iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 5 Issue: VI Month of publication: June 2017

DOI:

Volume 5 Issue VI, June 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Microstructures at Interface Regions and Fracture Behavior of Friction Stir Lap Welding of Al-Cu

Shubhavardhan R N[1]
[1]*Department of Mechanical & Industrial Engineering Ryerson University, Toronto, Canada*

Abstract*: *Friction Stir Welding (FSW) is a relatively new solid state joining technique, which is used not only for joining the aluminum and its alloys but also has potential for joining dissimilar metals with very different physical and mechanical properties that are hard to weld using conventional fusion welding processes. There have been a reasonable number of studies in the literature on microstructure and fracture behavior under static loading and very few studies on cyclic loading of FSW of Al 6060-T5 and copper. However, a better scientific understanding in a number of aspects is required. This include interface phenomena during FSW of Al 6060-T5 with copper with large differences in melting temperatures, how exactly the microstructure in the interfacial region is related to fracture behavior when subjected to static loading is far from being fully understood. Thus, this study aims to understand the uncertainty about the optimum or best pin position (Dp) for friction stir lap welding (FSLW) of Al-Cu, so that weld samples can achieve the highest attainable load during tensile-shear testing, tests were conducted to investigate the maximum tensile-shear load an Al-Cu FSLW sample of a set width (Fm/Ws) can withstand before fracture depends on the pin positioning related microstructures in the weld interface region. Interface microstructures differ depending on whether or not the tool pin penetrates the lapping interface. It has been found that Fm/Ws values of the defect free weld samples vary quite significantly and in general are significantly higher than those reported in the literature. When the pin penetration is close to zero no intermetallic layers were formed, hence value of Fm/Ws was zero. When the pin penetration is 0.4mm during FSLW and thus the commonly observed a thin Al–Cu interface layer forms and this layer does not grow beyond 500 nm. It will be shown that the thin interfacial layer can withstand a high tensile-shear load and thus the adjacent Al material shears to fracture. When the pin penetrates more than 0.4mm during FSLW and thus the commonly observed mix stir zone (MSZ) forms, values of Fm/Ws are lower than that of 0.4mm pin penetration welds but remain quite high.*
***Keywords:* Aluminium, Copper, Friction stir welding, Mixed stir zone, Intermetallics**

I. INTRODUCTION

This document is a template. For questions on paper guidelines, please contact us via e-mail. As introduced previously, Friction stir welding (FSW) is a solid state welding process invented and patented by The Welding Institute (TWI) in 1991, for butt and lap welding of ferrous and non-ferrous materials and plastics [1].In general, it is well known that fusion welding of one metallic alloy to another with considerably higher melting temperatures (referred to as a large *T Melting* couple, (such as Al to Cu, Al to Ti or Al to steel) is important in many industries but are very challenging due to physical mismatches such as differences in melting temperature, thermal expansion and thermal conductivity can make the joining almost impractical using conventional welding techniques. Formation of thick intermetallic layers (due to high heat input and liquation of aluminum) is known to deteriorate mechanical properties of the joints [2-8]. It is essential to develop more reliable joining procedures than those currently available for dissimilar metal joints. Therefore, development of FSW as a solid-state joining process is of high importance from both scientific and industrial point of view. Fig. 1 illustrates FSLW during which a section of lapping surfaces of the top and bottom plates is stirred and mixed in the stir zone (SZ) thus forming a weld behind the tool.

In FS welding of a large *T Melting* couple, aided by frictional and deformation heat, metallurgical bond is established through diffusion and subsequent formation of interfacial intermetallic. It is clear that a metallurgical bond is a condition for a quality joint and a metallurgical bond implies low electric resistance, although intermetallic are commonly viewed to affect joint strength adversely. The cited studies on FS Al-to-Cu [9-27] are basically the initial work showing FS Al-to-Cu weld able, providing detailed metallurgical analysis for understanding the interface microstructure and relating to properties. In the final section, the work is extended to FSLW of Al-Cu to explain how interface microstructures affect the fracturing process during tensile-shear testing and thus joint strength. A possible control method for producing Al-Cu welds for a higher joint strength can then be suggested.

Volume 5 Issue VI, June 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

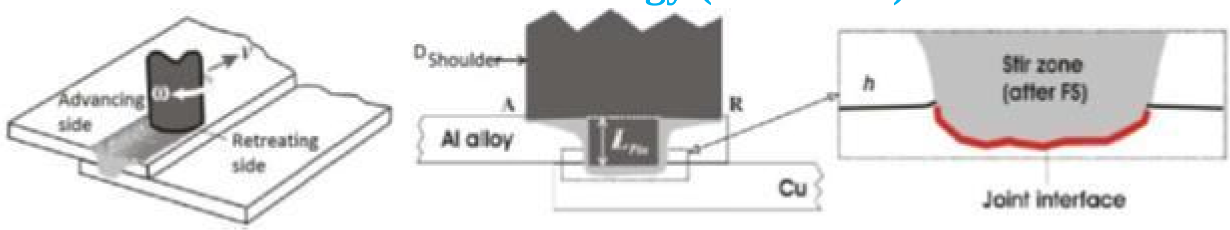


Figure.1. Schematics illustrations of FSLW of Al-C

II. EXPERIMENTAL PROCEDURE

All FSLW experiments were conducted using FV200 milling machine and thus the mode of FS was displacement control. Schematic illustration of FSLW process has already been provided in Fig. 1. Fig. 2 shows an actual FSLW experiment. A Lowstir^{TM} device, which is also shown in Fig. 2, was used in each FSLW experiment to monitor the downforce. Al 6060-T5 (300x100x6mm) placed on top of the and pure Cu (300x100x1.4mm) work pieces were FSL welded with 1400 rpm as a rotational speed (ω), 40mm/min as a traverse speed (v),3 degrees of tilt angle(Ө) and tool pin penetration Dp= 0 mm and Dp=0.4 mm respectively from the top surface of the bottom plate (Fig.3). Tools were made using H13 tool steel and the left-hand threads of the pins were made with a 1 mm pitch and a 0.6 mm actual depth[28]. The diameter of the concave shoulder was 18 mm and the pin outside diameter was 6 mm. K-type thermocouple will be used to measure the FSLW interface temperature.

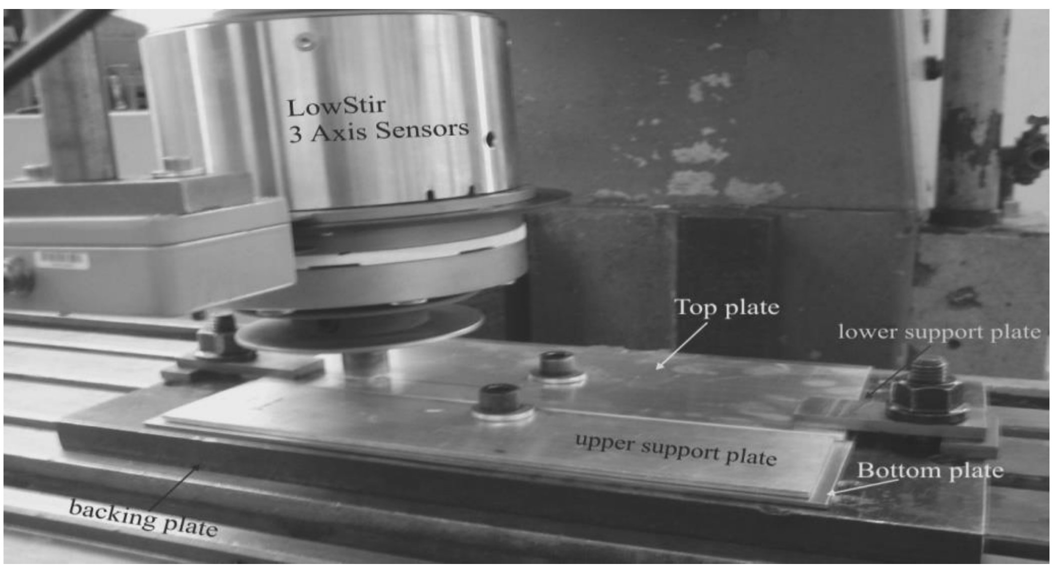


Figure2. FSLW using a FV200 milling machine with a Lowstir^{TM} force measuring device

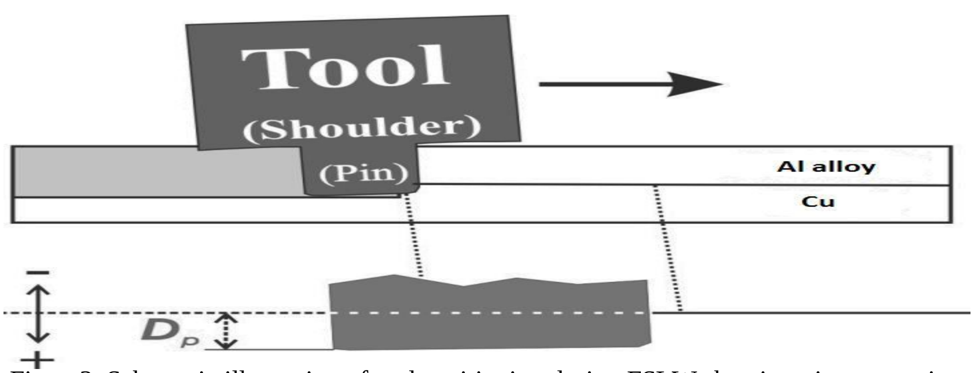


Figure3. Schematic illustration of tool positioning during FSLW showing pin penetration depth

Volume 5 Issue VI, June 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Metallographic samples were mounted and polished, and etched with modified Keller's reagent. Microstructures at the interface of Al-Cu were observed in SEM/EDS analysis were conducted. Tensile-shear testing of FS lap welds has been the major method used for evaluating strength of FSL welds in literature. This test method was adopted in this study. Test samples, 16 mm wide, perpendicular to the welding direction were machined from the welded plates[28]. Fig. 4 illustrates the positioning of a sample together with supporting pieces. Samples were tested at a constant crosshead displacement rate of 3 mm/min using a 50 KN Tinus Olsen tensile machine, with a 50 mm extensometer attached. The strength of a lap sample cannot be expressed using the normal load/area, as the stress distribution along the joint area during tensile-shear test is highly uneven. Instead, maximum failure load in a test divided by the width of the sample, Fm/Ws, is taken as strength.

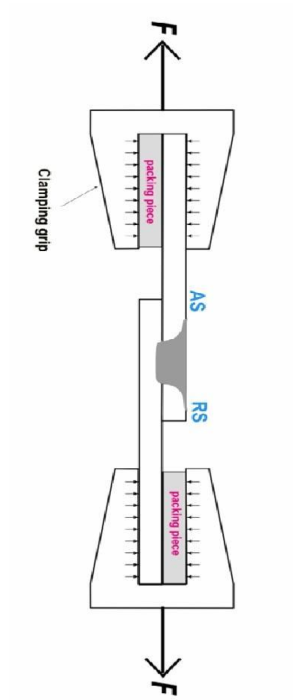


Figure4. Schematic illustration of tensile-shear testing

III. RESULTS AND DISCUSSIONS

To justify FSW is solid state welding process, (no melting of base metals). K-type thermocouple was placed at Al-Cu interface to monitor the temperature. Traces of temperature at SZ of these welds, during FSLW, are also presented in Fig 5. In each trace, there are disturbances in the peak temperature region because the thermocouple was pushed slightly by the lower stir flow as the pin approached the thermocouple. It is clear that the weld made using ω=1400 rpm has obtained higher peak temperature (*Tsz* =520ºC) and spent longer time at the elevated temperatures, compared to the weld made using ω=710 rpm (with *Tsz* =445ºC). Consequently, the recrystallized grains at SZ of the weld made using ω=1400 rpm were allowed to grow more; resulting in larger grains with subsequent reduced hardness (is not discussed in this paper).

Two selected samples are shown here to illustrate the importance of interface microstructures and based on this illustration a suggestion of FSLW control for maximum strength can then be made. Fig. 6(a) is the first example where no intermetallic layer (IMC) were formed for Dp≈0, I should say that there is no research work available in literature for this condition especially for Al-Cu FSLW, the reason for not forming any intermetallic layer at the Al-Cu weld interface may be because copper has conducted heat faster, since copper has higher thermal conductivity, but for the same pin penetration condition (Dp≈0) for Al-Steel FSLW, a continuous and thin intermetallic layer has been reported, with maximum value of Fw/Ws [28]. In Fig. 6(b) a thin and continuous intermetallic layer observed in stir zone (SZ) is shown between the top Al plate and the bottom Cu plate for *Dp*=0.4. When the pin penetration is further increased a non-uniform MSZ can be observed which is not shown here. The area of MSZ largely corresponds to the area of the pin penetrated into copper and this zone is a mixture of Al-Cu intermetallic thin. pieces embedded in the recrystallized Cu grains

Volume 5 Issue VI, June 2017
ISSN: 2321-9653

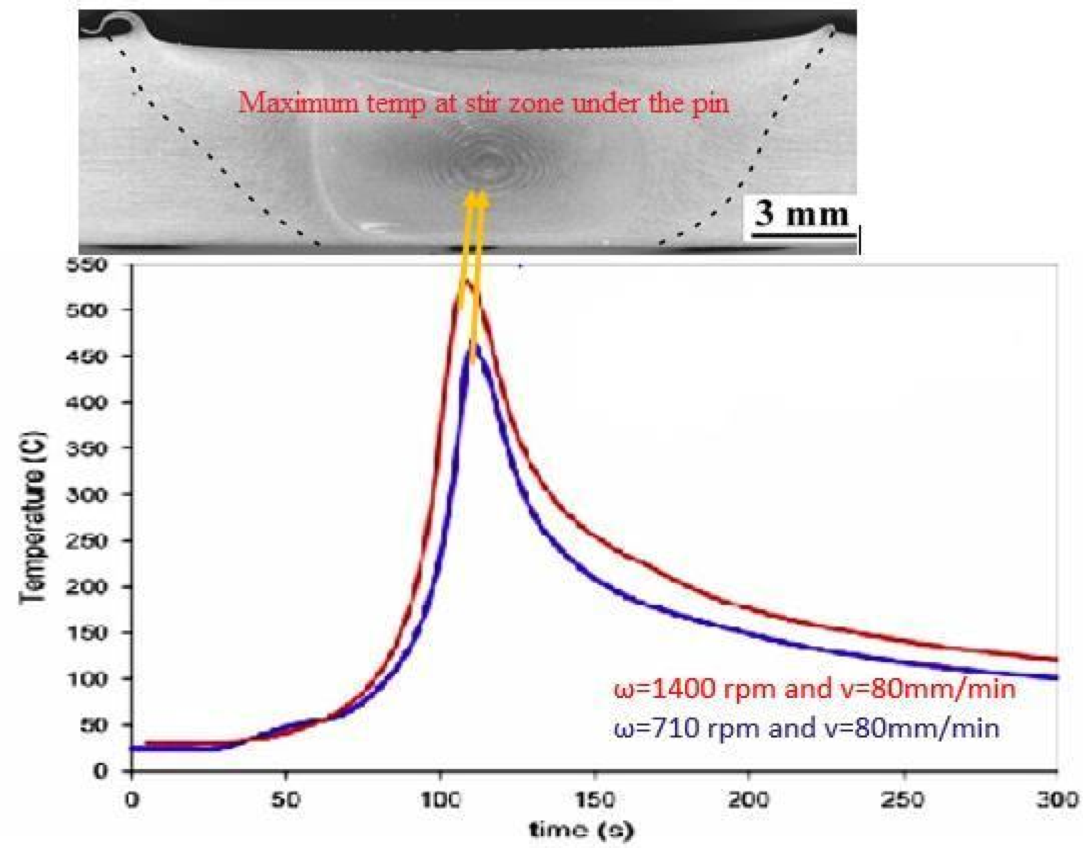


Figure5. Measured temperature at SZ of welds made using ω=1400 rpm and v=80mm/min (red color trace) and ω=710 rpm and v=80mm/min (blue color trace)

In Fig. 6(b) as mentioned earlier a thin and continuous intermetallic layer can be observed, a metallurgical bond between Al and Cu is established and thus a slight pin penetration (a slight positive *Dp*=0.4, referring to Fig. 3) is commonly believed to be the condition for a good weld strength. Naturally, no intermetallic layer or a MSZ cannot form and if *Dp* < 0. However, FS tool can be position controlled so that *Dp* ≈0. In this case, although there can still be an absence of intermetallic layer and MSZ, but it is totally different in case of Al-steel FSLW [28], because it is known thermal conductivity of steel is lesser than Copper, the reason may be steel conducted heat far slower than the copper forming a thin and continuous intermetallic layer at Al-Steel FSLW interface for Dp=0.A thin Al-Cu interface intermetallic compound layer can form when pin penetration is 0.4mm, metallurgical bonding the top and bottom plates together, as demonstrated by an example shown in Fig.7

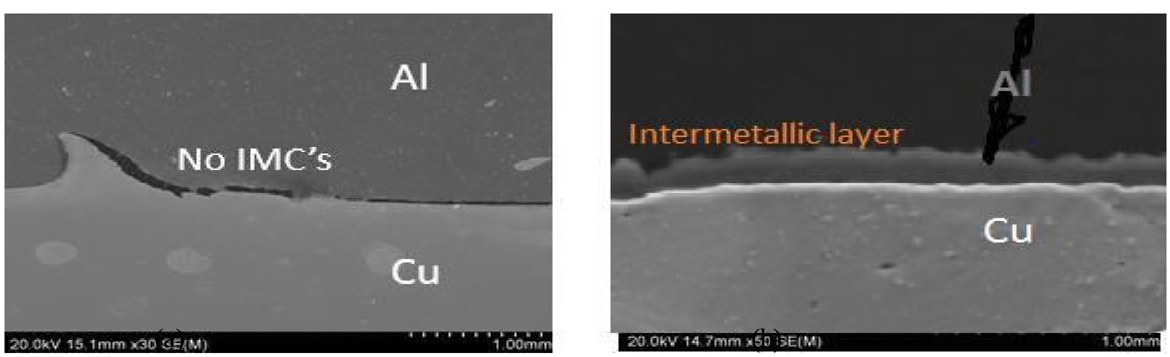


Figure6. Cross sectional view of an Al-Cu weld made with ω = 1,400 rpm, *v* = 40 mm/min, (a)*Dp*≈0, (b) *Dp*=0.4 mm displaying .

Three examples of tensile-tested curves are shown in Fig. 8 for the three different *Dp* conditions. For the penetrated sample more

Volume 5 Issue VI, June 2017
ISSN: 2321-9653

than 0.4mm, the amount of deformation before final fracture and thus fracture energy are reasonable. The weld strength at 302 N/mm is significantly higher than that of Dp ≈0 (0 N/mm, which is not discussed furthermore) but is considerably lower than that of Al FSL welds (> 450 N/mm), for Dp=0.4mm.

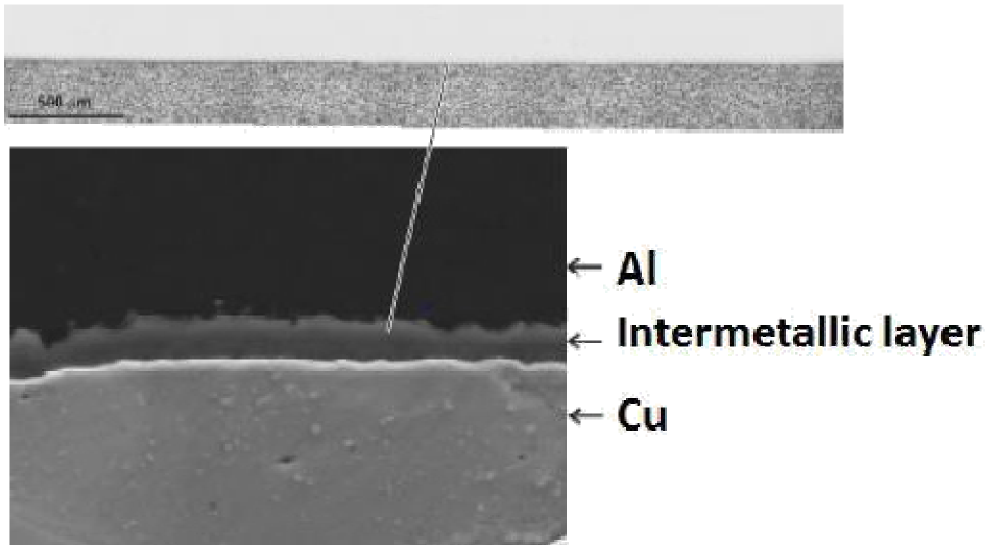


Figure7. Cross sectional view of an Al-Cu weld made with ω = 1,400 rpm, *v* = 40 mm/min and *Dp* ≈0.4 mm displaying no defect but a continuous thin interface layer

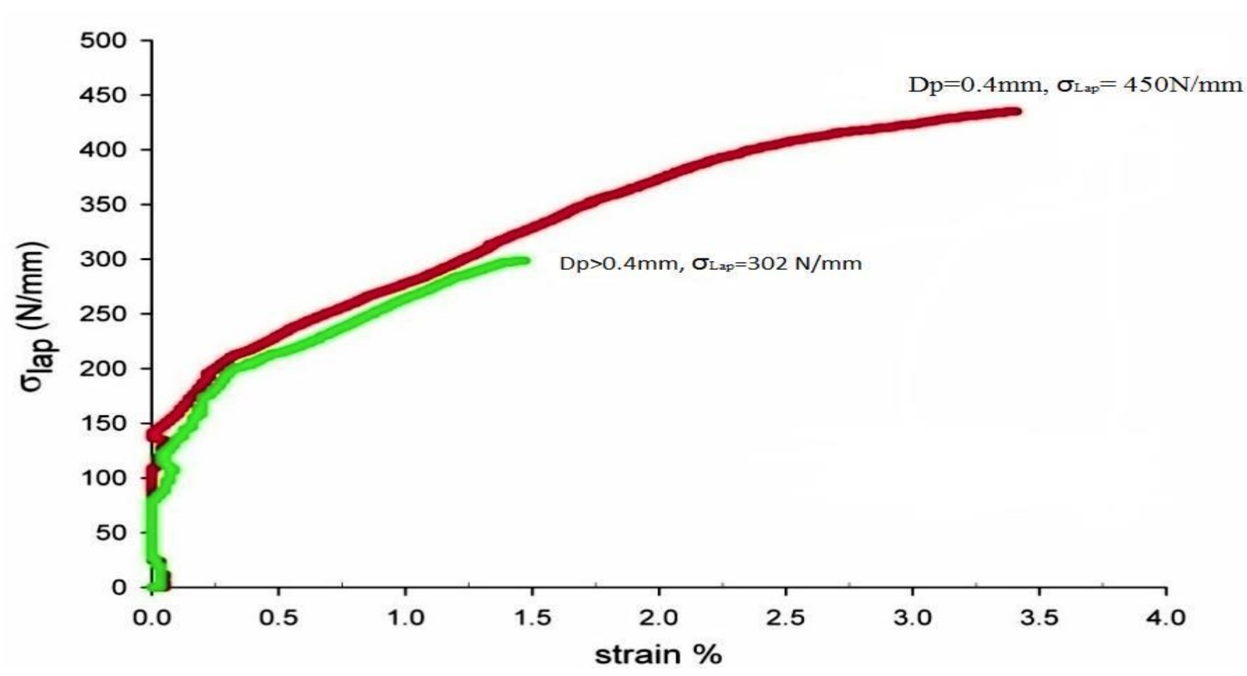


Figure.8. Tensile-shear curves of two samples of welds made with ω = 1,400 rpm, *v* = 40 mm/min and *Dp* values as indicated

The weld strength at 302 N/mm is higher to the values of 268 N/mm which is the maximum value for samples using a pin penetration [19]. In this latter study, when a weld is free of macro- defects the strength equivalent value is close to that maximum value, regardless of what the FS speeds condition.

When Dp =0.4 and an interface layer is established without MSZ, as shown in Fig. 8, fracture strength (450 N/mm) is considerably higher than that for the sample with MSZ (302 N/mm, fractured at SZ). The amounts of deformation and fracture energy as indicated by the curve suggest a considerably tougher weld made by the Dp =0.4mm condition. These are clear by viewing the tested samples in Fig. 9. For the pin penetrated sample Dp >0.4 mm, the sample having been slightly bent is evident. On the other hand, for the Dp=0.4mm sample, a large amount of local deformation and bending before the final fracture at SZ is clearly the feature. The presence of thin and continuous intermetallic layer in the Dp=0.4mm sample means a different fracture behavior. The large amounts of deformation and fracture energy for this sample means that the thin interface layer is not brittle under tensile-shear condition. From the present results, it can be suggested that careful positioning control for Al-Cu FSL welds is a mean for the optimal weld strength to be obtained.

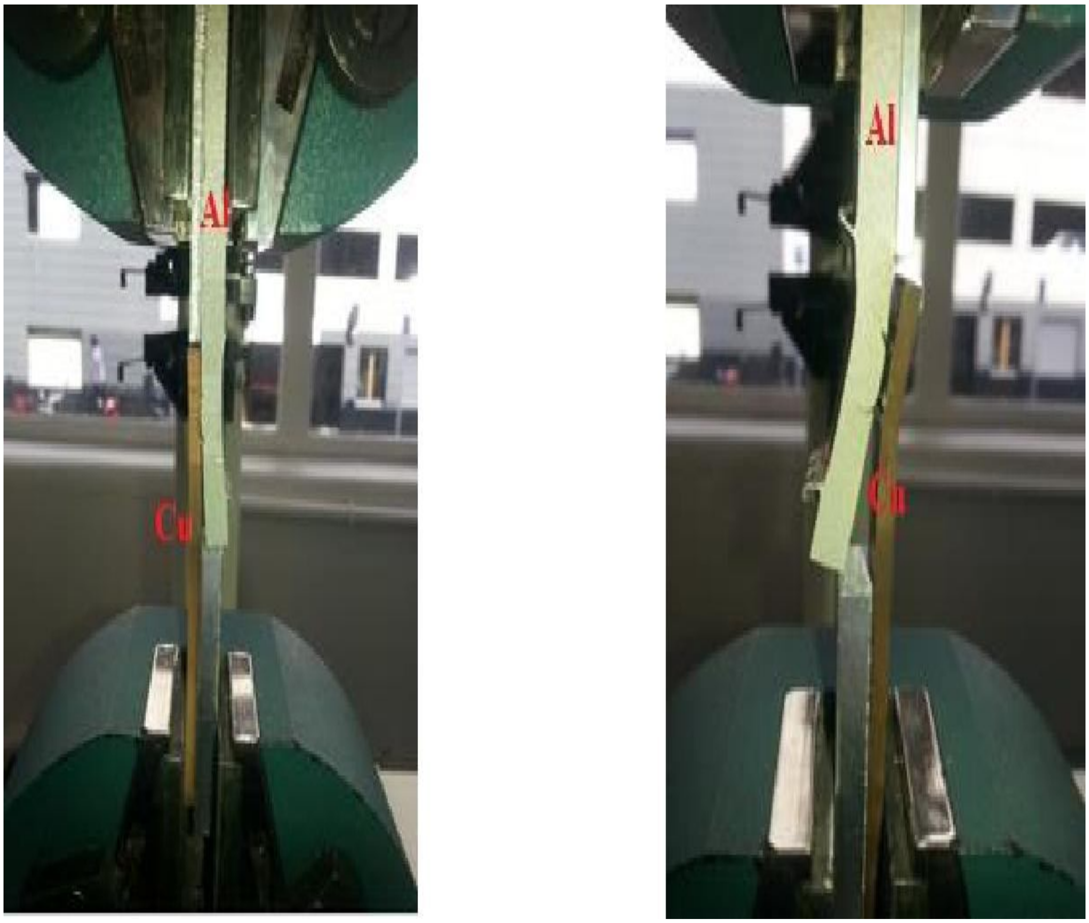


Figure.9. Tensile-shear tested samples of welds made with ω = 1,400 rpm, *v* = 40 mm/min and (a) Dp> 0.4 mm and (b) Dp= 0.4 mm.

Furthermore, Formation of intermetallic layers at the Al-Cu interface was further investigated using EDS spot analysis. Typical EDS spectra of intermetallic layers at the Al/Cu interface and inside the stir zone for Dp=0.4mm is presented in Fig 10 respectively. At point 1 we can notice copper rich phase present and Al rich phase at point 5 (which is placed at top and bottom of Al-Cu FSLW), point 2 indicate that the thin layer at Al-Cu interface is mainly Al4Cu9 intermetallic, according to Al-Cu phase diagram, On the other hand, point 3 and 4 indicate presence of AlCu intermetallic layer, the chemical composition of 61.8at%Al and 38.2at%Cu in Fig 10 at point 6 may indicate that the thin layer within the stir zone is likely to be Al2Cu intermetallic phase. Some of the observed intermetallic layers here were also found in literature [19]. However, due to the analytical spot size being large in SEM/EDS hence assigning the structure of Al2Cu, AlCu or Al4Cu9 to the small size intermetallic layers is not very reliable.

Volume 5 Issue VI, June 2017
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

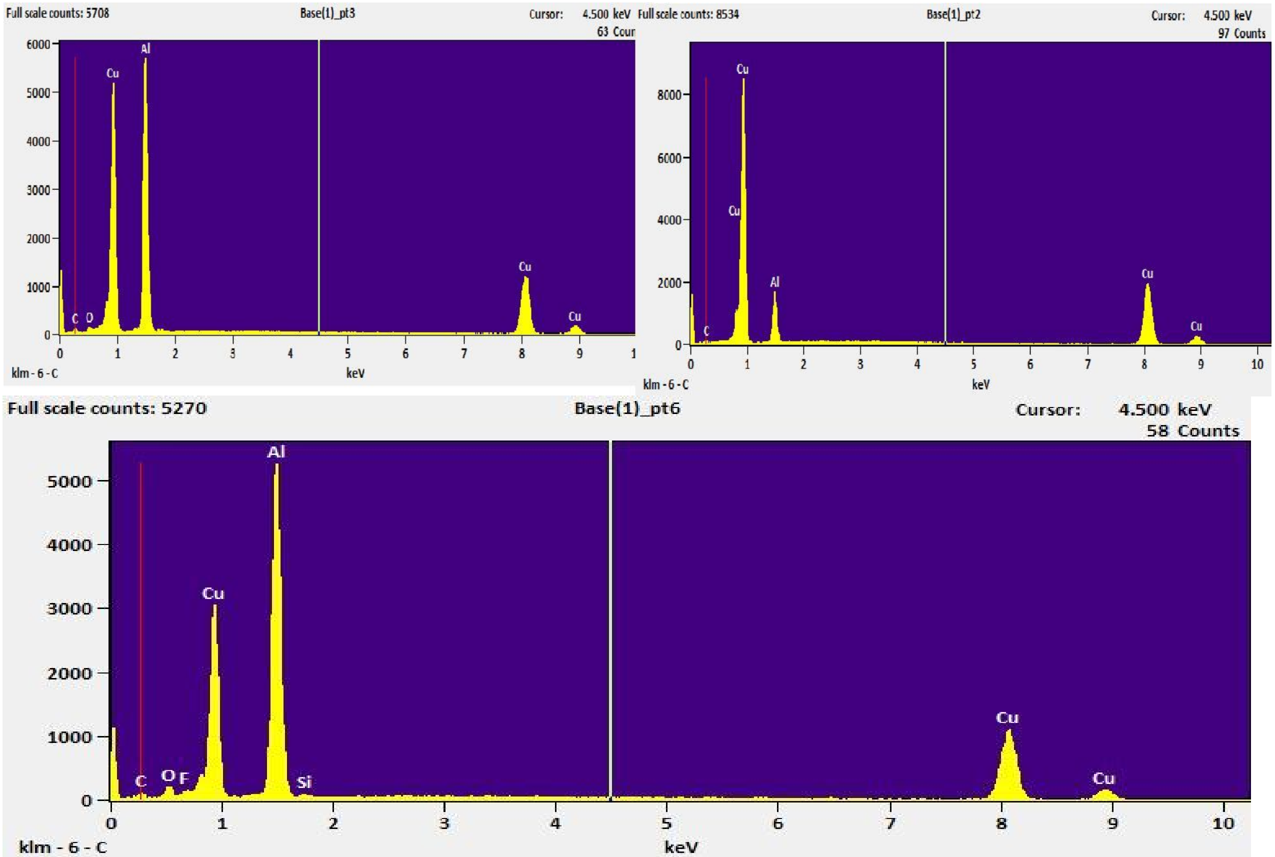


Figure10. SEM micrograph showing the intermetallic layers at Al/Cu interface, EDS spectra of intermetallic layer at different locations in stir zone are also shown.

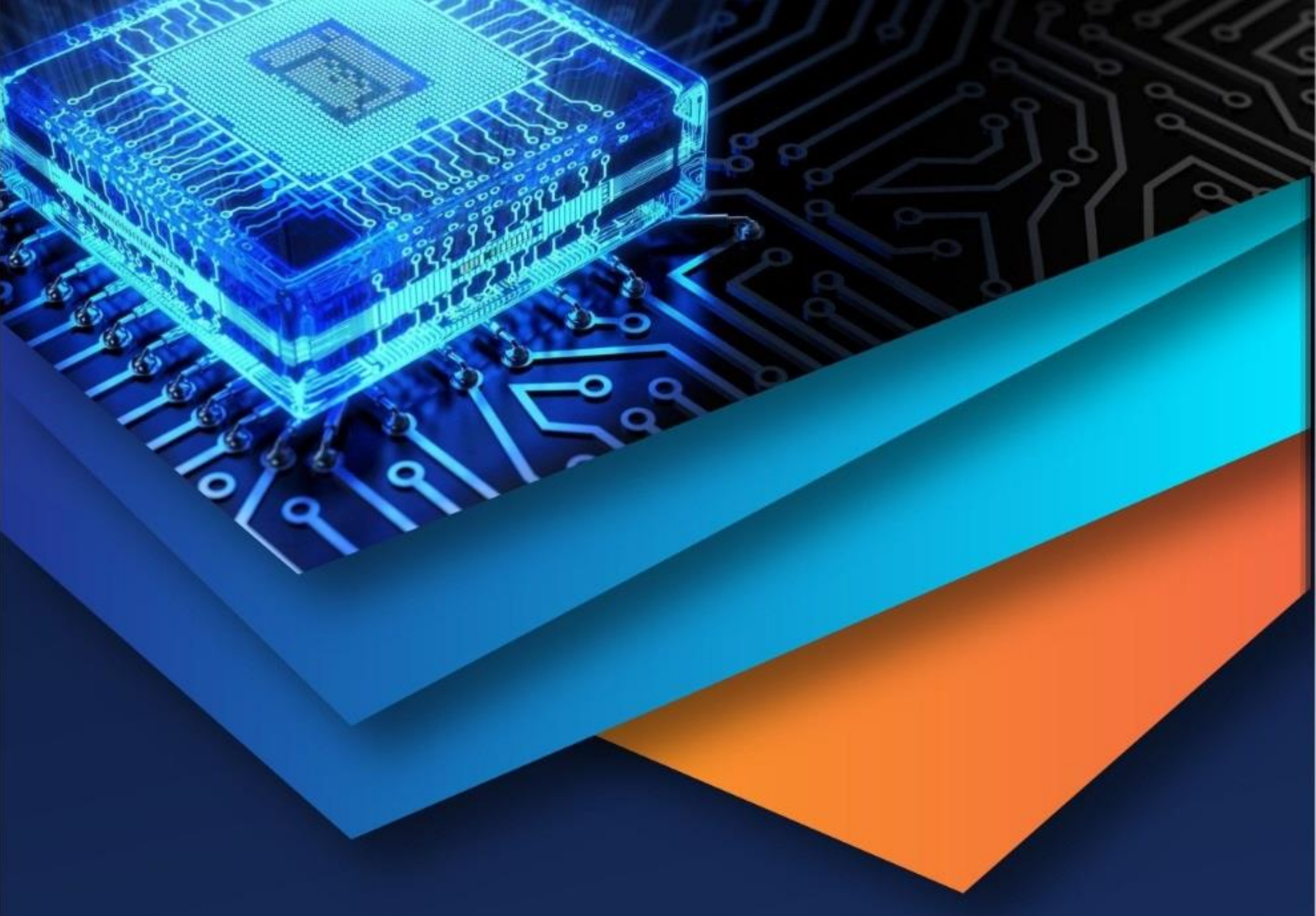
IV. CONCLUSIONS

For Al-Cu FSL welds, joint strength was found to be very sensitive to pin positioning during FSLW. When the Dp = 0.4 mm during FSLW, a single continuous intermetallic layer formed along the interface; and thus continuous metallurgical bonding established. The joint produced by this pin penetrating condition (with a single continuous intermetallic at interface) displayed a high σLap value (450 N/mm) which was ~ 49% increase in σLap in comparison to the case of Dp>0.4mm condition (with the mixed interface region).The condition of Dp >0.4 mm did not insure a continuous intermetallic layer and instead discontinuous intermetallic outbursts (non-continuous metallurgical bond) formed at the interface, resulting from the early stage of intermetallic growth, formed at the joint interface. Once the pin sufficiently penetrates to steel (Dp > 0.4 mm), the interface region was consisted of intermix and irregular layers of intermetallic and recrystallized Cu grains form. The value of σlap (≈302 N/mm) in pin penetrating condition, although Dp differ for different samples, indicates that σLap is not very sensitive to the size of the interface region (with intermix and irregular intermetallic layers), once it forms. Also value of σlap (≈302 N/mm, fractured at SZ) for the pin penetrated welds is itself higher than the maximum σlap value (268 N/mm, fractured at the SZ or interface) reported in literature when pin penetrating condition used. In tensile shear loading of Dp>0.4mm samples (with the mixed interface region) failure occurred through crack propagation along (parallel to) the intermetallic layers embedded inside the penetrated region, resulting in a brittle fracture. However, for the sample made using Dp = 0.4mm condition (with a single continuous intermetallic layer at interface), a ductile fracture was dominant with plastic deformation preceding failure mostly in aluminum adjacent to and on top of the interfacial intermetallic layer. Therefore, these results indicate that the notion of the presence of intermetallic layers embrittling the joint, is scientifically incorrect and a joint interface with single intermetallic layer can be highly shear fracture resistant.

REFERENCES

[1] Thomas W M, Nicholas ED, Needham JC, Murch MG, Templesmith P, Dawes CJ. Improvements relating to Friction Welding. international Patent

Application, PCT/GB92/02203 (Patent) December 1991.
[2] Mishra RS, Ma ZY. Friction stir welding and processing. Materials Science and Engineering R. 2005; 50: p1-78.
[3] R.S. Mishra and M.W. Mahoney (edited), “Friction stir welding and processing”, ASM International, Materials Park, Ohio, 2007 (360 pages).
[4] R. Nandan, T. DebRoy and H.K.D.H. Bhadeshia, “Recent advances in friction-stir welding – process, weldment structure and properties”, Progress in Materials Science 53 (2008) 980-1023.
[5] P.L. Threadgill, A.J. Leonard, H.R. Shercliff and P.J. Withers, “Friction stir welding of aluminum alloys”, International Materials Review 54 (2009) 50-93.
[6] L.E. Murr, “A review of FSW research on dissimilar metal and alloy systems”, Journal of Materials Engineering and Performance 19 (2010) 1071-1098.
[7] D. Lohwasser and Z.W. Chen (edited), “Friction Stir Welding – from basics to applications”, (ISBN 978-1-84569-450-0) Woodhead Publishing Ltd, Cambridge, and CRC Press, Roca Raton, 2010 (424 pages).
[8] R. Rai, A. De, H.K.D.H. Bhadeshia and T. DebRoy, “Review: friction stir welding tools”, Science and Technology of Welding and Joining 16 (2011) 325-342.
[9] Galvão 1, D. Verdera 2, D. Gesto 2, A. Loureiro 1 D. M. Rodrigues 1, “ANALYSING THE CHALLENGE OF ALUMINIUM TO COPPER FSW”, CEMUC, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal 2 AIMEN, Relva 27A Torneiros, 36410 Porriño, Spain
[10] Ahmed. ELREFAEY, Makoto. TAKAHASHI and Kenji IKEUCHI,“Microstructure of aluminum/copper lap joint by friction stir welding and its performance”, Joining and Welding Research. Osaka University (11-1 Mihogaoka , Ibaraki, Osaka 567-0047, Japan).
[11] A. Elrefaey, M. Takahashi and K. Ikeuchi, “Preliminary investigation of friction stir welding aluminium/copper lap joints”, Welding in the world 49 (2005) 93-101.
[12] A. Abdollah-Zadeh, T. Saeid and B. Sazgari, “Micro structural and mechanical properties of friction stir welded aluminum/copper lap joints”, Journal of Alloys and Compounds 460 (2008) 535-538.
[13] T. Saeid, A. A. Abdollah-Zadeh and B. Sazgari, “Weldability and mechanical properties of dissimilar aluminum/copper lap joints made by friction stir welding”, Journal of Alloys and Compounds 490 (2010) 652-655.
[14] P.Xue, B.L. Xiao, D. Wang and Z.Y. Ma, “Achieving high property friction stir welded aluminum/copper lap joint at low heat input”, Science and Technology of Welding and Joining 16 (2011) 657-661.
[15] M Satya Narayana Gupta, B Balunaik and KGK Murti, “Effect of tool geometry on joint properties of friction stir welded Al/Cu bimetallic lap joints”, The IUP Journal of Mechanical Engineering 1 (2012) 38-50.
[16] VAHID FIROUZDOR and SINDO KOU, “Al-to-Cu Friction stir lap welding”, Metallurgical and Materials Transactions A 43 (2012) 303-315
[17] MOSTAFA AKBARI and REZA ABDI BEHNAGH, “Dissimilar Friction- Stir Lap joining of 5083 Aluminum Alloy to CuZn34 Brass”, Metallurgical and Materials Transactions B 43B (2012) 1177-1186.
[18] P. Xue, B.L. Xiao, D. Wang and Z.Y. Ma, “Enhanced mechanical properties of friction stir welded dissimilar Al- Cu joint by intermetallic compounds”, Materials Science and Engineering A 527 (2010) 5723 5727.
[19] P. Xue, B.L. Xiao, D. Wang and Z.Y. Ma, “Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al-Cu joints”, Materials Science and Engineering A 528 (2011) 4683-4689.
[20] T. DebRoy and H.K.D.H. Bhadeshia, “Friction stir welding of dissimilar alloys – perspective”, Science and Technology of Welding and Joining 15 (2010) 266-270.
[21] J. Ouyang, E. Yarrapareddy and R. Kovacevic, “Micro structural evolution in the friction stir welded 6061 aluminium alloy (T6-temper condition) to copper”, Journal of Materials Processing Technology 172 (2006) 110- 172.
[22] A. Esmaeili, M.K. Besharati Givi and H.R. Zareie Rajani, “A metallurgical and mechanical study on dissimilar friction stir welding of aluminum 1050 to brass (CuZn30)”, Materials Science and Engineering A (2011)7093-7102.
[23] A. Esmaeili, H.R. Zareie Rajani, M. Sharbati, M.K. Besharati Givi and M. Shamanian, “The role of rotation speed on intermetallic compounds formation and mechanical behavior of friction stir welded brass/aluminum 1050 couple”Intermetallics 19 (2011) 1711-1719.
[24] H.J. Liu, J.J. Shen, L. Zhou, Y.Q. Zhao, C. Liu and L.K. Kuang, “Micro structural characterization and mechanical properties of friction stir welded joints of aluminum alloy to copper”, Science and Technology of Welding and Joining 16 (2011) 92-99.
[25] I. Galvao, J.C. Oliveira, A. Loureiro and D.M. Rodrigues, “Formation and distribution of brittle structures in friction stir welding of aluminum and copper: influence of process parameters”, Science and Technology of Welding and Joining 16 (2011) 681-689.
[26] C. Genevois, M. Girard, B. Huneau, X. Sauvage and G. Racineux, “Interfacial reaction during friction stir welding of Al and Cu”, Metallurgical and Materials Transactions A (2011) 2290-2295.
[27] I. Galvao, J.C. Oliveira, A. Loureiro and D.M. Rodrigues, “Formation and distribution of brittle structures in friction stir welding of aluminum and copper: influence of shoulder geometry”, Intermetallics 22 (2012) 122-128



10.22214/IJRASET

INDEX COPERNICUS 45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY