Journal of Advances in Mechanical Engineering and Science, Vol. 1(1) 2015, pp. 57-64

RESEARCH ARTICLE

Joining of AISI 1040 Steel to 6082-T6 Aluminium Alloy by Friction Welding

*C.H Muralimohan[1,2], S Haribabu[3], Y Hariprasada Reddy[3], V Muthupandi[1], K Sivaprasad[1]
[1]Department of Metallurgical and Materials Engineering, National Institute of Technology Tiruchirappalli 620015, Tamilnadu, India
[2]Department of Advanced Materials Engineering, Dong-Eui University, Busan 614714, Republic of Korea
[3]Department of Mechanical Engineering, Sri Venkatesa Perumal College of Engineering and Technology, Puttur 517583, Andhra Pradesh, India

Received-3 June 2015, Revised-4 July 2015, Accepted-8 August 2015, Published-11 August 2015

ABSTRACT

Aluminium alloys AA 6000 series are being used for automotive applications due to their ability to strengthen by artificial aging after forming. The joining of aluminium especially to other alloys becomes increasingly important. Joining of aluminium to steel presented distinctive metallurgical and mechanical properties and selection of suitable joining methods are challenging. This paper describes friction welding of 6082-T6 aluminum alloy to 1040 steel via several process parameters. The influence of friction time and forging pressure on mechanical and metallurgical properties were evaluated. The maximum joint strength of 220 MPa was achieved at optimized conditions and it has been observed that strength of the joints varied with increasing friction time at constant forging pressure. However, the strength of the welds varied gradually and increased with increasing forging pressure at constant friction time. Thus, the forging pressure has a major role over the friction pressure and friction time on strength of the joints. Microstructural characterization was done using optical microscopy and SEM analysis. The elemental composition of welds was analyzed by EDS technique. The presence of Al–Fe chemical species was characterized via a thin layer of transition zone on bond lines and the significance of percentage of compositions seems to be related to the Fe_2Al_5 and FeAl intermetallic compounds. The tensile fracture of the welded joint occurred in 6082-T6 aluminium side near the interface. The characterization of fractured surfaces reveals the pattern of dimple structure.

Keywords: Aluminium, Steel, Friction welding, Dissimilar metals, Mechanical properties, Microstructural characterization.

1. INTRODUCTION

Friction welding is a solid-state joining process enabling combinations of ferrous and non-ferrous metals and can be used to obtain perfect components which could not be obtained via conventional fusion welding processes. It has gained importance in the fabrication industry. The advantages of this process as the most economical and productive methods of joining different alloys are high reproducibility, short production time and low energy input [1]. The most important parameters in friction welding are friction pressure, friction time, forging pressure, forging time and rotating speed [2, 3]. The previous studies on effect of friction welding parameters were reported by [4].

In friction welding process, the joining surfaces of the substrates are heated to the desired temperature with the effect of friction developed by rubbing surfaces of the joining parts.

The joining of dissimilar materials passes the potential to utilize the benefits of different materials often providing distinctive solutions to many industrial applications [5, 6].

*Corresponding author. Tel.: +918951282192
Email address: muralicheepu@gmail.com (C.H.Muralimohan)
Double blind peer review under responsibility of DJ Publications
http://dx.doi.org/10.18831/james.in/2015011006

The main objective of joining dissimilar metals is to combine the beneficial mechanical and microstructure properties of one material and either extensive corrosion resistance or low specific weight or virtuous electrical properties of other substantial metals [7, 8]. In recent years, the joining processes for dissimilar materials is very demanding especially in automobile industry due to the weight reduction of vehicle components. It is essential to expand the use of lightweight structures in automobile industry and it has increased the interest in the use of both aluminium (Al) and magnesium as structural components. The cost of aluminium in contrast to carbon steels limits its applications intended for many industries. For instance as a result of this, it is necessary to produce joints between aluminum and steel. However, it is very difficult to produce a reliable joint because of their poor metallurgical compatibility and mismatch in mechanical properties. Conventional fusion welding cannot be feasible to make a reliable joint due to the occurrence of stress concentration, chemical segregation and formation of secondary phases.

The previous research reports on the joining techniques of steel to aluminium ranges from conventional welding methods to solid-state welding procedures such as various arc welding processes [9–12], explosive welding [13], resistance spot welding [14], mechanical joining [15], solid state welding methods such as friction welding [16], friction stir welding techniques [17] and vacuum diffusion bonding processes [18]. Many of the studies on friction welding of similar combinations are available, but the challenges in joining of dissimilar combinations and optimization of welding parameters were developed by [19]. They were attentive for practical and theoretical studies over optimization of process parameters in joining of dissimilar metals by friction welding technique. Other investigation has been done by [4] on physical and microstructural characterization of friction-welded structural steel-aluminium alloys, and aluminium to copper. The behavior of friction welding on aluminium and its alloys were investigated by [20]. The examinations of microstructure evaluation on 7075 Al with friction-stir process was done by [21] and the investigation of on amorphization processes between Al alloy and stainless steel (SS) by friction welding process by [22]. The joints between Al and steel exhibits imperfections such as micro-cracks, weld pores, unwanted secondary phases and alterations. The quality of the weld is determined by the appropriate set of optimized welding parameters. The selection of welding parameters will establish the metallurgical alterations and tension strength of the welded components. One of the friction welding parameters such as friction time is influencing other parameters. If the friction time is held long it resulted in wide diffusion zone with the presence of secondary phases, whereas at short friction times with low friction pressure and forging pressures the welds are weak in bond and voids are commonly found. To accomplish maximum efficient joints, the friction time is necessary to be maintained as low as required, although the friction and forging pressure can be taken for higher ranges [23]. Therefore, the aim of the present work is to characterize the metallurgical properties and the effects of process parameters on mechanical properties of friction welded joints of 6082-T6 aluminium to AISI 1040 steel.

2. MATERIALS AND METHODS

In this study, AISI 1040 steel and AA 6082-T6 aluminium rods were machined in the dimensions of 10 mm diameter and 80 mm length, respectively. The chemical composition of the substrates were analyzed by X-ray fluorescence (XRF) spectroscopy and are shown in table A1. The mechanical properties of the substrates are shown in table A2. Continuous drive friction welding process was used to produce the joints between AISI 1040 steel and AA 6082-T6 aluminium. During friction welding of steel to Al, the deformation resistance greatly varied due to axial pressure exerted by friction welding equipment and frictional heat generated by rubbing surfaces. Aluminium base metal experienced more plastic deformation nearer to the weld interface. The Al alloy was fixed on rotating side and 1040 steel sample was kept on stationary side. After welding the flash was machined on lathe to the base metal size. In the present study friction time, forging pressure and friction pressure were varied while the speed and forging time were held constant. Various welding trails were used to obtain the optimum welding conditions and are given in table A3. Tensile and charpy V-notch test specimens were prepared according to ASTM-E8 and ASTM-E23 standards respectively.

Standard metallographic techniques were applied for all welds produced at different welding parameters. All the joints were performed under drop test immediately after welding.

The cross-sectioned transverse welds were prepared for microstructural observation according to the standard metallographic procedures. Microstructural observations of the as-received rods and weldments were characterized using optical and scanning electron microscope (SEM). Energy dispersive X-ray spectroscopy (EDS) studies were used to confirm the intermetallic formation and chemical composition of the elemental distribution at the weld interface. Microhardness measurements were conducted across the weld interface using digital microhardness tester. A load of 300 g was applied for 10 s for 1040 steel, and 100 g for 10 s for aluminium alloy. The fracture surfaces of tensile and impact test tested samples were characterized by SEM to investigate the mode of fracture and failure location.

3. RESULTS AND DISCUSSION

3.1. Microstructure characterization

The resulted friction welded joints reveals the formation of weld flash of mixed material owing to severe plastic deformation with frictional heat and movement of aluminium in the interface of heterogeneous welds. Joint flash is formed at the aluminium side while the steel side is not externally changed. Figure 1 shows the macrostructural features of the interfaces with increasing the upset pressure.

With an increase in forging pressure, the amount of flash increases and the shape of the flash tilts toward aluminium from its original radial direction. The center of faying surfaces has a flat shape regardless of forging pressure, whereas the faying surfaces away from the center line has a mechanical mixing of aluminium and steel. This is due to the fact that edges (periphery) of the joint substrates are melted faster than the center of the joint and hence the frictional heat of the periphery of the joint is larger than the center of the joint. Consequently, plastic flow at the periphery of the joint is easier than the center of the joint. This produces an increase in surface area and results in improvement of the joint strength [24].

The microstructure of the base material 6082-T6 aluminium alloy is depicted in figure 2, with the insubstantial grains formed in equiaxed structure. Microstructure details exit

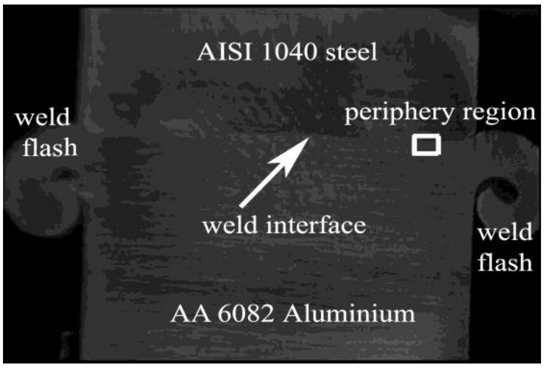

Figure 1.Macrograph showing the transverse section of the weld with interface

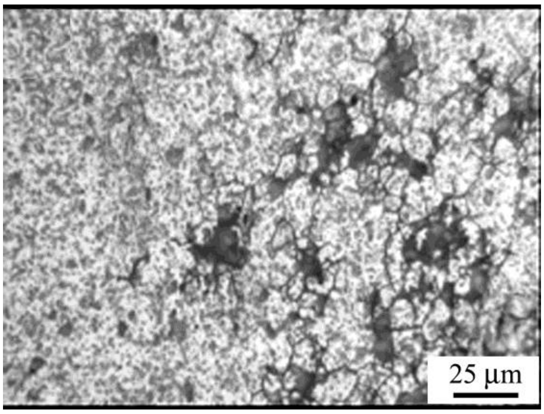

Figure 2.Optical microstructure of the 6082 Al alloy base material

and are studied at the aluminium–steel interfaces. In all the joints due to the effect of high rotation speed, friction pressure and upset pressure, aluminium grains which are close to the interface are mechanically deformed and recrystallized as fine equiaxed grains. With an increase in temperature due to friction, the yield strength of aluminium decreases and the atomic diffusivity increases which results in more interfacial deformation and facilitates the metallurgical bonding. The deformation zone on steel side indicates that the deformation is not only confined to aluminium because of its lower strength and melting point but steel also can affect to some amount of deformation in the region close to interface as can be seen in figure 3. The SEM image reveals good bonding along Al–steel interface and it is free from discontinuities and formation of micro-cracks. The interface between Al and steel was characterized by very thin diffusion transition layer which was formed along the bond line. It is observed that the transition layer thickness increases with increasing friction time. This linear dependence is due to the fact that interlayer thickness on the square root of friction time entails that the growth of the interface is affected by diffusion of elements [23]. The transition layer was homogeneously formed throughout the interface and appears with a light gray contrast.

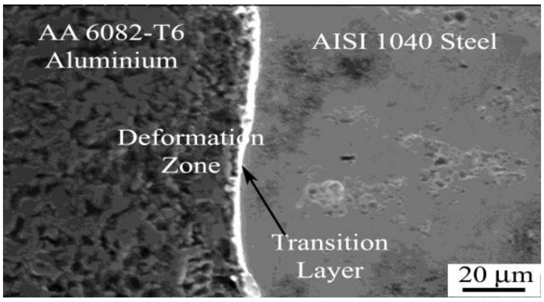

Figure 3.Scanning electron microstructure of the aluminium–steel weld interface

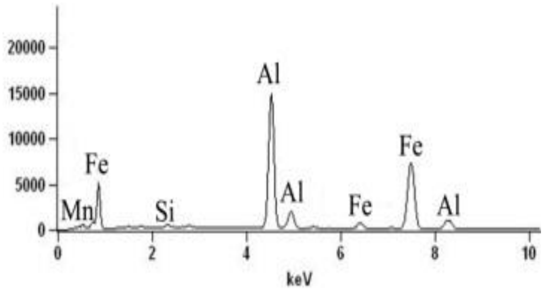

Figure 4.EDS spot scan spectrum of the Al–steel weld interface

The EDS spectrum of spot scan analyses of the optimal weld produced at friction pressure of 90 MPa, forging pressure p2–180 MPa and friction time t1– 4 s is shown in figure.4. The average chemical composition of elements Al (~52.8–60.5 at.%) and Fe (~46.2–50.8 at.%). According to the Al–Fe binary phase diagram, it is possible to form the FeAl and Fe_2Al_5 intermetallic phases [25]. The presence of Al–Fe secondary phases leads to deterioration in the mechanical properties of the joints.

3.2. Mechanical properties

The micro-hardness measurements were conducted across the Al–steel joint interface and are shown in figure 5. The maximum hardness peak was in joint interface where the transition layer is formed and it has been observed that with increasing the forging pressure the hardness peak increases at the interface. The microstructural changes suggest that low friction pressure and high forging pressure lead to higher hardness. These changes are caused due to the lesser frictional heat input available at the center resulting in higher degree of strain hardening effect. The highest hardness value on the aluminium side near the weld lines is directly associated to the microstructure crystallized in the weld as a result of high density dislocations during extensive plastic deformation. However, there is no appreciable increase in hardness in 1040 steel side in contrast to the original hardness of the parent material, representing that strain hardening is less and the extent of deformation is limited on steel compared to aluminium. The peak hardness recorded at Al/steel interface can be attributed to the formation of intermetallic compounds of Al–Fe and microstructural formation.

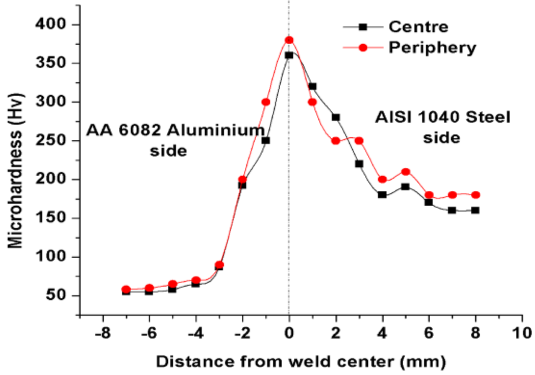

Figure 5.Hardness profile showing the variation in hardness at center and periphery regions recorded at the joint interface

Figure 6 shows the effect of forging pressure on tensile strength. The strength of the welds increased slightly by an increase in the forging pressure to more 160 MPa. Consequently the amount of upset increased constantly with increasing the forging pressure. In this regard forging pressure of 160 MPa does not contribute to increase in tensile strength regardless of friction time. Therefore, the optimal weld strength of 220 MPa is attained at a friction time of t1–4 s and forging pressure of p2–180 MPa. The tensile fracture took place on aluminum side near to weld interface with minimal elongation.

Figure 7 illustrates the increase in tensile strength with increase in friction time and forging pressure. The strength of the joint was very low at forging pressure of 140 MPa, even though the friction time increases from 1 sto 6 s. It can be seen that the thermal degradation region increases with friction time.

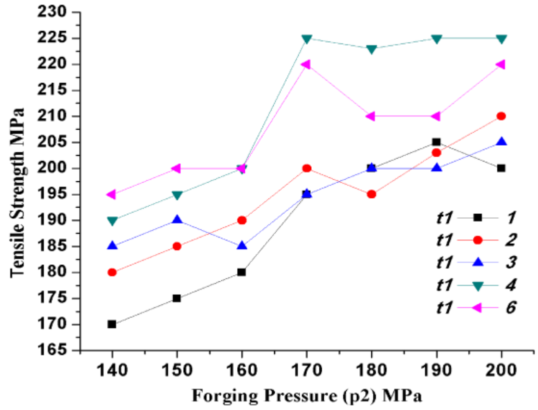

Figure 6.Variations of tensile strength with forging pressure (p2)

The lowest pressures cannot discharge thermal degradation region from the interface completely [18]. Hence, it is considered that the effect of welding parameters such as forging pressure plays a major role over the friction pressure and friction time on tensile strength.

The impact energy of the joints depends on the frictional heat generated at the joint interface. The toughness of the welds depends on the welding process and temperature. The higher forging pressure results in associating the stronger joint formation. The impact energy of the joints increased with forging pressure and maximum impact energy of 36 J is attained at forging pressure of 160 MPa, friction pressure of 100 MPa and friction time of 2 s. The gradual decrease of impact energy with increasing friction pressure is due to the frictional heat at the bonding area and its effect on grain coarsening. Toughness and tension strength increases with increasing forging pressure. This results from the equiaxed granulated grain pattern with exorbitant strain hardening effect on the heat affected zone and bond lines.

3.3. Fracture surface analysis

Failure occurred on aluminium base metal adjacent to the weld interface. Fracture surfaces were characterized by SEM in order to investigate the behavior of fracture surfaces and are illustrated in figure 8. The fracture morphology of the SEM images confirmed that the induced fracture is mixed mode with the appearance of ductile regions with the presence of small cleavage regions. These cleavage regions are probably the secondary phases initiating the fracture in the joints.

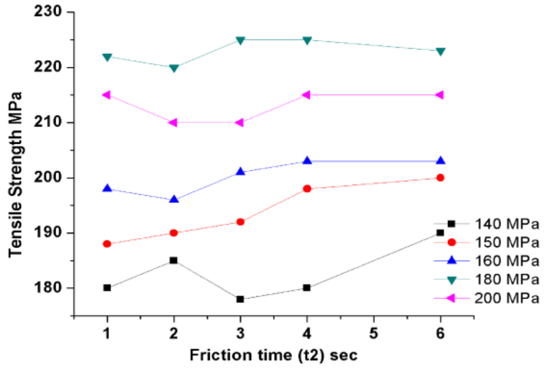

Figure 7.Effect of friction time on tensile strength at constant forging pressures

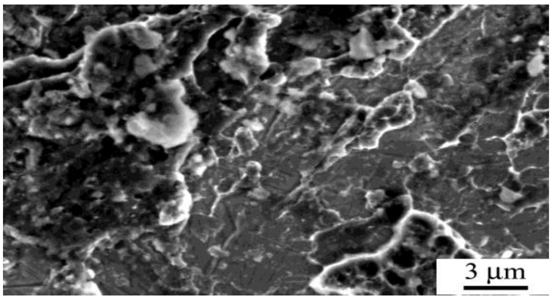

Figure 8.SEM fracture showing the morphology of joint with ductile failure

4. CONCLUSIONS

AA 6082–T6 aluminium to AISI 1040 steel was successfully joined by friction welding process. The microstructural changes of weld interface were studied at various friction welding conditions. The effects of welding process parameters on mechanical properties of the joints were examined. Following conclusions can be drawn from this study

1. The strength of the welds decreased with an increase in fiction time. The optimized welding conditions achieved the maximum strength higher than those of the base metal (Al).
2. The tensile fracture surfaces of the SEM images shows the ductile mode of failure.
3. The impact energy of the welds shows almost same value for the base material.
4. Micro-hardness profile shows the pattern of hardness values increase with forging pressure. The change in hardness value at the weld interface is due to the presence of Al-Fe secondary phases.
5. EDS analysis confirmed the presence of FeAl and Fe_2Al_5 intermetallic phases at the bond region.

ACKNOWLEDGMENTS

The authors would like to thank materials joining laboratory IIT Madras for permission to use the friction welding facility

REFERENCES

[1] J.Ruge, K.Thomas, C.Eckel and S.Sundaresan, Joining of Copper to Titanium by Fiction Welding, Welding Journal, Vol.65, 1986, pp. 28–31.

[2] C.H.Muralimohan, V.Muthupandi and, K.Sivprasad, The Influence of Aluminium Intermediate Layer in Dissimilarn Friction Welds, International Journal of Materials Research, Vol.105, No.4, 2014, pp. 350-357, http://dx.doi.org/10.3139/146.111031.

[3] C.H.Muralimohan, S.Haribabu, Y.Hariprasad Reddy, V.Muthupandi, and K.Sivaprasad, Evaluation of microstructures and mechanical properties of dissimilar materials by friction welding, Procedia Materials Science, Vol.5, 2014, pp. 1107-1113, http://dx.doi.org/10.1016/j.mspro.2014.07.404.

[4] B.S.Yilbas, Ahmet Z.Sahin, Nafiz Kahraman and Ahmed Z.AlGarni, Friction Welding of StAl and AlCu Materials, Journal of Materials Processing Technology, 1995, pp. 431-443.

[5] C.H.Muralimohan and V.Muthupandi, Friction Welding of type 304 Stainless Steel to CP Titanium using Nickel Interlayer, Advanced Materials Research, Vol.794, No.13, 2013, pp. 351-357, http://dx.doi.org/10.4028/www.scientific.net/AMR.794.351.

[6] C.H.Muralimohan, V.Muthupandi and, K.Sivaprasad, Properties of Friction Welding Titanium-Stainless Steel Joints with a Nickel Interlayer, Procedia Materials Science,Vol.5, 2014, pp. 1120-1129, http://dx.doi.org/10.1016/j.mspro.2014.07.406.

[7] S.Fukumoto, T.Inuki, H.Tsubakino, K.Okita, M.Aritoshi and T.Tomita, Evaluation of Friction Weld Interface of Aluminum to Austenitic Stainless Steel Joint, Materials Science and Technology, Vol. 13, No.8, 1997, pp. 679–686, http://dx.doi.org/10.1179/mst.1997.13.8.679.

[8] Murali Mohan Cheepu, V. Muthupandi and S. Loganathan, Friction Welding of Titanium to 304 Stainless Steel with Electroplated Nickel Interlayer, Materials Science Forum, Vol. 710, 2012, pp. 620–625, http://dx.doi.org/10.4028/www.scientific.net/MSF.710.620.

[9] Hongtao Zhang, J.C.Feng, P.Heb, B.B.Zhang, J.M.Chen and L.Wang, The Arc Characteristics and Metal Transfer Behaviour of Cold Metal Transfer and its use in Joining Al to Zinc-Coated Steel, Fifth International conference on Physical and Numerical Simulations of Metal Processing, China, 2009, pp. 111–113, http://dx.doi.org/10.1016/j.msea.2007.11.124.

[10] S.B.Jamaludin, M.Z.A.L, M.Mohd Noor and K.Hussin, Joining Dissimilar Metals between Steel and Aluminum by TIG Welding, Materials Science Forum, Vol. 819, 2015, pp. 45–49, http://dx.doi.org/10.4028/www.scientific.net/MSF.819.45.

[11] S.Chen, J. Huang, K. Ma, X. Zhao and A.Vivek, Microstructures and Mechanical Properties of Laser Penetration Welding Joint with/without Ni-Foil in an Overlap Steel-on-Aluminum Configuration, Metallurgical and Materials Transactions A, Vol. 45, No. 7, 2014, pp. 3064–3073, http://dx.doi.org/10.1007/s11661-014-2241-1.

[12] S.Chen, Z. Zhai, J. Huang, X. Zhao and J. Xiong. Interface Microstructure and Fracture Behavior of Single/Dual-Beam Laser Welded Steel-Al Dissimilar Joint Produced with Copper Interlayer, The International Journal of Advanced Manufacturing Technology, 2015, pp. 1-13, http://dx.doi.org/10.1007/s00170-015-7390-x.

[13] M.Acarer and B.Demir, An Investigation of Mechanical and Metallurgical Properties of Explosive Welded Aluminum-Dual Phase Steel, Materials Letters, Vol. 62, No. 25,

2008, pp. 4158-4160, http://dx.doi.org/10.1016/j.matlet.2008.05.060.

[14] R.Qiu, N.Wang, H.Shi, L.Cui, L.Hou and K.Zhang, Joining Steel to Aluminum Alloy by Resistance Spot Welding with a Rivet, International Journal of Materials Research, Vol. 106, No.1, 2015, pp. 60–65, http://dx.doi.org/10.3139/146.111146.

[15] M.Jackel, C.Kraus and T.Kropp, Effects of Increased Tool Velocity on Mechanical Joining of Steel and Aluminum Sheet Metals, Procedia CIRP, Vol. 23, 2014, pp. 24–28, http://dx.doi.org/10.1016/j.procir.2014.10.062.

[16] O.Chayaphum, S.Prombanpong, and V.Tangwarodomnukun, Process Characteristics of Friction Bonding of Stainless Steel 430, Aluminum 1100 and 3003, Procedia CIRP, Vol. 17, 2014, pp. 795–799, http://dx.doi.org/10.1016/j.procir.2014.01.118.

[17] T.Watanabe, H.Takayamaand, and A.Yanagisawa, Joining of Aluminium Alloy to Steel by Friction Stir Welding, Journal of Materials Processing Technology, Vol. 178, 2006, pp. 342-349, http://dx.doi.org/10.1016/j.jmatprotec.2006.04.117.

[18] M.K.Karfoul, G.J.Tatlock and R.T.Murray, The Behaviour of Iron and Aluminum during the Diffusion Welding of Carbon Steel to Aluminum, Journal of Materials Science, Vol. 42, No. 14, 2007, pp. 5692-5699, http://dx.doi.org/10.1007/s10853-006-0742-z.

[19] K.G.K.Murti, and S.Sundaresan, Parameter Optimization in Friction Welding Dissimilar Materials, Metal Construction, Vol. 15, 1983, pp. 331-335.

[20] B.S.Yilbas,A.Z.Sahin,A.Coban and B.J. Abdul Aleem, Investigation into the Properties of Friction: Welded Aluminium Bars, Journal of Materials Processing Technology, Vol. 54, 1995, pp. 76-81, http://dx.doi.org/10.1016/0924-0136(95)01923-5.

[21] C.G.Rhodes,M.W.Mahoney,W.H.Bingel, R.A.Spurling and C.C.Bampton, Effects of Friction Stir Welding on Microstructure of 7075 Aluminum, Scripta Materialia, Vol. 36, No. 1, 1997, pp. 69-75, http://dx.doi.org/10.1016/S1359-6462(96)00344-2.

[22] S.Fukumoto, H.Tsubakino, K.Okita, M.Aritoshi and T.Tomita, Amorphization by Friction Welding between 5052 Aluminum Alloy and 304 Stainless Steel, Scripta Materialia, Vol. 42, No. 8, 2000, pp. 807-812, http://dx.doi.org/10.1016/S1359-6462(00)00299-2.

[23] M.Yilmaz, M.Col and M.Acet, Interface Properties of Aluminium/Steel Friction Welded Components, Materials Characterization, Vol. 49, No.5, 2002, pp. 421-429, http://dx.doi.org/10.1016/S1044-5803(03)00051-2.

[24] Y.K.Seong, B.J.Seung, and C.S.Chang, Mechanical Properties of Copper to Titanium Joined by Friction Welding, Journal of Materials Science, Vol. 38, No. 6, 2003, pp. 1281–1287, http://dx.doi.org/10.1023/A:1022890611264.

[25] T. B. Massalski, Binary Alloy Phase Diagrams, ASM International, Materials Park, Ohio, 1996.

BIOGRAPHICAL NOTES

Corresponding Author: CH. Muralimohan obtained his Masters degree in Welding Engineering and he is a research scholar from National Institute of Technology Tiruchirappalli. His current research interests include solid state welding processes and welding metallurgy. (Email. muralicheepu@gmail.com) Corresponding Address: CH. Muralimohan, Department of Metallurgical and Materials Engineering, National Institute of Technology Tiruchirappalli, Tiruchirappalli, Tamilnadu, India- 620 015 Ph- +91 8951282192.

APPENDIX A

Table A1.Chemical composition (wt. %) of base materials

AA 6082	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
	0.9	0.4	0.1	1.02	0.96	0.2	0.1	0.22	Bal
AISI 1040	C	P	S	Mn	Si	Ni	Mo	Cr	Fe
	0.42	0.04	0.05	0.79	0.3	–	–	–	Bal

Table A2.Mechanical properties of materials used in the experiment

Samples	YS (MPa)	UTS (MPa)	Elongation (%)	Hardness (Hv)
AA 6082	215	240	11	105
AISI 1040	348	510	28	152

Table A3.Friction welding conditions

Forging Pressure p1 (MPa)	Friction Time t1 (sec)	Friction Pressure p2 (MPa)	Forging Time t2 (sec)	RPM
140–200	1–8	60–120	6	1500