Journal of Manufacturing Engineering, December 2010, Vol. 5, Issue 4, pp 254- 261

EXPERIMENTAL INVESTIGATIONS ON THE IMC IN FRICTION STIR WELDED AA7075 ALUMINUM JOINTS WITH COPPER INSERTS

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ABSTRACT

Friction Stir Welding (FSW) is an innovative and promising solid state joining process invented by The Welding Institute (TWI). FSW can arguably be said to represent one of the most significant developments in metal joining technology over the last two decades. The intense plastic deformations and temperature fluctuations generated by the rotating and traversing tool in FSW have a significant impact on the micro structural modifications in the weld zone and thereby on the mechanical properties of the welded joint. Experiments were conducted on 6 mm thick AA7075, commercially available aluminum plates, widely used in structural fabrication of critical components in aerospace, defence and military applications, where the weld strength is expected to be very near to the parent metal strength. The plates were joined by FSW on both sides, with and without a thin layer of copper insert in-between the two aluminium plates. Mechanical and metallurgical characterization of the welded joints shows superior strength in copper inserted joints as compared to the joints without intermediate copper layer. Influence of the newly formed Inter Metallic Compound (IMC) with copper particles dispersed in a solid solution of aluminium matrix enhances the joint strength. High hardness with fine grains of the IMC in weld nugget improves the tensile strength of the joint.

Keywords: *FSW, AA7075, Copper Insert, IMC, Mechanical Properties, Macrostructures and SEM.*

1. Introduction

The Friction Stir Welding technique is a solid-state welding process, developed at The Welding Institute (TWI), United Kingdom, avoids the conventional defects associated with the fusion welding processes.[1,2] Absence of traditional fusion welding defects, reduced distortion and residual stresses, improved mechanical and metallurgical properties, fine grains with primary particle fragmentation, are the major benefits of FSW as welding takes place without melting of the plates.[3] This method overcomes the difficulties like hot cracking, porosity and distortion which happens often in fusion welding. During welding, the material is frictionally heated to a temperature, at which it becomes more plastic. The heat of friction and the plastic flow arising from the rotating tool produces significant microstructural changes, which leads to a metallurgical bond with local variation in the mechanical properties of the weld. P.Cavaliere et.al have characterized the 2198 Al – Li weldments for mechanical and microstructural properties by numerical evaluation and experimental validation. Thermographic infrared techniques were applied for investigating the real-time crack initiation, growth and propagation behaviour due to fatigue. The crack initiation, crack propagation and thermo elastic stress analytical analysis are validated with the experiment results. Decrease in ductility and an increase in necking in the weldments were reported with microstructures and the thermal profiles.[4,5] Yingchun chen et.al have performed experiments to analyze the failure locations in the heat affected zone on the retreating side through weld morphology, onion ring visibility for different set of weld conditions.[6] T.Tanaka et.al have investigated the weld joint strength of mild steel and AA7075 aluminium alloys by analyzing the intermetallic compound at the weld interface EPMA and FESEM analysis were performed for quantitative verification of the thickness of the hard brittle IMC.[7] Weifeng Xu et.al have examined the microstructures, second phase particles, mechanical behaviour and the fracture surface to investigate the effect of degree of deformation to grain growth. Observations made on the weldments indicates that the crack initiation is found always on the retreating side of the welded joint in bend test.[8]

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A.Kosttka et.al have examined the one micron layer IMC of aluminium and magnesium using TEM to find the crystallographic information Al/Mg IMC reaction and phases that leads to the formation of nano size grained particles which is a part of the solid state welding of dissimilar materials.[9] Exhaustive analysis on the microstructure, residual stress and mechanical behaviour across the welded joints in as welded, post weld aged and post weld solution treated were reported. Residual stress distribution is found to be asymmetric on either sides of the weld joint with high gradients of the residual stresses being noticed on the advancing side. Compressive nature of residual stress is observed in the shoulder region. Conclusion is arrived as, the state of the base material plays a significant role in the influence of the residual stress distribution during welding.[10] From the available literature, it is observed that many researchers have conducted experiments on friction stir welding of similar metals, alloys dissimilar alloys like Al-Mg, etc. To the authors' knowledge, no report has been seen in the open literature about the influence of the intermetallic compound or to improve joint strength by using an additive in similar aluminium alloys. The objective of the present investigation is therefore, to evaluate the joint strength of similar aluminium alloys influenced by the IMC developed with copper inserts. Copper is selected as the intermediate insert because, from the previous experiences of the authors indicates that the weld failure starts with a crack initiation from the root of the retreating side, due to the temperature gradient that exists in-between the top and bottom side of the plates. Existence of this temperature gradient favours the resistance of the metal flow at the root side, that causes the root of retreating side weaker and the bond formed being vulnerable as compared to the top side. To minimize the temperature gradient and to improve the strength of the intermediate developed IMC, copper has been selected as intermediate insert layer.

2. Experimental Details

The base metal used in this investigation was 6 mm thick AA7075 aluminium alloy plates. The standard chemical composition, experimental chemical composition, mechanical properties and physical properties of the parent material are furnished in the following Tables 1, 2, 3 and 4 respectively. The microstructure of the workpiece before welding is presented in the Fig. 1. The workpieces to be welded are made to the dimensions of 120 × 60 × 6 mm as shown in Fig. 2.

Table 1: Standard Chemical Composition as per ASM Norms

Si	Fe	Cu	Mn	Mg	Zn	Cr	Al
0.07 – 1.3	0.5	1.2 – 2.0	0.4 - 0.8	2.1 – 2.9	5.1 – 6.1	0.18 – .28	Remaining

Table 2: Experimental Chemical Composition of the Workpiece

Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
0.93	0.46	1	0.57	2.55	5.134	0.14	Remaining

Table 3: Mechanical Properties

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Elongation (mm)	Hardness (BHN)	Shear Strength (MPa)	Fatigue Strength (MPa)
AA7075	380	150	20	150	330	160

Table 4: Physical Properties

Density	Melting Point	Modulus of Elasticity	Electrical Receptivity	Thermal Conductivity	Thermal Expansion
2.81 g/cm^3	555°C	70 GPa	0.038 ×10^{-6} Ωm	172 W/mK	46 ×10^{-6} /K

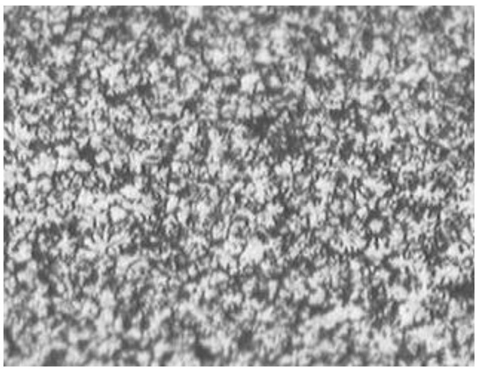


Fig. 1 Microstructure of the Base Material AA7075

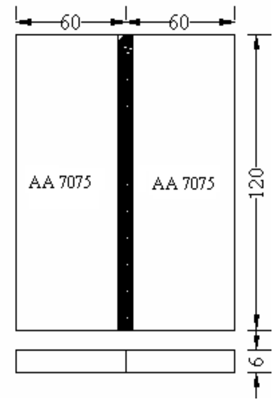


Fig. 2 Plates with Copper Insert in the Faying Sides, Before Welding

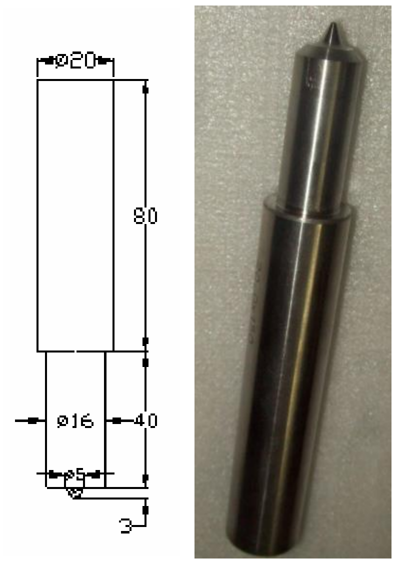


Fig. 3 Tool Drawing and the Manufactured Tool

The friction stir welding tool is made of high speed steel with 10% cobalt with a tapering pin. The tool is designed based on the briefly available literature and the tool proportions are decided in terms of the plate thickness to be welded. This attempt was made in particular with special care to set the dimensions of the tool in standard relation with the thickness of the plates to be joined, so that the best weld can be obtained by the future researchers.

Friction stir welding was performed on the Al 7075, 6 mm thick plates with and without an intermediate copper insert placed in between the faying sides of the aluminium plates in the weld zone. The workpiece samples were butt welded in a FSW adapted vertical axis CNC milling machine with FANUC controller. The tool dimensions are tabulated in Table 5 and the corresponding tool drawing with pin details are shown in Fig. 3. The welding process parameters used in running the experiments are optimized for AA7075 for maximum weld strength and maintained throughout the research as charted in Table 6.

Table 5: Tool Dimensions

Shoulder Diameter (mm)	Pin Diameter (mm)	Pin Length (mm)
16	5	2.9

Table 6: Welding Parameters

Tool Rotational Speed (rpm)	Tool Travel Speed (mm/min)	Axial Force (kN)
650	16	5

3. Results and Discussion

3.1 Hardness properties

The welded joints were tested for hardness across the weld direction as shown in Fig. 2 and the obtained Vicker's Hardness Numbers (VHN) are plotted in graph as shown in Fig. 5. The hardness profile across the weld direction indicates a sudden increase from the base metal hardness to TMAZ, varies constantly from the advancing side of the weld with a gradual fall in the retreating side of the weldment. This may be due to the difference in the tool rotation velocity vector and the tool feed direction vector. High value of hardness in the advancing side is noted due to recrystallization, fine dispersening and diffusion of the copper particles into the aluminium matrix exhibiting to fine equivaxed grains.

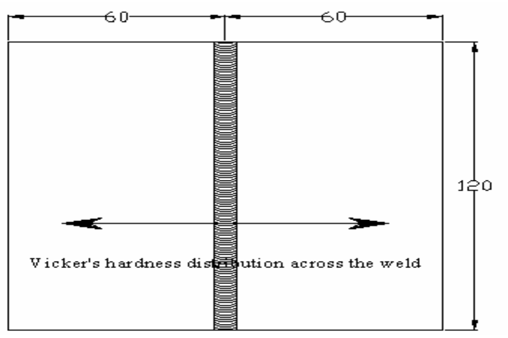


Fig. 4 Welded Joint Hardness Distribution

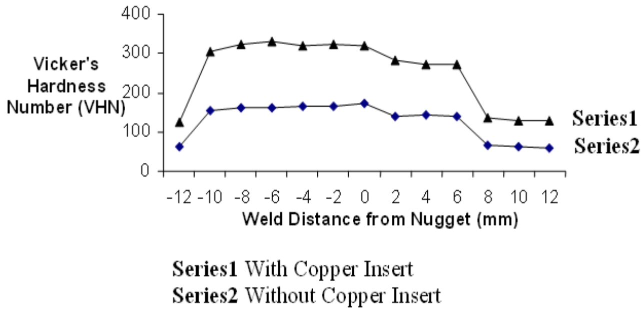


Fig. 5 Vickers Hardness Distribution

3.2 Tensile properties

The specimens for the tensile tests were prepared as per ASTM standard norms. E8 standard test specimens of gauge length 25mm has been extracted in longitudinal direction and transverse orientation of the weldment in WEDM machine as shown in Fig. 6. The test samples were tested on a computer controlled Instron UTM at a crosshead speed of 1 mm/min, with hydraulic loading facility. The test results obtained for samples extracted across and along the weld direction are tabulated in Table 7 and Table 8 respectively. The graphs plotted in Fig. 7 and Fig. 8 indicates the variation in tensile strengths for different weld conditions, along and across the weldments respectively. The obtained results show a considerable improvement in the joint strength in tension both along and across the weld direction for copper inserted joints. The tensile strength of the joints made of AA7075 with copper insert in the faying surfaces shows superior weld tensile strength as compared to joints without copper inserts. This may be due to the reason that, inclusion of copper in the weld nugget zone of aluminium plates makes it alloyed to produce a new intermetallic compound of ductile nature thereby improving the tensile strength properties. Reduced value of hardness with coarse grains in the retreating side, accompanied by the temperature gradient inbetween the top and root sides of the weldment leads to consistent failure on the TMAZ of retreating side during tension tests with crack intiation always noticed on the root of TMAZ in the retreating side.

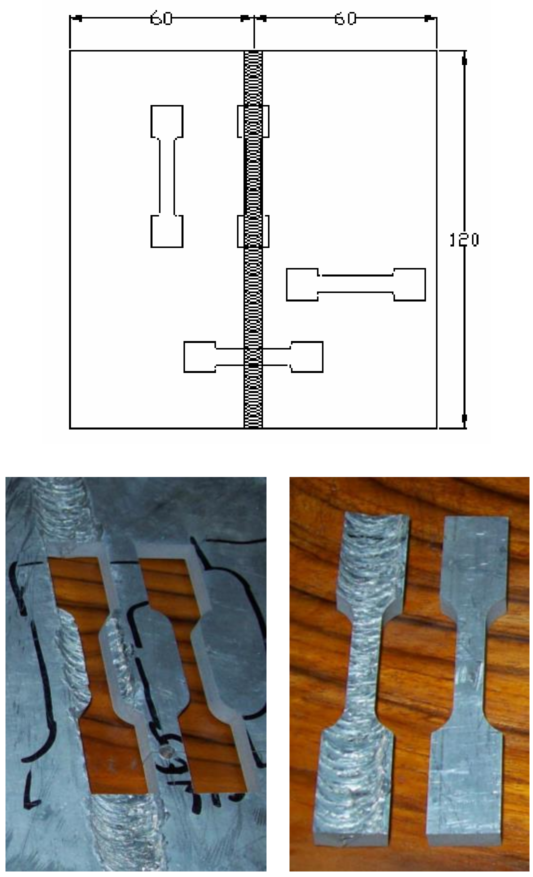


Fig. 6 Sample Drawing and Specimens Extracted for Tensile Test

The fracture location is observed to be in between the heat affected zone and the thermo mechanically affected zone on the retreating side of the joint. From this observation, it is well thought-out that the tensile strength of the joint apparently depends on the hardness distribution

Table 7: Tensile Strength across the Weld Direction

Type of Specimen	Tensile Strength (MPa)
Base material	375
Without copper	225
With copper	260

3.3 Macrostructures

All technical properties of materials are directly connected to their microstructures. Among these properties, strength, deformation characteristics, wear and corrosion can be changed dramatically by slight changes in the microstructures. The structure in the welding seam and its direct surrounding is strongly influenced by the welding process. The mechanically polished surfaces of the weldments were chemically etched with Kellers reagent to determine the microstructure of the welded aluminium alloys.

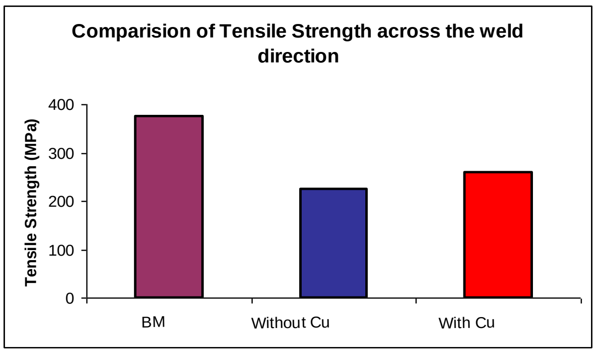


Fig. 7 Tensile Strength Comparison across the Weld Direction

Table 8: Tensile Strength along the Weld Direction

Type of Specimen	Tensile Strength (MPa)
Base material	375
Without copper	240
With copper	295

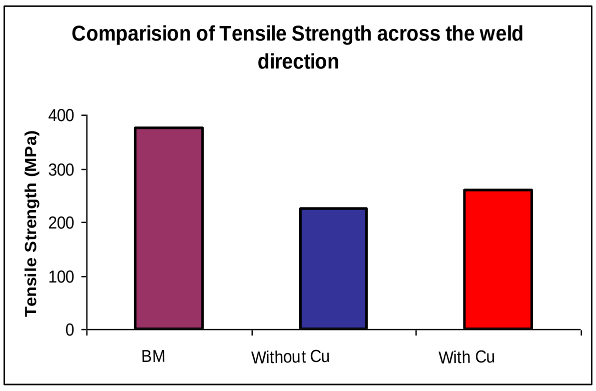


Fig. 8 Tensile Strength Comparison along the Weld Direction

Optical microscope with 20X magnification was used to identify the microstructures of the weldments and the structures of various zones are displayed in Fig. 9. There is very less variation in the macrostructure of the onion rings obtained in AA7075 joints with and without copper inserts Nevertheless, the microscopic structures of the joints with copper inserts show considerable variation, as the copper particles get dispersed into the aluminium matrix

3.4 SEM results

SEM analysis of the tensile tested fracture surfaces in the weld zone shows the presence of long and large voids, small depressions, tear ridges, particle matrix de cohesion, all indicating the possibility of ductile failure. The fracture surfaces show wide distribution of microscopic voids revealing ductile behaviour of the welded joint before fracture. The fractography analysis done of the fractured coupons of the tensile test specimens of the copper inserted aluminium alloy joint shown in Fig. 10 reveals the presence of very small voids and elongation of the dimples.

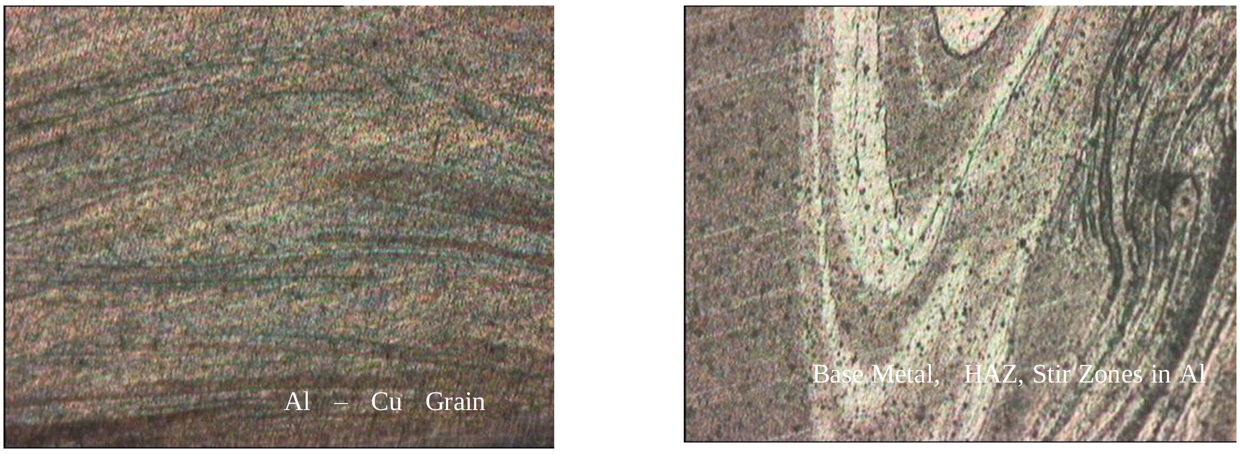
It is noted from the SEM results that the failure of the joint starts from the advancing side of the due to more stress as compared to retreating side. The SEM results of the aluminium alloy joints without copper inset reveals kissing bond, in the fracture spot. It clearly indicates that the kissing bond is due to the lack of frictional heat generated to form the nugget. Subsequently the metal around the tool could not infuse and recrystallize, it stucks to the each other leading to a kissing bond, which is identified as the predominant factor for the joint failure.

From the above observations of the fractographic results, it is considered that the copper strip, which has high thermal conductivity makes the joint temperature nearly 0.7Tm, thereby making the material to flow easily when compared with the stucking nature of flow in conventional joints.

4. Conclusions

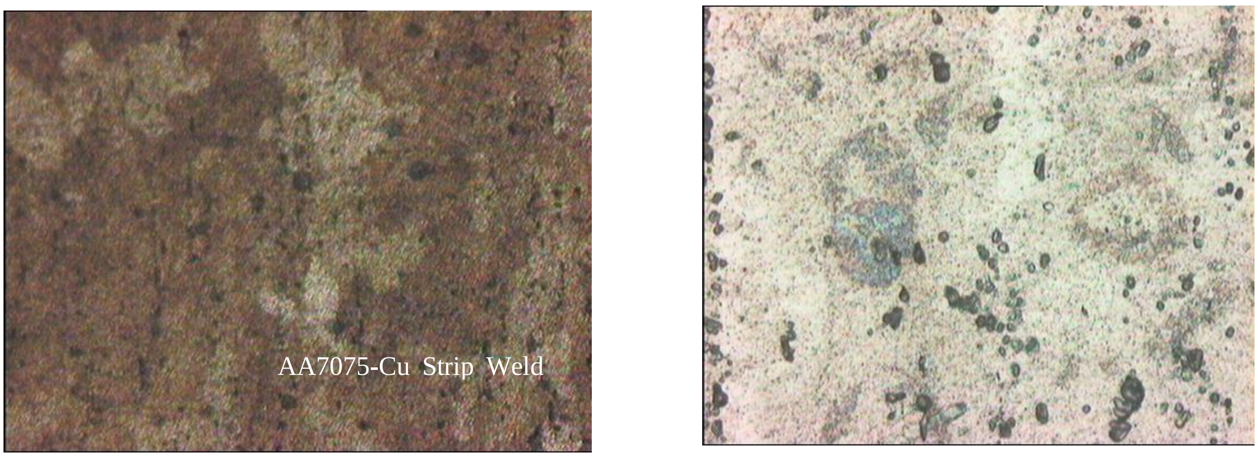
The main aim of this research study, to characterize mechanical properties and to study the metallurgical behaviour in friction stir welded AA7075 alloys with and without copper inserts was successfully achieved. The variation of the hardness across the weld was found to be non uniform and inhomogeneous in nature with the distribution of the interfaced strengthening of the copper precipitates in the aluminum matrix and not on the size of the newly formed grains during the friction stir welding process.

The assessment of the mechanical properties suggests that mechanical stirring is the major flow mechanism in metallurgical bond formation. Comparison of the tensile properties of copper inserted joints shows superior behaviour and performance than the conventional joints, without copper inserts.



(a)Weld Nugget with formation of the IMC

(b) BM, HAZ, TMAZ and WN

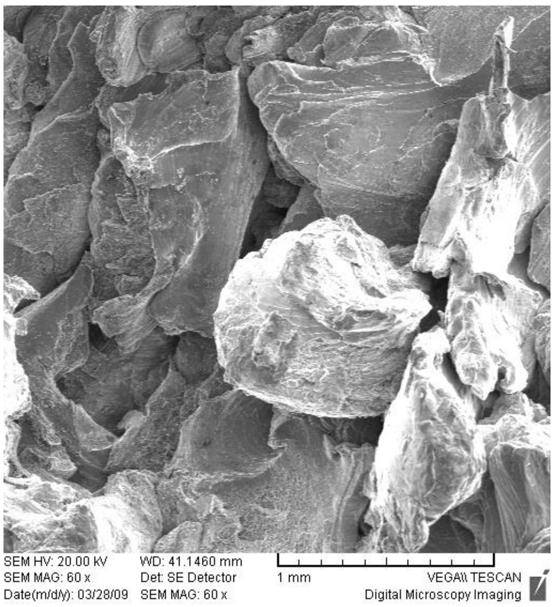


c) **AA7075 - Copper (IMC) and grain boundaries**

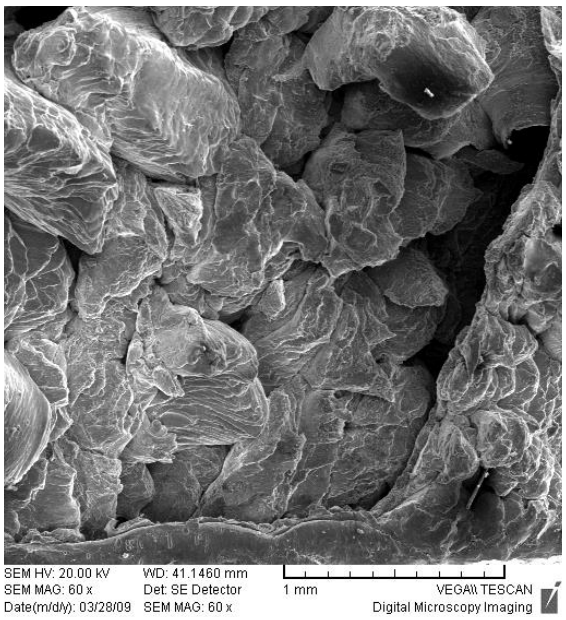
(d) AA7075 Base metal

(e) Weld cross section showing the weld line

Fig. 9 (a-e) Microstructures of the Weldments and the Structures of Various Zones



(a) Fracture Behaviour of the Copper Strip Inserted Joint



(b) Fracture Behaviour of the Joint without Copper Strip

Fig. 10 (a-b) Fractographic Results

FSW of AA7075 without copper inserts show discontinuities in the retreating root side of the joint due to insufficient heat leading to resistance metal flow between the top and root sides of the weldments. This is overcome by placing a copper insert in the joint line, that enhanced the heat flow for easy plastic flow of the material and increasing the weld strength by formation of the copper dispersed IMC in aluminium matrix

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