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ARTICLE OF PROFESSIONAL INTEREST

Tensile Strength and Hardness Correlations with Microscopy in Friction welded Aluminium to Copper

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Abstract Aluminium and copper are good conductors of heat and electricity, copper being the better conductor, is a costly metal indeed. On the other hand, aluminium is cheap, easily available and also has a lower density than copper. Hence, worldwide efforts are being made to partially replace copper wire. Solid state welding should be used to join aluminium to copper. This is because the use of fusion welding results in brittle phases formed in the weld interface. One of the solid state welding techniques used for joining aluminium to copper is friction welding. In this paper, an attempt has been made to join aluminium to copper by friction welding by varying the friction welding parameters, namely friction pressure, upset pressure, burn-off length and speed of rotation of the workpiece. Nine different friction welding parameter combinations were used during welding in accordance with ASTM standards and results have been reported. Tensile strength and hardness tests were carried out for each parameter combination. Optimum friction welding parameter combination was identified with respect to tensile strength. Scanning Electron Microscopy and Electron dispersive spectroanalysis were obtained to identify modes of fracture and presence of intermetallic phases for each friction welding combination with the aim to narrow down friction welding parameters that give good properties on the whole.

Keywords Friction welding · Aluminium to copper · Mechanical properties · Microstructures

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Introduction

In solid state welding processes, like friction welding, the temperature generated during welding is below the melting point of the metals but above the re-crystallization temperature. The temperature is high enough to create plastic flow of metal and results in an intermolecular bond. Application of friction pressure further enhances the temperature and mechanical rubbing action. While, applying frictional pressure, one workpiece is stationary and another one is rotating. After completing the application of friction pressure, upset pressure is applied which leads to purging of impurities in the weld zone (if any) into the flash, while at the same time increasing the temperature to get recrystallized grains. Burn-off length is specified in force the welded zone mechanically into both metals. Finally, the speed of rotation of the rotating workpiece can also be adjusted to aid in getting a proper defect free weld.

Literature Review

Methods of Welding Al and Cu

Aluminium and copper can be joined by Cold Roll Welding. The main steps associated with welding of Al to Cu by Cold Roll Welding process are as follows:

(i) Surface treatment of both Al and Cu to remove surface contamination.
(ii) Aligning and fixing the aluminum and copper strips in a pack.
(iii) Cold rolling of pack to produce a metallic continuity between Cu and Al at the interface. For roll welding of Al to Cu, a roll pressure between 1000 and 3400 MPa threshold hold reduction between 40 and 80 % has been reported [1].

The growth note of intermetallic compounds at the interface of cold roll bonded Al/Cu bimetal at 250 °C was studied and compared with the result of a similar study on friction welding of Al to Cu [2, 3].

Aluminium and copper have also been joined by laser welding. A study has been made using Nd: YAG laser high beam quality (12 mm rad) on Al and Cu. The beam power utilized was 2 kW. This process has been used for welding of copper tubes (with water running through them) and aluminum serving in the collection of solar radiation. Through process optimization, crack free weld seams have been created. The structure consisted of mostly Al enriched Cu mixed crystals (brittle intermetallic phases existed only as small islands within the joint zone) [4].

Ultrasonics have been used for a long time in various fields of Engineering and Medicine. Aluminum and copper plates have been welded using a 19 kHz ultrasonic welding system with a complex vibration welding tip. Metal plates of various thickness have been welded in these Al–Al, Al–Cu and Cu–Cu plate specimens with weld strengths almost equal to the specimen strength [5].

Impact welding of aluminum onto copper by the gas gun method has been reported. An Al projectile has been impact welded onto a copper target at an impact velocity ranging from 200 to 370 m/sec. Formation of $CuAl_2$ phase leads to sound welding during impact welding. But the crack information in the brittle θ phase causes decrease in bonding strength of Al/Cu joints [6].

Friction stir welding (FSW) has been in use for welding aluminium to copper from the 21st century onwards. Here, the constituent materials are welded with a rotating tool. Variables that can be altered are tool geometry (shape and size), tool speed, thickness of material etc. With copper 6061 aluminium alloy has been joined. The weld zone consists of several intermetallic compounds such as $CuAl_2$, CuAl and Cu_9Al_4. Distinctly different micro hardness levels from 136 to 760 Hv are produced corresponding to various microstructural features in the weld nugget [7].

Flash Butt welding has been used to weld Al to Cu. Brittle alloy is formed at the interface and it is necessary to control the thickness of this layer. Heating prior to upsetting causes considerable change in plasticity of materials. This variation in plasticity causes non-uniformity during upsetting and entire upset is made up of aluminium. Upset formation in this manner reduces the thickness of intermetallic layer [8].

Successful flash butt welding of aluminium to copper has also been reported. Similar mechanisms of formation of flash and reduction in thickness of intermetallic phase formation have been observed by some researchers while performing friction welding of aluminium to copper as given in the next paragraphs in this research work. These findings gave a strong case for performing friction welding of aluminium to copper [9].

Friction welding consists of clamping the cylindrical specimens in a friction welding machine and welding the specimens by an appropriate combination of friction pressure, upset pressure, RPM and burn-off length. Friction welding of aluminium alloys to copper has been carried out under different friction pressures based on the hardness and heat conductivity of each joining aluminium alloy [10].

The effect of tool geometry on the nature and formation of intermetallic phases during friction stir welding of aluminium plates with copper plates [11]. Intermetallic phase formation is governed by material flow mechanisms during FSW. Tool geometry strongly influences the intermetallic nature and distribution. The quantity and distribution of the intermetallics determine weld characteristics. The scrolled tool promoted the formation of a mixing region almost exclusively composed of $CuAl_2$ and the conical tool gave rise to the formation of a mixture of aluminium, copper, $CuAl_2$ and Cu_9Al_4 mixture, with higher heterogeneity and lower intermetallic content [12].

In this work, friction welding has been used as it is a very simple technique and suitable for mass production since time of welding is of the order of a few seconds or at most a few minutes.

Experimental Procedure

In the present sudy, commercially available pure grade Al and Cu were welded through FSW. The Friction welding machine is shown in Fig. 1.

The friction welding machine "FWG 20/300-S" is a machine capable of operating with high precision and excellent repeatability of all weld parameters. The spindle is driven by an AC spindle motor. Friction and upset forces are read by a load cell and precisely controlled by a hydraulic servo valve. The machine is controlled by an individual computer and the data of every weld is recorded. There is provision for retrieval of weld data. The machine has a stroke of 300 mm and maximum upset force of 200 kN can be applied. The spindle motor is of 20 HP, 3 phase AC and operating speed can be varied from 1 to

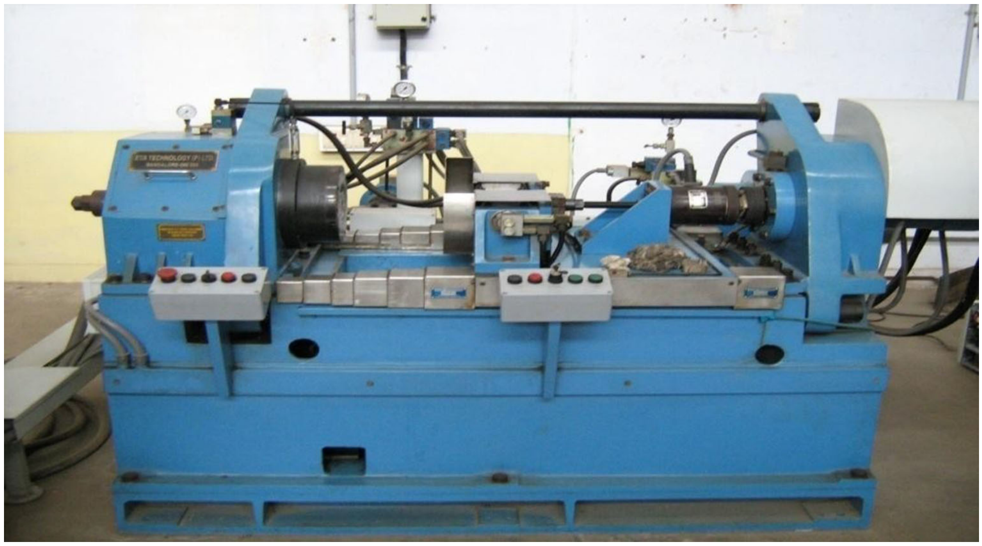

Fig. 1 Friction welding machine

Table 1 Chemical composition of aluminium specimen

Elements	Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
%	97.961	0.596	0.424	0.092	0.094	0.567	0.033	0.009	0.021

2500 RPM. The test reference that has been used for the chemical analysis of this specimen is ASTM E1251. Tables 1 and 2 show the chemical analysis of Al and Cu used in this work. The diameter of workpieces used in the work was 20 mm for both Al and Cu.

Friction welding was performed on dissimilar metals like Cu and Al to enable mechanical bonding. An ETA welding machine was used to weld the work pieces. The workpiece was turned to a diameter of 20 mm and an average length of 75 mm. Initially 50 pairs of specimens were tested on a trial and error basis and prior experience in welding Al to Cu narrowed down the friction welding parameters to 18 different welding parameter combinations A total of 18 pieces were prepared since the experiment was planned to perform using an L9 array. The process parameters such as friction-pressure, upset-pressure, burn-off length, speed combination are shown in Table 3 with three levels. Further, Table 4 shows the combination of four parameters, namely, friction-pressure, upset-pressure, burn-off length and speed.

Tensile Test

The specimens for tensile testing were prepared by machining them into a dog-bone shaped specimen with a specific holding length of 50 mm in order to get good gripping (Fig. 2). The diameter of both aluminium and

Table 2 Chemical composition of copper specimen

Elements	Cu	Si	P
%	99.987	0.007	0.006

Table 3 Parameters and levels

Parameter	Level 1	Level 2	Level 3
Friction pressure (MPa)	64	80	96
Upset pressure (MPa)	128	160	192
Burn off length (mm)	1	2	3
Speed (rpm)	500	750	1000

Table 4 Parameter combinations used in this work

S. No.	Friction Pressure (MPa)	Upset Pressure (MPa)	Burn-off length (mm)	Speed (rpm)
1.	64	128	1	500
2.	64	160	2	750
3.	64	192	3	1000
4.	80	128	2	1000
5.	80	160	3	500
6.	80	192	1	750
7.	96	128	3	750
8.	96	160	2	1000
9.	96	192	1	500

Fig. 2 Dimensions of tensile testing specimen

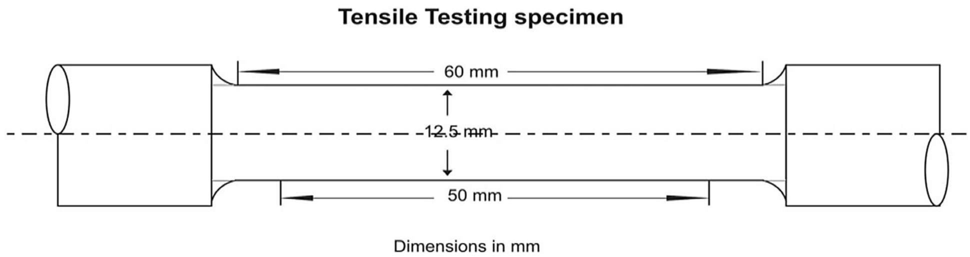

Table 5 Tensile test results

S. No.	Friction pressure (MPa)	Upset pressure (MPa)	Burn off length (mm)	Speed (mm)	UTS (MPa)
1	64	128	1	500	67.613
2*	**64**	**160**	**2**	**750**	**135.068**
3	64	192	3	1000	100.704
4*	***80***	***128***	***2***	***1000***	***28.318***
5	80	160	3	500	114.704
6	80	192	1	750	102.136
7	96	128	3	750	31.023
8	96	160	1	1000	94.818
9	96	192	2	500	59.023

* Indicates the parameters for high UTS

** Indicates the parameters for low UTS

Table 6 Hardness values

Sample no.	Friction Pressure (MPa)	Upset Pressure (MPa)	Burn-off length (mm)	Speed (rpm)	Copper haz (H_v)	Aluminium haz (H_v)	Weld zone (H_v)
1	64	128	1	500	95.367	86.967	101.234
2	64	160	2	750	93.934	78.334	102.967
3	64	192	3	1000	91.167	83.267	78.034
4	80	132	2	1000	89.634	98.634	125.600
5	80	160	3	500	93.500	p87.167	76.034
6	80	192	1	750	92.900	91.900	79.334
7	3.0	128	3	750	93.367	87.667	102.634
8	3.0	160	1	1000	90.434	101.900	75.367
9	3.0	192	2	500	88.134	94.600	86.100

copper specimens were 20 mm. All dimensions were in accordance with ASTM E-08 specifications.

Results and Discussions

Tensile Test Results

The tensile test results are shown in Table 5 and it depicts that low friction pressure with moderate upset pressure, burn off length, speed gives higher tensile strength.

Generally, it is seen that hardness in the weld zone is higher than hardness in the heat affected zone of aluminium as well as copper. This could be due to recrystallization of grains in the weld zone. The actual value of hardness at the interface depends upon the combination of all friction welding parameters.

Fractography

SEM-EDAX for aluminium–copper are shown in Figs. 3 and 4.

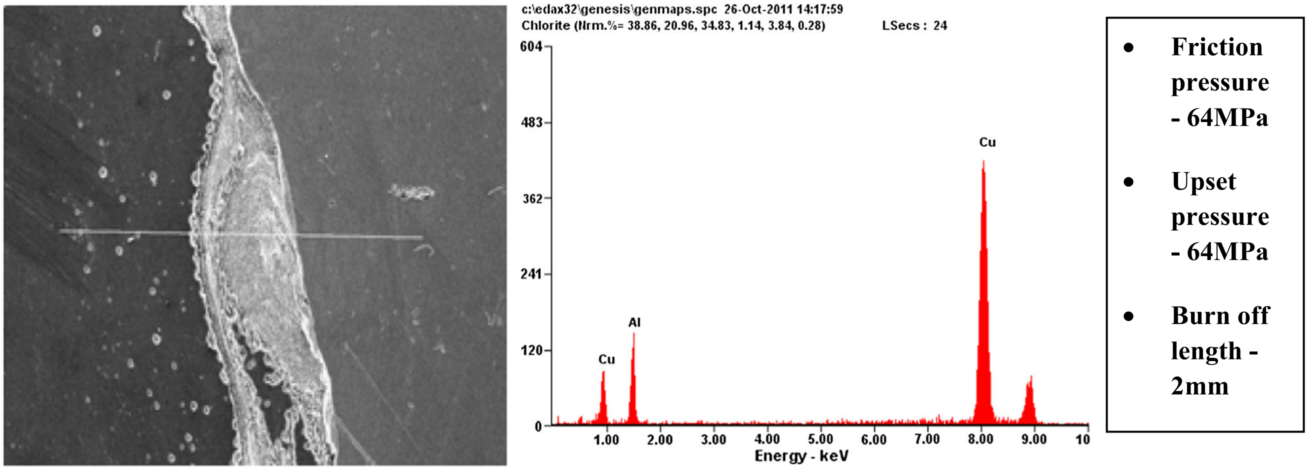

Fig. 3 SEM micrograph and SEM–EDS of Al–Cu weld under the conditions

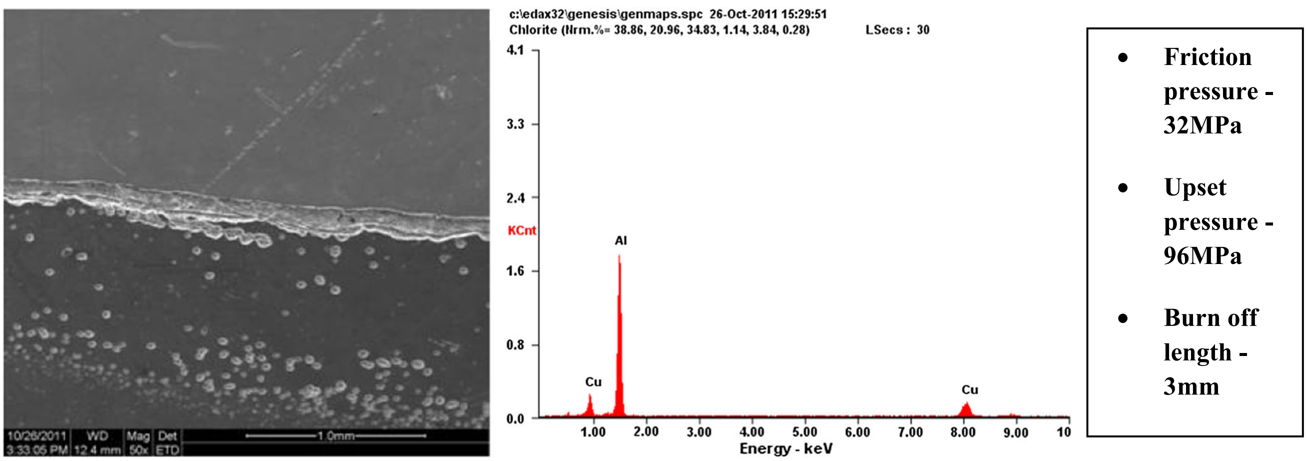

Fig. 4 SEM micrograph and SEM–EDS of Al–Cu weld

SEM Photographs of aluminium–copper show the interface. SEM-EDAX has been taken for two different friction welding conditions. For both the conditions presence of intermetallics are seen at the weld interface. It is seen that ductility is poor of the order of 0.5–1.0 % and hence there is a possibility of brittle intermetallic formation. Also the presence of grey layer at the interface containing both aluminium and copper can be seen in Figs. 3 and 4. Similar type of SEM-EDAX has been observed. These observations indicate the presence of intermetallic phases.

Conclusion

(i) Maximum tensile strength was 135.068 MPa. It was obtained at the combination of parameters given below in Table 7.

Table 7 Optimum welding parameters

Friction pressure (MPa)	Upset pressure (MPa)	Burn off length (mm)	Speed (rpm)
64	190	2	750

(ii) Hardness values are generally high of the order of 95–101 HR_V. This indicates the presence of intermetallic phases. This finding has been confirmed by the SEM photographs which show a brittle fracture. EDS also confirms the presence of intermetallic phases in the weld zone.

(iii) It is expected that use of an interlayer between the aluminium and copper workpieces would enhance tensile strength in the weld zone. Use of a suitable interlayer compatible to both aluminium and nickel is recommended.

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