Effects of Friction Stir Welding Tool Plunge Depth on Microstructure and Texture Evolution of AA1100 to A441 AISI Joint

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Abstract: The aim of this article is the study of tool plunge depth (TPD) effects on mechanical properties of friction stir welding of AA1100 aluminium alloy to A441 AISI steel. For this purpose, the 0.1, 0.2, 0.4, and 0.6 mm TPDs are selected and other welding parameters are kept constant. The results show that the frictional heat increases and stir zone grain size decreases with increasing TPD at both base metals. At higher TPD, the material press out from shoulder and base metals interface. The highest tensile strength is allocated to the joint which were welded with 0.2 mm plunge depth. This joint has appropriate joint efficacy, material flow and microhardness in comparison to other joints.

Keywords: Dissimilar joint, Friction stir welding, Mechanical properties, Tool plunge depth

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1 INTRODUCTION

Compare to other welding processes, friction stir welding (FSW) is a solid state joint that enables joining dissimilar materials. In this process, a non-consumable rotational tool penetrate joint line and makes surrounding material pasty, by generation of frictional heat after penetration, welding tool starts moving forward and pull plastic materials from front to rear side with forging force and combine them [1]. Existing disturbs and heat in friction stir welding are causing changes in the impurities distribution and the grain size surrounding and the joint centre. Figure 2 presents a schematic view of the FSW process.

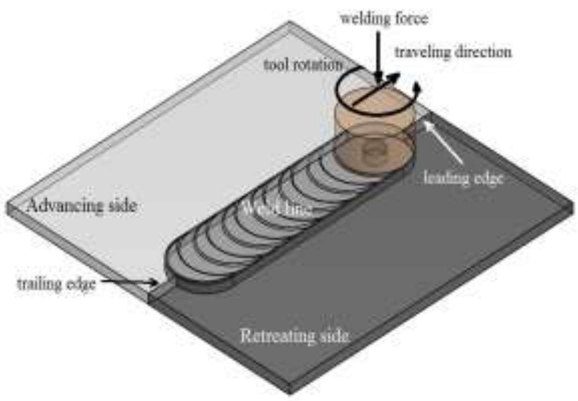

Fig. 1 Friction stir welding process

In joining of aluminium's and steels by fusing welding methods, due to high heat input into the junction, thick brittle and hard compound layer is formed. This compound can damage the mechanical properties of the joints [2, 3]. Therefore in recent past the researchers focus on joining such materials by FSW process. They extensively used FSW for joining aluminium alloys to steels and studied mechanical properties, microstructures, material plasticization and etc.

Jiang and Kovacevic [4] succeed to joint 6061 aluminium alloy to AISI 1018 steel by FSW process. The joint had desirable mechanical strength and they showed that by increase in tool rotary speed defect free joint are produced. Elrefaey et al. [5] were reported that in dissimilar joint between commercially aluminium and low-carbon steel, joint strength is depended on the pin plunge depth into the steel surface. Uzun et al. [6] Investigated the properties of friction stir welded 6013-T4 aluminium alloy to X5CrNi18 - 10 stainless steel. Watanabe et al. [7] conducted experiments on the effects of a FSW tool offset and tool rotational speed on the tensile strength and the microstructure of the SS400 mild steel and A5083 aluminium alloy. The maximum tensile strength of the joint was about 86% of that of the aluminium alloy base metal when 90% of the cross-sectional area of pin was placed in the aluminium side. Chen [8] performed a parametric study on FSW of Al6061-T651 aluminium alloy to low carbon steel. They indicated that lower rotational and linear speed can result in higher impact values of weld strength. Their maximum tensile strength can reach 76% of the aluminium base metal. Dehgani et al. [9] investigated effects of FSW parameters on mechanical properties of aluminium alloys to mild steel. They reported the joint strength more that 90% of aluminium base metal reachable by controlling of intermetallic compound and heat impact factor. Liu et al. [10] attempted to join 6061-T6 aluminium and TRIP steel. They reported welding speed had an insignificant effect on mechanical welding force, temperature distribution, strain rate and intermetallic layer composition. On the other hand higher rotational speed can elevate the temperature distribution, vertical and lateral force and can also influence the composition of the formed intermetallic compound layer.

Among the FSW parameters, the tool plunge depth (TPD) is a key factor to material flow and heat generation [11]. The tool plunge depth defined the amount of tool shoulder distance with top face of work-piece. In real situation, the plunge direction is "-Z" but for simplification of explanations, the tool plunge depth is represented by positive numbers which means the shoulder fall distance in to the work-pieces. Figure 2 presents a schematic view of the FSW tool plunge depth.

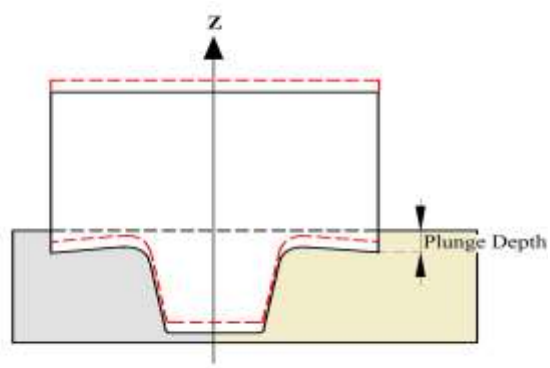

Fig. 2 Friction stir welding tool plunge depth illustration

Kwon et al. [12] investigated the effects of plunge depth on the FSW of aluminum alloy. They reported the maximum tensile shear load of the welded plates exhibits much higher than that of the adhesive bonded aluminum alloy plate with increasing plunge depth. Ramulu et al. [13] analyzed the effects of plunge depth on the formability of 6061 Aluminum alloy. They reported that when plunge depth is, the forming limit of friction stir welded, blanks have increased. This is mainly due to the evolution of thickness gradient during necking of un-welded and welded sheets. They were found from the analysis that, the higher plunge depth produces a weld without internal defects. Although there are numerous works which join the various aluminium alloys to steels by FSW process, joining AA1100 aluminium to A441 AISI has not been reported so far. Due to the low weldability of both alloys, joining them needs a careful control on process parameters and sheets setting. In the present study an extensive experimental approach is made to find effects of FSW plunge depth on tensile strength, microhardness and plastic flow. Then the optimal parameter setting for each quality characteristic is presented and completely discussed.

2 EXPERIMENTAL PROCEDURE

In this research AA1100 aluminium alloy and A441 AISI plates with 3mm thickness were cut into required sizes by a universal sawing machine. The mechanical properties of base metals are presented in Table 1. A flexible clamping system made of high carbon steel was designed to secure the plates in their proper positions. Non-consumable tool with taper profile and 20 mm shoulder diameter made of tungsten-carbide was used to fabricate the joints (Fig. 3). A TABRIZ/4301 milling machine modified with FSW tool attachment was used to fabricate joints. In this experiment, steel sheets were located on advancing side.

Table 1 Physical and mechanical properties of base metals [14-15]

Parameters	A441 AISI	AA1100
ρ , kg/m^3	7800	2713
MP[1] ,^{o}C	1400	657
K[2] ,W/m.k	42.7	222
C_P[3], J/kg. K	477	900
σ_Y, MPa	344	34
σ_{UTS}, MPa	580	90
τ, MPa	380	62
E[4], %	15	35
VB[5]	355	23

For conducting the experiments, a single factor experimental design was used. It means that for finding effect of a given parameters, it varies through the levels while the others are keeping constant. In this study the tool rotation direction was CCW and had 2^o title angle from plate's normal surfaces and 1.5 mm offset in aluminium side. The entire process of welding, tool rotational speed was 710 rpm and linear speeds that aluminium and steel sheets welded together were 40 mm/min. the tool plunge depth (shoulder distance from top surface of workpieces) were 0.1, 0.2, 0.4 and 0.6 mm respectively. The tool movement was negative direction at "Z" axis for plunge depth. For simplification of results, explanation of the negative sign in plunge depth was neglected and all the depth is reported by positive numbers.

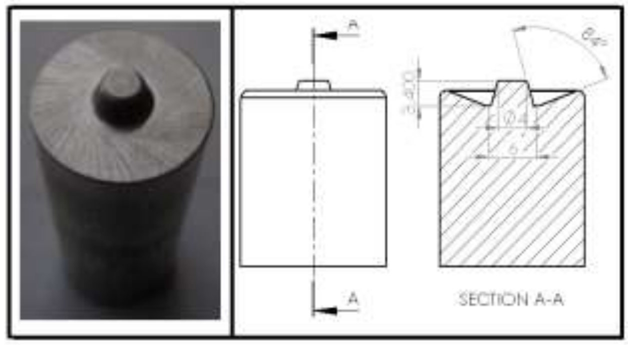

Fig. 3 FSW tool

To study the welds behaviour in tensile test, three samples were wire cut from each joint according to ASTM E8-M03 standard. For measuring tensile and yield strengths, the tensile test specimens which cut from welded joint have been gripped by grippers of 100 KN servo-controlled universal testing machine and the values of tensile strength and yield strength have been measured. Also, the Vickers hardness of welded joints have been measured by Vickers's micro-hardness, testing machine (Make: Shimadzu and Model: HMV-2T) with 0.05 kg load at 15 seconds was utilized to measure the hardness of weld nugget. The specimens for metallographic examination were sectioned to the required sizes from the joint comprising FSP zone and then were polished using different grades of emery papers. Final polishing was done using the diamond compound (1 lm particle size) in the disc polishing machine. The polished samples were etched using 1% HF, 2.5% HCL, and 1.5% HNO_3 for aluminium and 5% HCL and 95% ethanol to show general flow structure of the steel. Macro and micro-structural analysis have been carried out using a light optical microscope (VERSAMET-3) incorporated with an image analysing software (Clemex-Vision). Furthermore, to analyse the material flow, the video visual measurement machine (VMM) was utilized. Also, for finding formation of intermetallic compound in weld region, EDX and SEM analyse were used. The K-type thermocouples were used to measure the temperature, which were embedded at mid-plate thickness for both sides of sheets. A groove was prepared in the middle of sheets that were supposed to be welded and one thermocouple was determined as origin. For more accurate study of heat flow, two more thermocouples were used. Each of them placed with 3 cm distance from the indicator thermocouple at aluminum and steel side. The thermocouple set up illustration is shown in Fig. 4.

[1] Melting Point
[2] Thermal conductivity
[3] Specific heat
[4] Elongation
[5] Vickers Hardness

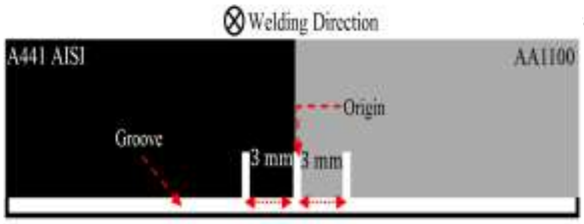

Fig. 4 The thermocouple set up illustration

3 RESULTS AND DISSCUSIONS

3.1. Thermal History

A sample of temperature graph which were welded at 0.6 mm plunge depth recorded by thermocouple is shown in Fig. 5.

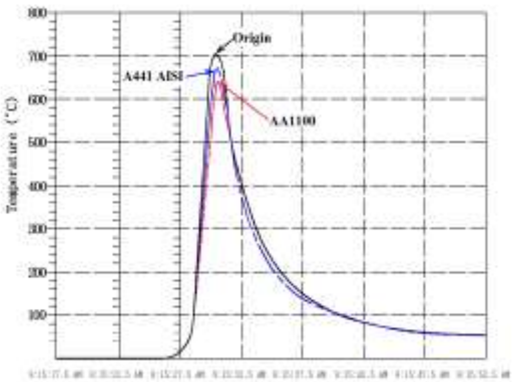

Fig. 5 A sample of temperature graph

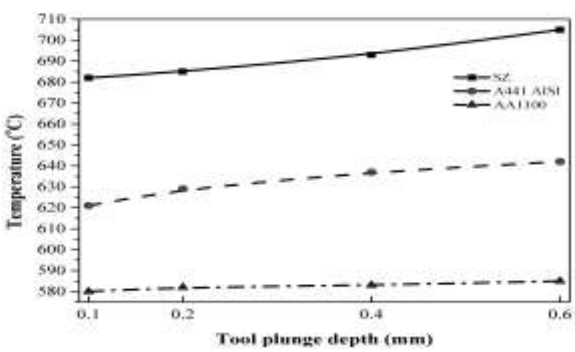

Fig. 6 Measured temperatures at different tool plunge depth

The produced heat at aluminium side is lower than steel side. This is due to lower shear stress and higher thermal conductivity of aluminium compared to steel. The peak temperature which was recorded by original thermocouple indicates the temperature at stir zone. This trend is governed at all plunge depths. The maximum produced temperature at 0.1, 0.2, 0.4, 0.6 mm plunge depth was 682^{o}C, 685^{o}C, 693^{o}C and 705^{o}C, respectively. The results are shown in Fig. 6. The temperature growing trend by increasing shoulder plunge depth has strait relation with more contact area between tool and work-pieces. Increasing tool plunge depth causes more plastic deformation and downward forging force which leads to higher heat generation.

3.2. Material Flow

Tool plunge depth plays a predominant role in determining FSW process characteristics. It has a direct impact on heat generation and amount of friction between the tool and sheets. The tool plunging refers to welding axial force and welding pressure [3]. By an increase in tool plunge depth, the friction between the tool and the sheets increase and causes higher amount of heat in tool-sheets interface [16]. In the present study, the plunge depth vary over 0.1, 0.2, 0.4 and 0.6 mm while the other factors are kept constant (i.e. 1.3 mm tool offset, 710 RPM tool rotational speed and 40 mm/min traverse speed). Figure 7 presents effects of tool plunge depth on the surface material flow and material mixing.

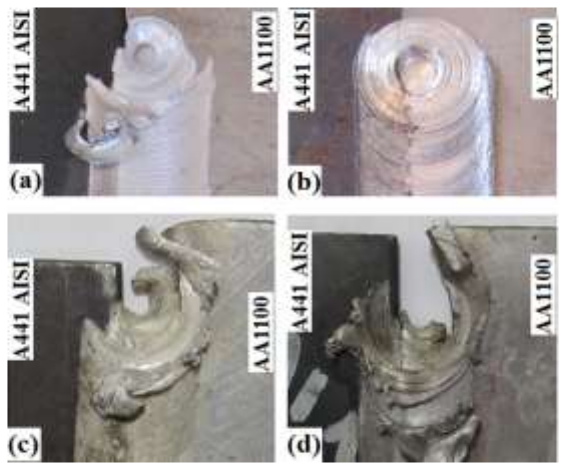

Fig. 7 Surface material flow at (a) 0.1, (b) 0.2 (c) 0.4 and (d) 0.6 mm plunge depth

At 0.1 mm plunge depth, the combination between the two metals was not appropriate. The butt line between the two metals which is located at fixture was approximately unchanged. This event indicates weakness of mingle between the two metals. With increasing tool plunge depth till 0.2 mm, more uniform composition was created at top of the joint line. The butt edge between two sheets shifted to aluminium side. This behaviour of materials shows more plasticization of A441 AISI and mixing with AA1100. The aluminium flash and flakes can be seen in the joint which welded with 0.4 mm plunge depth. These effects represents the volatile material from under the tool shoulder that indicates exceed downward forging force. This condition was aggravated in the 0.6 mm plunge depth. The internal material flow is shown in Fig. 8. In 0.1 mm tool plunge depth the upper zone of sheets welded together (Fig. 8-a). The low plunge depth causes poor material mixing, incomplete superficial flow and emergence crevice inside the joint. Formation of these defects decreases the ultimate tensile strength and joint efficacy [17].

As shown in the Fig. 8-a, due to improper inadequate mixing of the sheets, the fracture location on the tensile test relatively likes a straight line without any elongation that implies low tensile strength. In 0.2 mm plunge depth, material flow and interlace increased and according to Fig. 8-b, stirring occurred completely. The separation path in tensile test was placed in the thermos-mechanical affected zone. By increase of tool plunge depth up to 0.4 mm, downward forging force increases, correspondingly it will increase stir zone squeezing. Therefore, hot metal sticks on the shoulder surface as shown in Fig. 8-c. As a result of the higher force in this plunge depth, plasticized materials were driven toward out of stir zone. This phenomenon causes the dislodge materials from the joint zone and makes poor mixing in stir zone. For this reason AA1100 and A441AISI joints was broken from abutting edges of sheets in tensile test.

When the plunge depth is equal to 0.6 mm, due to excessive heat input, material flow under tool shoulder becomes easier, these softened material stick on the shoulder surface and a round plate is formed around the weld region (Fig. 8-d).

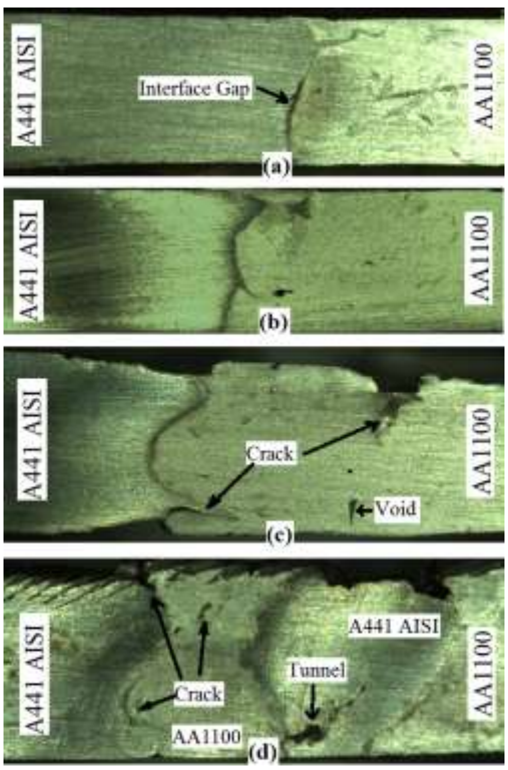

Fig. 8 Internal material flow at (a) 0.1, (b) 0.2 (c) 0.4 and (d) 0.6 mm plunge depth

Large chunks of steel and aluminium, those are visible in the cross section of the joint, represent the excessive downward forging force and sticking of materials. This excessive force leads to formation of unsound joint and produces narrow crack and tiny holes.

3.3. Microstructure of joint

In this study, the maximum temperatures were about 704°C for 0.6 mm plunge depth which was far away from the melting temperature of A441 AISI base metal. But this temperature is over of AA1100 melting point. During the experimental test, no sign of melting was observed. It seems that this temperature is produced locally undersized. Figure 9 shows micrographs of the SZ for both alloys at different plunge depth.

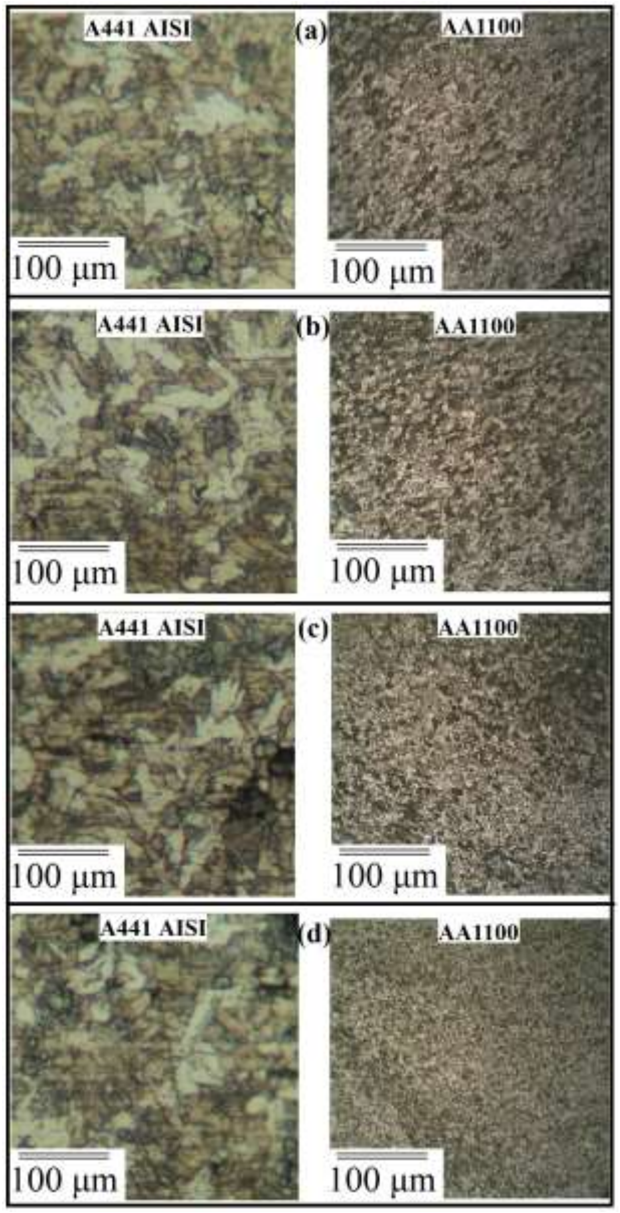

Fig. 9 Microstructure of joint which welded at (a) 0.1, (a) 0.2 (a) 0.4 and (a) 0.6 mm plunge depth

In addition to a thermal cycle, the stir zone also will endure a mechanical cycle. In spite of the high strain rate, recorded temperature and pictures from stir zone, it can be suggested that the A441 AISI steel structure was under dynamic recrystallization (DRX) at stir zone. Not many changes in steel microstructure are observed at lower plunge depth. The lower heat generation, axial force and plastic deformations at 0.1 mm and 0.2 mm plunge depth caused the gross microstructure changes which were insignificant at steel side. With increasing heat generation and plastic deformation at higher plunge depth, A441 AISI microstructure in the stir zone transformed to tiny austenite and after cooling converted to the small grains of ferrite and pearlite. In general and due to softness and low shear stress of AA1100 aluminium alloy, the material in the stir zone are affected with high temperature and intense plastic deformation.

These microstructure changes were exacerbated by increasing the tool plunge depth on the AA1100. According to results, the AA1100 was subjected to high temperature and plastic deformations compared to A441 AISI. The results shows that the average grain size at AA1100 side in SZ were 2, 1.6, 1.2 and 0.9 µm at 0.1, 0.2, 0.4 and 0.6 mm respectively. The optical microscope results shows that with increasing plunge depth, the plastic deformation and small grains at upper area of SZ are produced more than lower area of joint at steel side. There is a bimodal distribution of large and small ferrite grains in upper area of joint which welded at 0.6 mm plunge depth, whereas this situation is not visible for joint that welded at 0.1 mm plunge depth region. The average ferrite grain size of this region in the 0.1, 0.2, 0.4 and 0.6 mm welds is 9, 8, 7 and 5 µm, respectively.

3.4. Tensile properties of joints

The results of tensile test and tensile specimens after test are shown in Fig. 10. The ultimate tensile strength of joints which welded at 0.1, 0.2, 0.4 and 0.6 mm plunge depth were 62, 72, 55 and 51 MPa respectively. To the better understanding of the joint strength compared to base metals, a factor is defined which called Joint Efficacy (JE), written as follows:

$$\text{Joint Efficacy} = \frac{\text{Joint ultimate tensile strength}}{\text{Base metal ultimate tensile strength}} \times 100 \quad (1)$$

Figure 11 presents the joint efficiency of welded samples at different plunge depths compared to AA1100 base metal. It can be inferred from the figure that the joint efficiency increases by increasing the plunge depth and reaches to a maximum value at 0.2 mm. Then by further increase in values of plunge depth (i.e. 0.4 and 0.6) the joint efficiency decreases correspondingly. When the plunge depth is relatively low (i.e. 0.1 mm) the joint efficiency reaches to 68% aluminium base metal. At 0.2 mm plunge depth, the joint efficiency is about 80% aluminium base metal strength. The joints that were welded together in 0.4 mm and 0.6 mm plunge depths had, 61% and 56% aluminium base metal strength, respectively. Due to high axial force and propulsion of the material from the stir zone, intermix of AA1100 and A441 AISI is not as well in 0.4 mm tool plunge depth.

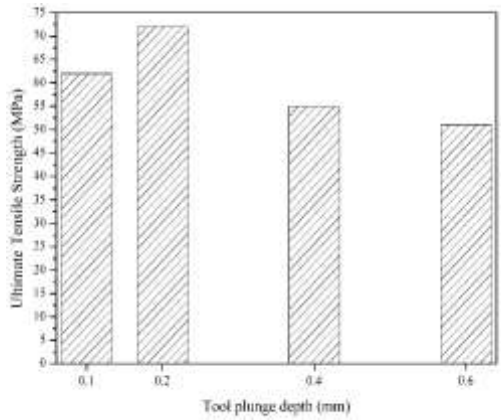

Fig. 10 Tensile strength of joints

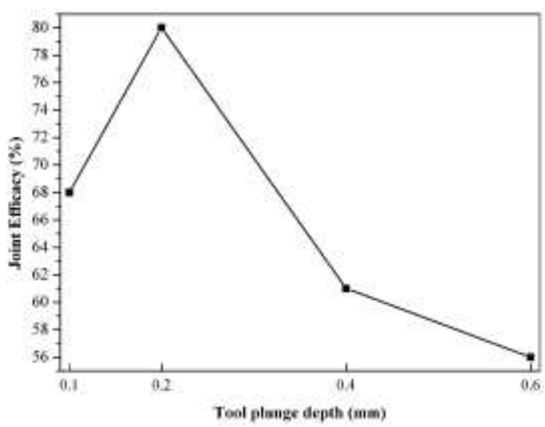

Fig. 11 JE of welds based on aluminum alloys

Formation of internal and surface defects in the weld that is produced at 0.1 mm plunge depth, reduces the strength of the joints. The fracture path in this joint was at TMAZ. Due to appropriate mix between the two base metals, the separation of the joints in tensile strength test at 0.2 mm plunge was at HAZ. The fracture location at joint which were welded at 0.4 mm plunge depth was in stir zone. Fracture path at 0.6 mm plunge depth was steel pieces and aluminium base metal interfacial boarders. This failure type is due to improper material mixing between aluminium and steel that causes reduction in joint efficiency. The samples of tensile specimens after test are shown in Fig. 12.

Fig. 12 Fracture specimens of (a) 0.1, (b) 0.2, (c) 0.4, and (d) 0.6 mm plunge depth

3.5. Microhardness

The microhardness is another response which was analyzed in this work. The hardness profile along joint length is shown in Fig. 13.

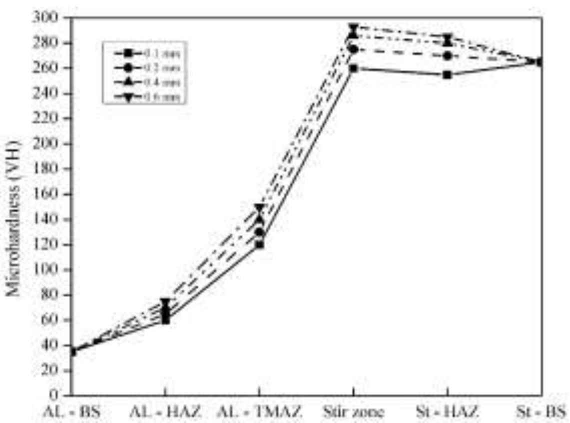

Fig. 13 Joints microhardness

It is seen that the hardness of steel side are higher than that of aluminium side. Also, by increasing tool plunge depth, the interface microhardness increase. The reason is to from thermal and mechanical deformation in welding zone that causes fine-grain structure, steel particles which are separated at stir zone and intermetallic compound (IMC) were formed in two sheets interface and stir zone. The sample of steel particles separated at aluminium side which formed at 0.1 and 0.6 mm plunge depth is shown in Fig. 14. In addition to the fine grain size, at higher plunge depth of the tool, the intermetallic compounds are formed during dynamic recrystallization that causes increasing in micorhardness [18]. SEM images of pint (1) that are marked at Fig. 14 are shown in the Fig. 15. The results indicated that with increasing tool plunge depth from 0.1 mm to 0.6 mm, intermetallic layer thickness increase and these changes is one of reasons for the increased hardness of the interface of joints. Intermetallic layer thicknesses in joints which were fabricated with 0.1, 0.2, 0.4 and 0.6 mm plunge depth are 1, 1.5, 2 and 4 µm, respectively.

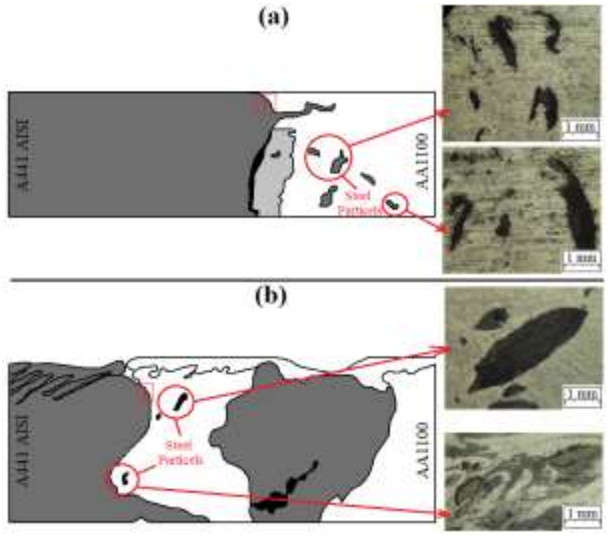

Fig. 14 Separated steel particles in stir zone at joints which welded at (a) 0.1 mm and (b) 0.6 mm plunge depth

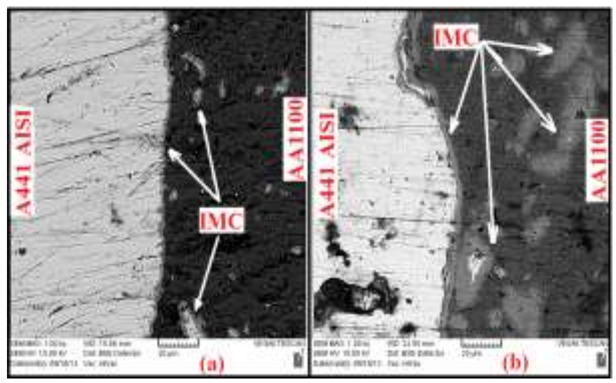

Fig. 15 IMC at base metals arbitrary edge which formed at (a) 0.1 mm and (b) 0.6 mm plunge depth

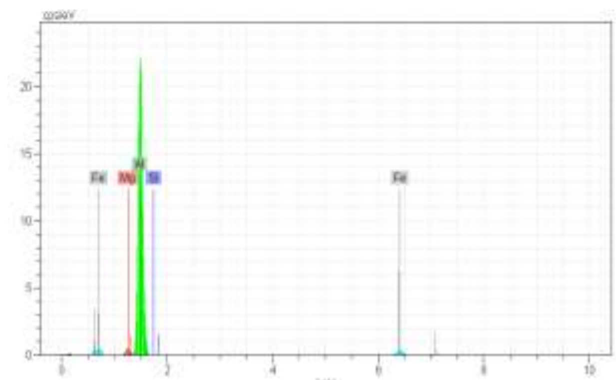

Fig. 16 Sample of EDX analysis from joint interface

EDX analysis of the interface reveals different type of IMCs. The chemical composition of IMCs is various at different points. The EDX analyses reveal that the interfacial layer is composed of two IMCs, namely AL_3Fe and Al_5Fe_2. With increasing plunge depth, the material flow and heat generation increased and caused the proportion of Al and Fe changed at Al_xFe_y compounds. The sample of EDX analysis from joint interface is shown in Fig. 16. The results of EDX reveal that the IMCs at interface which were welded at 0.1, 0.2 and 0.4 mm plunge depth were AL_3Fe and at joint which were welded at 0.6 mm was Al_5Fe_2.

7 CONCLUSION

In this research the AA1100 aluminum alloy and A441 AISI steel was successfully welded by friction stir welding process at different tool plunge depth. The results of the investigation on mechanical properties and material flow of these joints are presented as follows:

1. Among the selected TPD, It was found that the best TPD is 0.2 mm while the heat generated and the plasticized material flow in the other plunge depths were not appropriate.
2. The most appropriate mixing pattern and joint strength were achieved in 0.2 mm plunge depth. The joints which were produced in 0.1 mm plunge depth had not enough strength and the joints that were welded in more than 0.2 mm plunge depth had inappropriate internal plastic flow.
3. By increasing TPD from 0.1 mm to 0.6 mm, tool forging force within the plastic material increased and this event resulted in deteriorate material flow and fabrication of joints with big defects.
4. With the increase in TPD, the thickness of intermetallic compounds which were formed in the material interface increased and the joint micro-hardness increased.

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