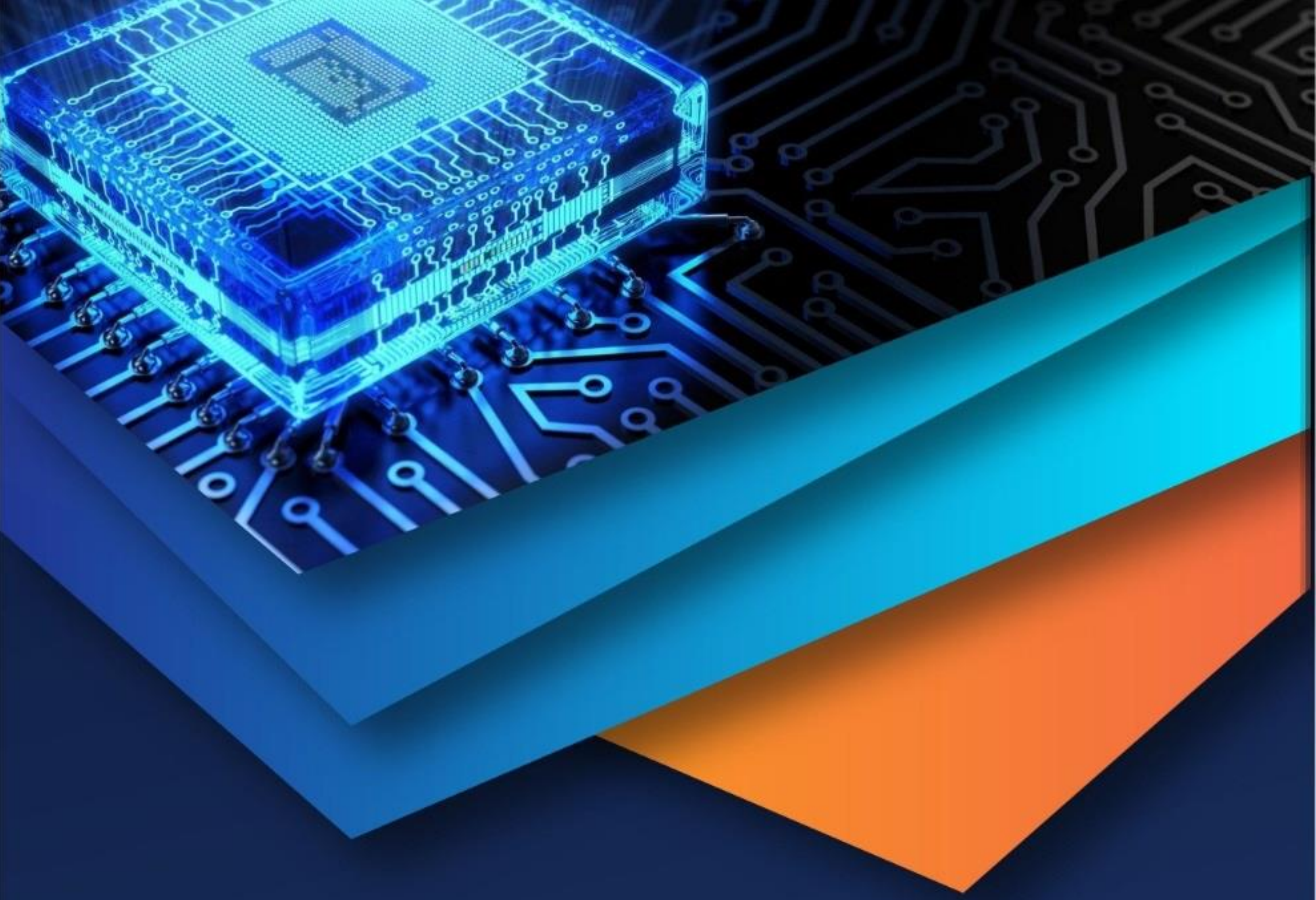

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