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Investigation of Microstructure and Mechanical Properties of Friction Stir Lap Welded AA6061-T6 in Various Welding Speeds

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Abstract: Friction stir welding of Aluminum alloys has been increasingly used in the industry on the ground of higher welding quality in comparison with conventional methods. However, not enough studies have been done on a lap joint of AA 6061-T6 which widely been used in aerospace industries. In this article, friction stir lap welding of 6061-T6 aluminium alloy with 5 mm thickness was carried out by using various welding speeds. The effect of welding speed on microstructure, lap shear performance, micro hardness, failure mode and effective plate thickness was investigated. Results showed that tensile shear strength of weld increased by the rising welding speed. Rising welding speed caused hooking and thinning approaches to two plate interfaces which in turn concluding in higher tensile shear strength. The fracture surface of welds was analyzed by field emission scanning electron microscopy (FE-SEM). Study of the fracture surface of the nugget zone by EDX indicated the Fe compounds in that region.

Key words: Aluminum alloy, friction stir lap welding, mechanical properties, effective plate thickness, hooking

INTRODUCTION

By outreach of Friction Stir Welding (FSW), the solid-state joining method may possibly present excessive potential for aluminum alloys since it can perform without any toxic fumes and ease or remove some welding defects that related to solidification. Among these alloys, AA6061-T6 is progressively used in many industries (Liu *et al*., 1997; Mishra and Ma, 2005). In addition to welding in a butt shape, friction stir welding is also, widely used in lap joints forms in some industries such as automotive, aerospace, shipbuilding and so on. Figure 1 shows a lap joint as illustrated, two metal plates are overlapped by a certain width (upper plate and bottom plate). A rotating tool, plunged into the material for prearranged depth with the tool shoulder in adjacent interaction with the upper plate, is traversed along the centerline of the overlap.

More than a few efforts were carried out to completely recognize FSW process mechanics and to develop joint performances in butt joints but in fact, the very restricted effort has been achieved for the friction stir welding of the lap joints (Mishra and Ma, 2005; Cederqvist and Reynolds, 2001).

Material flow in FSW is asymmetrical due to the fact that tool rotation direction and welding direction are different in advancing and retreating sides. In advancing side these two are in the same direction whereas in retreating side are in opposite (Arbegast *et al*., 2003). Joining two plates together in a lap joint configuration needs the welding tool to penetrate to the lower plate in a certain depth. Inserting the pin causes the interface to bend upward or downward depending on the pin shape and welding parameters. The curvatures (bends) were known as hooking effect (Cantin *et al*., 2005). This wavy flaw in advancing side called hooking whiles in retreating

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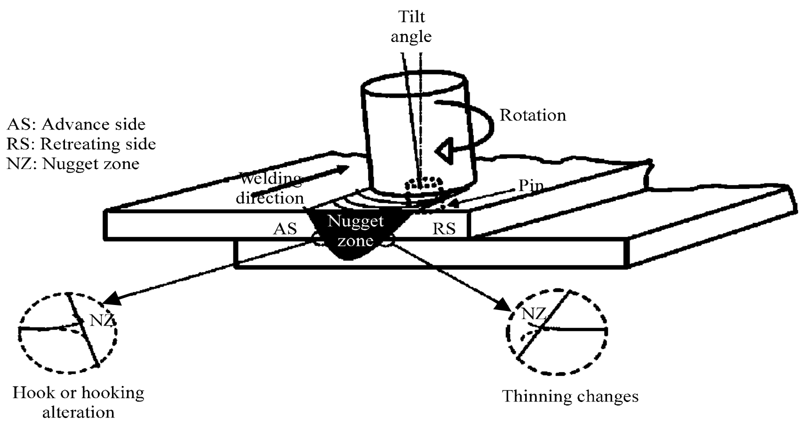

Fig. 1: Schematic friction stir lap welding (joint design was used in this research) and hook and plate thinning geometries

side called thinning. Moreover, the hook and plate thinning geometries on these two sides display heterogeneity (Fig. 1). Hooking height and size alteration will change the Effective Plate Thickness (EPT) which has a greater effect on welding strength than microstructure (Babu *et al*., 2012; Yazdanian *et al*., 2012). The EPT is known as a minimum plate thickness determined by measuring the smallest distance between hooking flaw (hooking or thinning) and the top of the upper plate if the flaw located in the upper plate (and/or, the bottom of the lower plate if the flaw located in lower plate (Cederqvist and Reynolds, 2001). Moreover, decreasing in EPT lowers the load carrying capacity.

In the current research, the effects of welding speed on the microstructure and mechanical properties of FSW AA6061-T6 aluminum alloy lap joints were studied. Four different welding speed (30, 40, 50 and 60 mm min^{-1}) was used. Regarding to above subject, microstructure, hardness and tensile shear properties were investigated and, also, hooking effect and its effect on tensile with Effective Plate Thickness (EPT) were illustrated.

MATERIALS AND METHODS

Base metal: Plates of Al-alloys AA6061-T6, 5 mm thick, 220 mm long and 140 mm wide were selected for both the top and bottom plates of lap joints. The chemical compositions in mass% of the parent metals AA6061-T6 is 1.0 Mg, 0.66 Si, 0.27 Cu, 0.30 Fe, 0.03 Mn, 0.02 Ti, 0.05 Zn, 0.18 Cr and Al balance (UNS A96061). The mechanical properties of this alloy are shown in Table 1.

Table 1: Mechanical properties of the 6061-T6 aluminum alloy used in this work

Plate thickness (mm)	Yield strength (Mpa)	Ultimate strength (Mpa)	Elongation (%)	HV
5	280	310	15	105

Tool and joint design: The longitudinal direction of the plates was parallel to the plate rolling direction. The overlap along the linear direction of the plates was 50 mm wide. The designed tool for Friction Stir Lap Welding was cylindrical (Ø 8×5 mm) with a sub-conical headpin (Ø 8×3 mm) having standard left-hand threads and a cylindrical shoulder (Ø 20 mm), which was made from hardened high-speed tool steel (AISI H13). This twofold pin was modeled from multistage pins (for top plate was cylindrical and for bottom plate was conical). The reason for selecting this design for the pin was focusing on interface behavior for hooking and thinning.

Welding procedure: FSLW was performed at a constant rotation speed (ω) of 1000 rpm together with different welding speeds in 20, 40, 50 and 60 mm min^{-1}. To improve weld joining, the tool was tilted at 3 degrees from the normal direction of the plate in the direction of the behind the tool during welding and the rotation direction was selected in clockwise. In addition, the tool shoulder was plunged into the upper workpiece by a depth of around 0.15 mm. Dwell time at the start point of welding was 20 sec.

Lap Shear and hardness test: Strength of welds loaded technically in lap shear test was inspected. Dimensions of the samples that used for overlap shear testing shows in Fig. 2. Due to the asymmetric feature of Friction Stir Lap Welding, two welding locations were considered, thus resulting in two different loading forms. In type (a) The advancing side of a lap weld on the upper workpiece is loaded, while in type, (b) The retreating side of a lap joint on the upper workpiece is loaded, as schematically explained in Fig. 3 (Babu *et al*., 2012). To balance the offset axes of the lab samples and reduce the bending

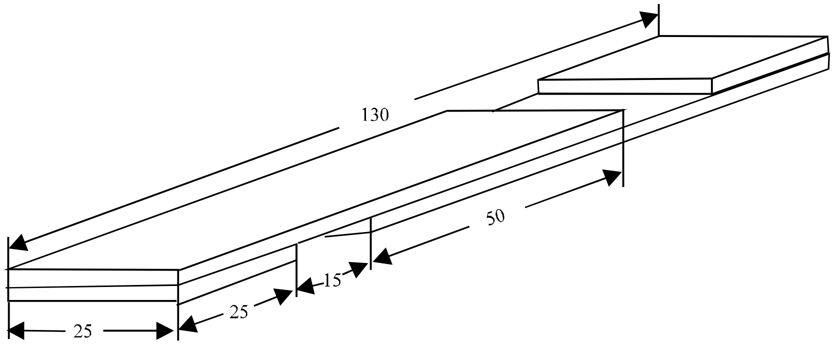

Fig. 2: Overlap shear test sample (thickness is 5 mm and all dimensions are in mm)

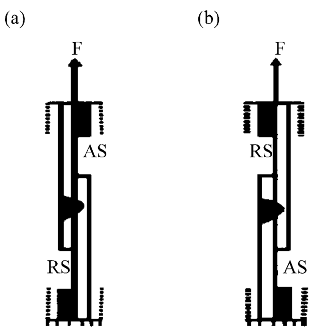

Fig. 3(a-b): Overlap shear testing methods, (a) Type A, (b) Type B

effects, two compensation pieces with the plate thickness were applied for each specimen, during the tensile shear testing as indicated in Fig. 3. Room temperature lap shear tests were done by using a 100 KN Instron mechanical testing machine with the cross head speed fixed at 2.0 mm min^{-1}. No fewer than three specimens were examined to find average weld strength for a process condition. For each tensile shear-testing specimen, fracture locations were recorded. Vickers hardness (HV 0.5) of the FSW region was measured on cross-section perpendicular to weld direction of the mid-thickness of the plate using a load of 100 g and a dwell time of 10 sec.

Metallography and SEM: Macro structural and microstructural examinations were performed on as-welded specimens. The metallographies samples were exposed to mechanical grinding and then polished with1-micron diamond paste. The specimens were then etched with Keller's reagent. Microstructure, hook and plate thinning were characterized using Lecia light microscope joined with a Qwin image analysis. Hooking and plate thinning geometry was measured on planar macrostructures. The fracture surfaces were investigated using Field-Emission Scanning Electron Microscopy (FEI, Nova NanoSEM 230) by selecting the condition of 20 KV and 15 mm work-distance and also Energy-Dispersive X-ray Spectroscopy (EDX).

RESULTS AND DISCUSSION

Visual inspection and microstructural study of weld zones: All of the samples that cut in perpendicular to welding direction, indicates the free defects regions of welds. Figure 4 displays a macrostructure and related microstructures of each zone of the weldment. That will be demonstrated later.

Nugget zone (NZ, region d, Fig. 4d) represented a wider range near the top of the upper plate than lower plate like a semi-taper shape because the upper plate undergo the maximum deformation and frictional heat began with directly contacting welded plates with the shoulder. Macroscopic inspection of the weld zone revealed a comparative non-symmetric nugget zone that was mainly related to the tilt angle of the tool and the relation between the direction of tool rotation and welding direction (Mishra and Ma, 2005; Liu *et al*., 2004). It was obvious that the weld zone exhibited any discontinuity and porosity. In spite of the base metal (BM, Fig. 4a), NZ, in upper plate (Fig. 4d) and in bottom plate (Fig. 4d), has fine and equiaxed grains and the grain size was much smaller than that of the BM. This structure (NZ) was produced by the dynamic recrystallization and static grain growth after welding, which was caused by the frictional heat and plastic deformation. It was evident that the original grain structure was microscopically disappeared in the thermo-mechanically affected zone (TMAZ, Fig. 4c) and the transient microstructure between NZ and heat affected zone (HAZ, Fig. 4b) was achieved. The elongated grains (in the same direction) and dynamic recovered grain structure are regarded as TMAZ because the

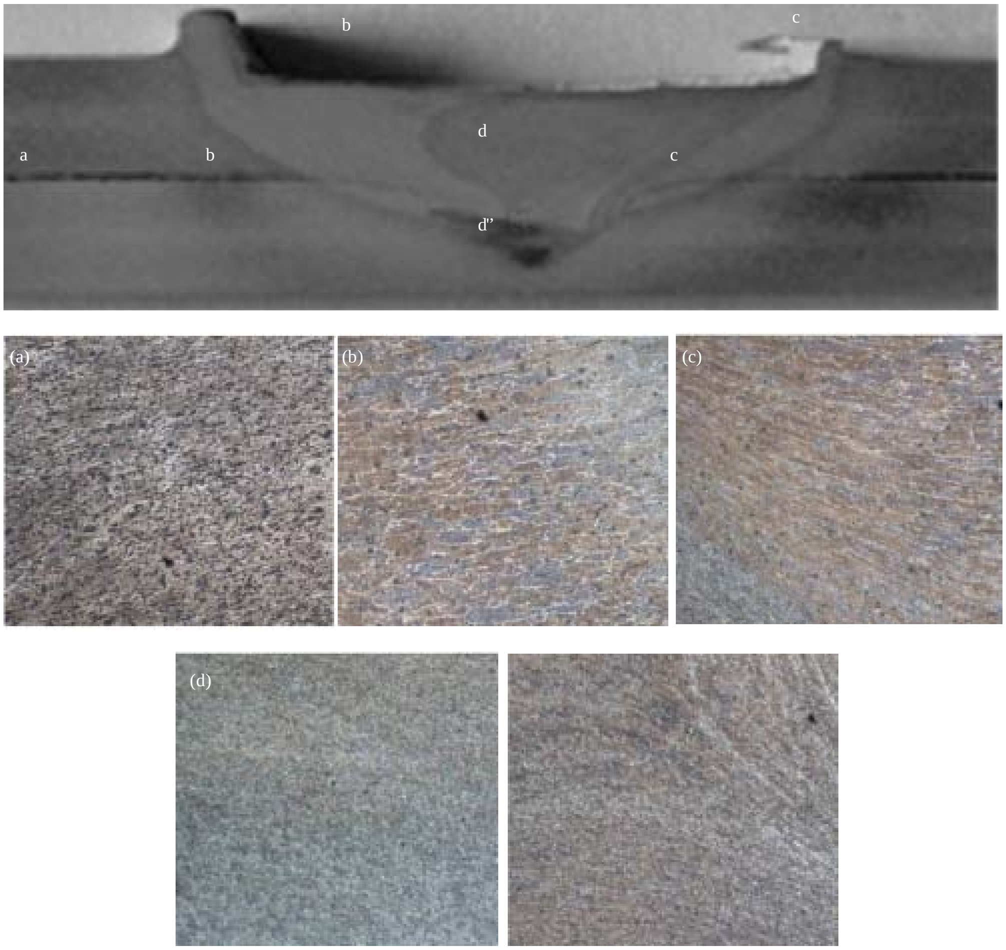

Fig. 4(a-d): Cross-section macrostructure of lap joint section AA6061-T6 in 60 mm min^{-1} and related microstructures indicated in the macrograph, (a) BM (base metal), (b) HAZ (heat-affected zone), (c) TMAZ (thermo-mechanically affected zone), (d) NZ (nugget zone) in upper plate, (d') NZ (nugget zone) in bottom plate (all images are in 75X)

thermal and deformation condition was not enough to create the recrystallized grain structure. The HAZ has a coarser grain size than the unaffected Base Metal (BM).

Due to higher pressure on the upper plate than the bottom plate, the grain size in upper nugget was smaller than in lower nugget. The actual results that were measured by Hean method is in full agreement with Table 2. It also shows that although increasing welding speed from 20-60 mm min^{-1} decreases grain size 9.8 μm in upper nugget and 9.7 μm in the lower one but the grains at lower nugget remain always bigger than that the grains in upper one. These, also, have been reported by Rajakumar *et al.* (2011). Changes in grain size in different zones of weld can clearly be seen in hardness of weldments.

Table 2: Grain sizes of nugget zones in upper plate and bottom plate (lower)

Welding speed (mm min^{-1})	20	40	50	60
Upper NZ grain size (μm)	39.0 μm	34.7 μm	32.1 μm	29.2μm
Lower NZ grain size (μm)	42.5 μm	37.9 μm	35.3 μm	32.2μm

Investigation of hardness in different areas of weldment: Figure 5 indicates the hardness distributions in the middle of the upper and bottom plates in the lowest welding speed (20 mm min^{-1}) and the highest welding speed (60 mm in^{-1}). That is almost symmetric around the weld centerline. It can be seen that, by applying the higher welding speed, the hardness in NZ, HAZ and TMAZ increased meanwhile the difference between the top and the bottom plate hardness', in NZ decreased. Microstructure variation is the main reason for the above mentioned phenomenon. It is justified by grain size

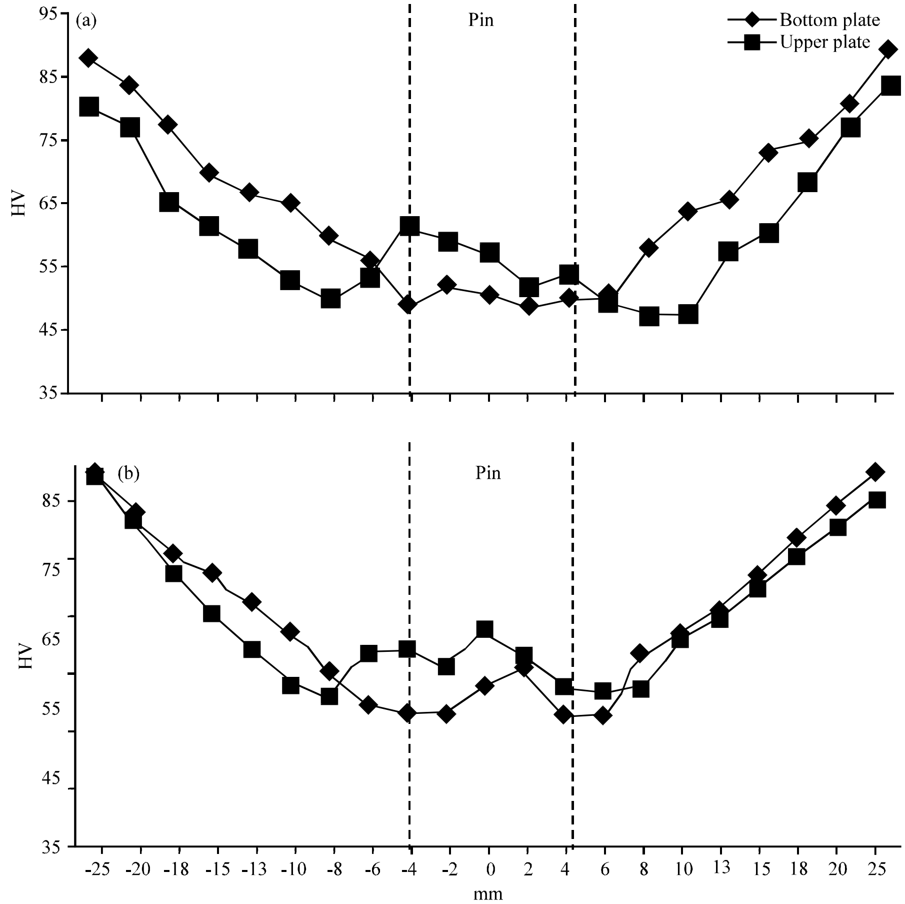

Fig. 5(a-b): Hardness distribution in the middle of upper and bottom plate (a) 20 mm min^{-1} welding speed and (b) 60 mm min^{-1} welding speed

changes in different area of weld (NZ, HAZ and TMAZ) and also the contrast between up and bottom NZ's microstructure (Liu *et al*., 2004). The HAZ areas at the both AS and RS of the joints (almost 10 mm distance from weld center) were found to have the minimum hardness among the other regions of the weld reported because of the grain coarsening.

Weld flaws (hooking and thinning): Due to hooking effect that explained in introduction part and illustrated in Fig. 1, strength of friction stir welded samples in lap joint condition is affected by hooking and thinning. Variations in height and size of hooking and thinning can change the Effective Plate Thickness (EPT) that's known as a minimum plate thickness determined by measuring the smallest distance between hooking flaw (hooking or thinning) and the top of the top plate if the flaw located in top plate and the bottom of the bottom plate if the flaw located in there (Babu *et al*., 2012). EPT of all four samples in different welding speeds are indicated in Table 3. According to data from this table, increasing welding speed from 20-60 mm min^{-1}, causes EPT to rise 0.79 mm. Yazdanian *et al*. (2012) and Buffa *et al*. (2009) have shown hooking and plate thinning are looming to the interface of two plates with increasing of welding speed. It means that the height of hooking and plate thinning (compared with interface line) will be decreased when the welding speed is increasing. In this research, due to the shape of pin, that changes from cylindrical to conical at interface, the position of hooking and thinning firstly was placed in the lower plate (Fig. 4 macrostructure) but, based on increasing welding speed; variation in these positions can be noticed, even Fig. 6 indicates that in 60 mm min^{-1} welding speed direction of hooking tip is altering toward

Table 3: Effective plate thickness-EPT

Welding speed (mm min^{-1})	20	40	50	60
EPT (mm)	3.39	3.65	3.92	4.10

Fig. 6(a-c): Changing in hooking shape and direction, (a) 40 mm min^{-1} welding speed (hooking tip is moving down), (b) 50 mm min^{-1} welding speed (tip is almost parallel to interface) and (c) 60 mm min^{-1} welding speed (tip is folding up) (all images are in 150X)

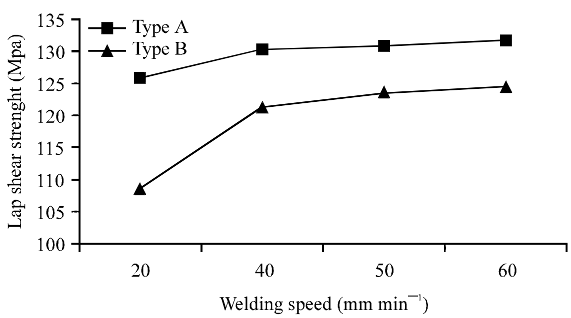

Fig. 7: Overlap shear test results

the top plate. The importance of hooking and thinning tip direction identified in selective path for fracture in shear overlap testing.

Mechanical properties of lap joints by using overlapping shear method: Shear Tensile test specimens were prepared perpendicular to welding line. The interval between welding and shear testing was five days. In consequence of the asymmetric nature of the weld and related zone of FSW a lap joint shall be tested with two conditions as mentioned in Material and Method part, which results were illustrated in Fig. 7. It appears that increasing welding speed from 20-40 mm min^{-1}, causes shear strength to soar up to 12% for type A followed by a steady increase in shear strength for both types in higher welding speeds. Moreover, the test results also show that shear strength in type A is always higher than type B. In these tensile shear tests, fracture path occurred at two locations. In samples with 20 and 40 mm min^{-1} welding speed, as it can be seen in Fig. 8a (upper right corner), the direction of the tip is toward the bottom plate, fracture taken place from thinning to the bottom plate.However, in specimen with 50 mm min^{-1}, due to higher welding speed, hook tip is an almost parallel with interface of two plates and even in specimen with 60 mm min^{-1} is changing up (Fig. 6), route of fracture, in these samples, was started from hook or advancing side and then, thinning in retreating side also started to break (both through nugget zone) and connected to each other in lower NZ (Fig. 8b-upper right corner).

Surfaces of fractures were investigated by FE-SEM and EDX. Figure 8a shows the fracture surface of the sample with 40 mm min^{-1} welding speed that failed due to break from retreating flaw (thinning) toward bottom plate. The fracture surface is composed of areas which clearly exhibit the features of ductile fracture such as relatively deep dimples.

But in Fig. 8b that shows fracture located through the welds nugget zone (sample with 50 mm min^{-1} welding speed). It's illustrated shallow dimples and sheared cleavage facets these introduce mixture fracture (Zadpoor *et al*., 2009). The dimples relate to the onset of the fracture. After beginning of breaking, consequently the specimen experiences overloading and the dimples are sheared (cleavage). EDX analyze of initial points (dimples) emphasizes existing intermetallic compounds of Fe/Al as it can be seen in Fig. 8 (point A). Niranjani *et al*. (2009) has shown that majority of precipitation components of AA6061 can be solved about 600°C and, also, perceptions dissolution could have occurred due to the large plastic deformation imposed on the alloy, whereas Al/Fe compounds are the most stable among these intermetallic compounds and they can be created above 500°C and remain stable till 600°C and more. In FSW of AA6061-T6, temperature under tool shoulder rises from 550°C up to 650°C (Nandan *et al*., 2008) and because of high plastic deformation in NZ (Mishra and Ma, 2005), the majority of precipitations can be dissolved. Due to mentioned reasons, Al/Fe compounds, due to high stability, are expected as an effective point in fractures that can be seen in Fig. 8.

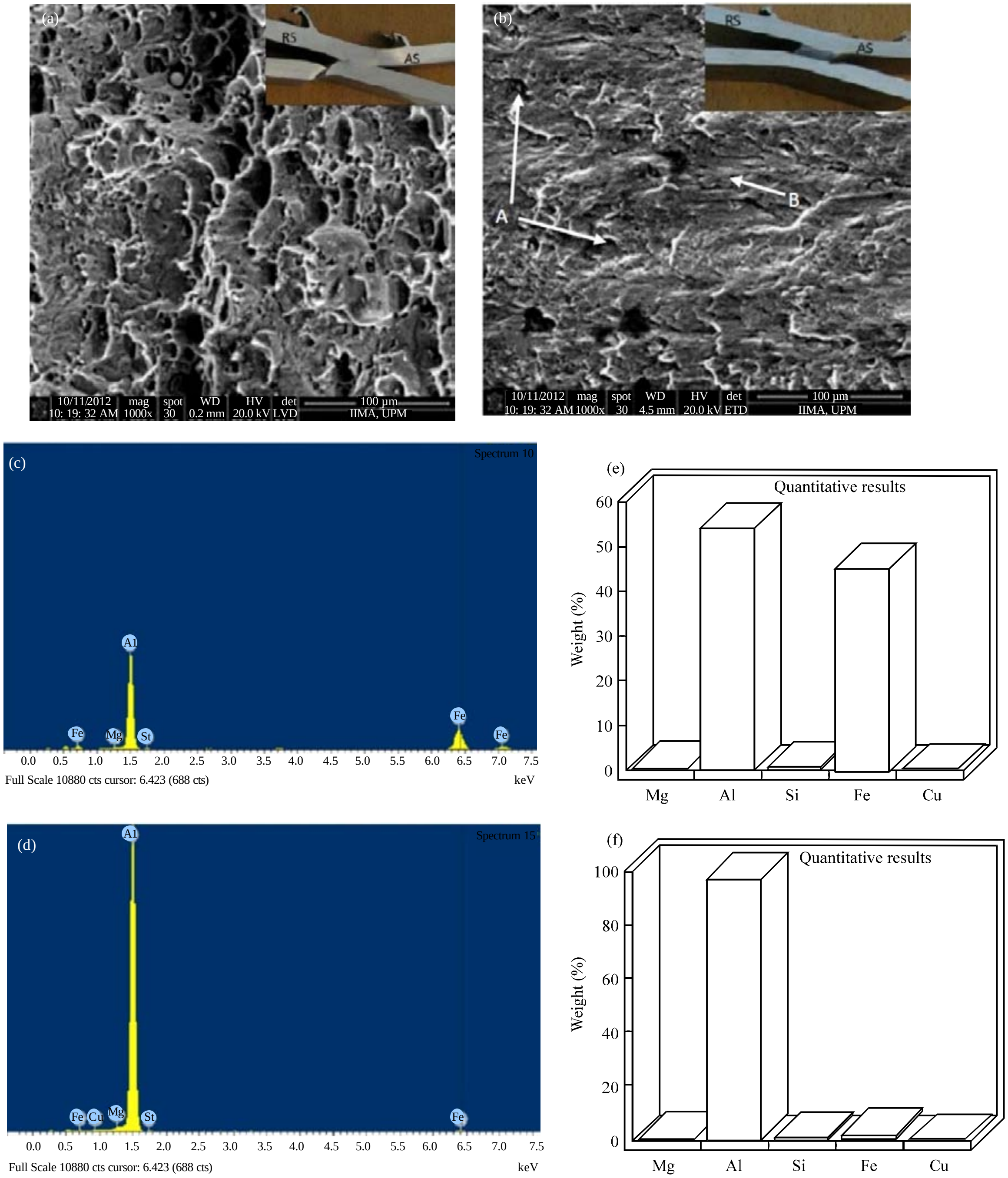

Fig. 8(a-f): Fracture surface of the overlap shear test samples, (a) 40 mm min^{-1} welding speed-fracture from thinning to the bottom plate and (b) 50 mm min^{-1} welding speed-fracture through nugget zone, (c) EDX spectrum of point A, (d) EDX spectrum of point B, (e) Quantitative results of point A and (f) Quantitative results of point B

CONCLUSION

The gained outcomes, in this research, permission to appeal the following conclusions: With increasing welding speed, microstructure of NZ gets finer which is a reason for increasing the hardness and Due to shoulder pressuring, grains in the top plate are smaller than the bottom plate whereas. This alteration is less at higher welding speed. The minimum hardness is in the HAZ and NZ belongs to the lower welding speed.

The result of overlap shear testing shows that the motivation of hooking and thinning in fracture is related to the size and orientation of them. In this way, the maximum EPT-effective plate thickness formed in maximum welding speed (60 mm min^{-1}) that shows the highest amount of shear tensile strength among samples. The height of hooking and plate thinning (in analogy with interface line) will be decreased when the welding speed is increasing.

FE-SEM study of fracture surface indicates that initial point of fracture can be caused by Fe/Al intermetallic compounds through NZ.

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