Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 64 (2013) 1514 – 1523
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference on DESIGN AND MANUFACTURING, IConDM 2013

Evaluation of Mechanical and Metallurgical properties of dissimilar materials by friction welding

Shanjeevi.C[a]*, Satish Kumar.S[b] , Sathiya.P[c]

[a]*Research Scholar, Department of Mechanical and Production Engineering, Sathyabama University, Chennai, India*
[b]*Professor, Department of Production Engineering, Velammal Engineering College, Chennai, India*
[c]*Associate Professor, Department of Production Engineering, NIT, Trichy, India*

Abstract

Friction welding has been widely used to metals with dissimilar materials due to solid state joining process and shows good mechanical properties. In this study, the effect of mechanical and metallurgical properties of austenitic stainless steel (304L) and copper were experimentally investigated by tensile and hardness test while the metallurgical properties of optical, scanning electron microscopy and atomic force microscopy was used to analyze the microstructure of the welded joint. The joints were also examined with EDX line in order to understand the phases formed during welding. The material is evaluated by tensile test and their strength is determined and the hardness test measurements are examined in base metal and heat affected zone. The bonded materials of austenitic stainless steel and copper joint were produced by varying the friction pressure, upset pressure and rotational speed through Taguchi's orthogonal array. The highest tensile strength obtained in friction welded joint was 2.52% higher than parent material of copper. The effects of metallurgical characterization are discussed based on the microstructural studies.

Selection and peer-review under responsibility of the organizing and review committee of IConDM 2013

Keywords: Friction welding; Taguchi method; Mechanical properties; Atomic force microscopy

1. Introduction

Friction welding is a solid state joining process that uses rotational motion and high axial pressures to convert rotational energy into frictional heat at a circular interface. The heat produced by this rubbing action raises the

* Corresponding author. Tel.: +91-978-736-8813.
E-mail address: shanjeevii@gmail.com

Selection and peer-review under responsibility of the organizing and review committee of IConDM 2013
doi:10.1016/j.proeng.2013.09.233

Nomenclature

AC	Alternating Current
RPM	Revolution Per Minute
HP	Horse Power
mm	millimeter
nm	nanometers
MPa	Mega Pascal
VH	Vickers Hardness
SEM	Scanning Electron Microscopy
EDAX	Energy Dispersive Analysis of X-rays
AFM	Atomic Force Microscopy
WZ	Weld Zone
HAZ	Heat Affected Zone

inter-surface temperature of the two parts to the plastic state where the high thrust load extrudes metal from the weld region to form an upset. When sufficient energy is developed, the rotation is stopped and thrust load increased, to forge the parts together and form a solid state bond. Friction welded joints have very reliable integrity and becomes stronger than that of the individual base materials.

The friction welding of mild steel and stainless steel are studied and the strength of the joints obtained were good and reasonable [1]. An experiment conducted in continuous friction welding on sintered powder metallurgical steel to wrought copper material and the deformation is confined only to copper side due to high thermal conductivity [3]. A study focused on dissimilar materials of austenitic stainless steel to copper and aluminium and the bond shows poor strength on some weld joints due to some accumulation of alloying elements at the interface result of temperature rise and the existence of intermetallic layers by using friction welding method [4,5]. A statistical approach has been conducted for optimum parameters in the dissimilar materials of joining the copper and aluminium materials by friction welding and grey layer was observed at the fracture surfaces of welded parts and thus decreased the strength of the joints [6]. The study of mechanical properties and microstructure of friction welded joint of ductile iron with stainless steel related to the fracture morphology and phase transformations during friction welding [7]. The dissimilar materials of austenitic stainless steel and ferritic stainless steel were studied by different mechanical properties exhibited by friction processed joints which exhibits better properties when compared to the fusion processed joints. The joints exhibited 90–95% of the parent material's tensile strength and the failure obtained in the weld interface region [8]. Sare Celik et al [9] carried out the dissimilar material of AISI 4140 steel and AISI 1050 steel and mechanical properties are investigated. The highest tensile strength developed in the welded specimens is 6% higher than parent AISI 1050 steel and the lowest tensile strength obtained was 1.9% lower than the parent AISI 1050 steel. Sathiya et al [10] compared the friction processed joints to the respective parent materials which exhibits better properties when compared to the fusion processed joints. The problems associated with fusion joining are minimized in friction welding and exhibited 95.52% of parent material's tensile strength.

The joining of stainless steel with dissimilar materials are studied extensively based on strength and metallurgical aspects and good amount of literature are available in friction welding process. However, the joining of austenitic stainless steel and copper material are very limited. In this present work, austenitic stainless steel and copper materials were studied based on its mechanical and metallurgical behaviours of friction welded joints.

2. Experimental Methods

Friction welding machine used is capable of operating with high precision and excellent repeatability of weld parameters. Friction and upset forces are read by a load cell and precisely controlled by a computer. The machine has a stroke of 300 mm and a 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 2500 RPM. The friction welding machine used for this study is shown in fig 1.

Fig.1. Friction welding machine

The base materials of Tension test, hardness test (Table 1) and chemical analyses of austenitic stainless steel and copper (Table 2 and 3) used in present study were performed with test samples of 24 mm diameter and 75mm length were prepared for friction welding experiments. Prior to friction welding, the surfaces were polished using emery papers and cleaned using acetone.

Table 1.Tensile Strength and hardness of parent metals

Mechanical Properties	Austenitic Stainless Steel	Copper
Tensile Strength (MPa)	647	232
Hardness (Hv)	286	82

Table 2. Chemical composition of Austenitic stainless steel

Element	C	Si	Mn	P	S	Ni	Cr
%	0.03	0.39	1.63	0.042	0.027	8.99	19.05

Table 3. Chemical composition of Copper

Element	Cu	Fe
%	99.99	<0.01

In this experimental work, a Taguchi method was selected with a L_{27} (3^4) orthogonal array (27 tests, 4 variables, 3 levels) for the process parameters. The friction welding parameters used in this study are listed in Table 4.

Table 4. Experimental factors and their levels

Factors	Levels		
	1	2	3
Friction pressure (MPa)	22	33	43
Upset pressure (MPa)	65	87	108
Burn-off length, (mm)	1	2	3
Spindle speed, (rpm)	500	1000	1500

The mechanical characteristics were evaluated from tensile tests and hardness tests. Microstructural features of the friction welds were examined by optical microscopy, scanning electron microscopy and energy dispersive analysis of X-rays are investigated to identify the phases that occur at the fractured surface. The friction welding parameters for this study are listed in Table 5.

3. Results and Discussion

3.1. Appearance of joint

Fig. 2 shows the appearance of copper-stainless steel joint. Joint flash was formed at the copper side while the stainless steel side is not fractured. It was also seen that the total length of the specimen decreased with increasing upset pressure.

Fig.2. Friction welded joint (Sample 7)

Table 5. Experimental Levels and Results

Experiments	Friction welding Parameters				Tensile Strength (Mpa)	Vickers Hardness (HV)	
	Friction Pressure (MPa)	Upset Pressure (MPa)	Speed (RPM)	Burn off length (mm)		Copper	Austenitic Stainless Steel
1	22	65	500	1	191	86	257
2	22	65	1000	2	227	83	251
3	22	65	1500	3	177	81	244
4	22	87	1000	1	228	84	252
5	22	87	1500	2	189	82	246
6	22	87	500	3	202	82	256
7	22	108	1500	1	190	84	248
8	22	108	500	2	188	84	258
9	22	108	1000	3	205	82	251
10	33	65	500	1	204	84	252
11	33	65	1000	2	183	81	245
12	33	65	1500	3	205	79	239
13	33	87	1000	1	203	83	247
14	33	87	1500	2	182	81	241
15	33	87	500	3	213	81	250
16	33	108	1500	1	238	83	242
17	33	108	500	2	220	82	252
18	33	108	1000	3	134	80	246
19	43	65	500	1	204	82	246
20	43	65	1000	2	203	80	240
21	43	65	1500	3	238	78	234
22	43	87	1000	1	213	82	242
23	43	87	1500	2	219	80	235
24	43	87	500	3	157	79	245
25	43	108	1500	1	193	81	237
26	43	108	500	2	203	81	247
27	43	108	1000	3	193	79	240

3.2 Tensile properties

The input parameters developed based on Taguchi technique, were used to evaluate the friction welded joints by conducting the experiments. The tensile strength of the weld joints are listed in Table 5. To achieve higher strength, the friction time should be held as short as possible, while the friction and upsetting pressures should be as high as possible [7]. Among all the samples made by friction welding, the sample S18 and S21 are obtained as lowest (157 MPa) and highest (238 MPa) of tensile strength values respectively. Low upset pressure results insufficient time for the material to heat up and bond strength is reduced. The bond strengths were comparable to that of parent material in copper. The highest tensile strength obtained in friction welded joint was 2.52% higher than parent material of copper whose tensile strength was 232 Mpa. The welded sample confirms that all the joints were fractured in copper material as shown in Fig.3. The results of the cold tensile tests performed on the welded specimen showed a relatively ductile manner in tension (Fig.4). This behavior can also be seen from the SEM micrographs of the fractured surfaces (Fig. 5). It shows a dimple pattern in the whole width of the specimen and confirms the ductile mode of fracture.

Fig.3. Macro photograph of tensile tested specimens of (a) ductile fracture in copper and (b) fracture in weld interface

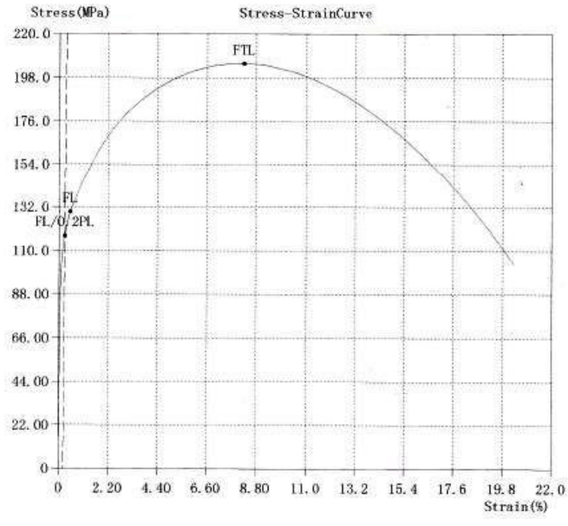

Fig.4. Stress-Strain curve of weld material (Sample 12)

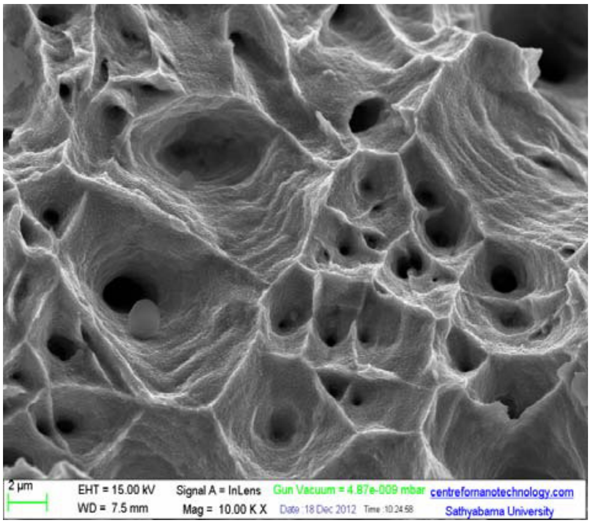

Fig.5. SEM microstructure of the tensile tested fractured surface

3.3 Hardness test

Vickers microhardness measurements were made across the weld on all samples to identify the strength in the three microstructural zones of the weld Base Metal (BM), Heat Affected Zone (HAZ) in austenitic stainless steel (304L) and copper respectively as shown in Fig.6. Vickers microhardness measurements were down in accordance with ASTM E384-09 and ASTM E407-99 standards respectively. A maximum hardness of 258 HV has been obtained near the weld interface in austenitic stainless steel (304L) and 86 HV in copper. In weld zone (WZ) hardness is negligible in both the materials and hence the joining of welded area appears as a straight line. This is due to the different thermal diffusivity of materials and intermetallic layer existing at the interface cause hardness variations [4].

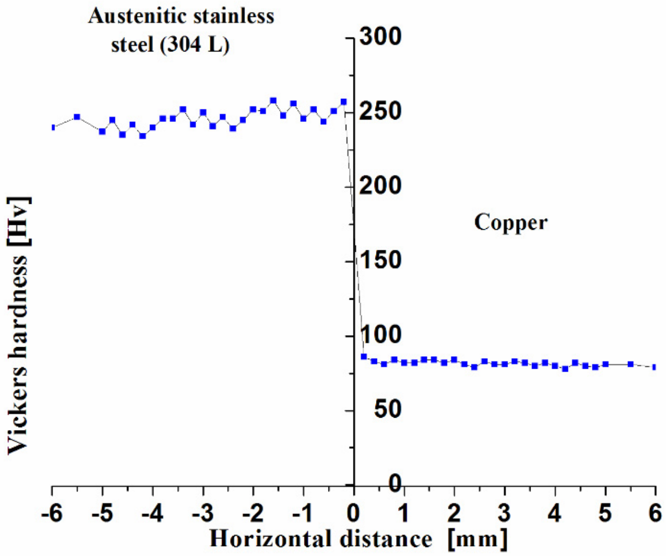

Fig.6. Microhardness profile across the interface on friction welded joints

3.4 Microstructure properties

Samples for optical metallography were prepared by sectioning the welded joint at right angles to the bond-line. The micro-structural examinations were prepared under standard metallographic procedure. The specimens are well polished with different grades of emery paper and etched by 10% oxalic acid. The friction welded samples are examined in the metallurgical microscope and microstructures are analyzed in base metal and HAZ of the two dissimilar materials. In austenitic stainless steel, the parent metal revealed “step” between the grains with annealed twin boundaries present and particles of carbide present in the austenitic matrix (Fig. 7a). In copper, the parent

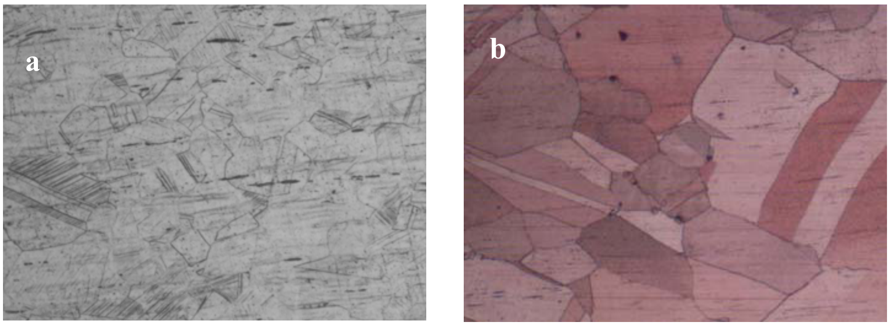

Fig.7. Optical microstructure of (a) parent metal of Austenitic Stainless Steel and (b) Parent metal of Copper

metal (Fig. 7b) shows coarse alpha grains whereas in HAZ the microstructure (Fig. 8b) shows clear visibility of recrystallized alpha grains after friction welding and appears coarser. The grain size in austenitic stainless steel after welding is similar to parent material whereas in copper material indicates fine grains than the parent material (Fig. 8c). Due to fine grains, hardening is increased and structure exhibits copper oxide particles. Constituent elements of both materials had interdiffused through the weld interface, and some intermetallic compounds were formed at the weld interface.

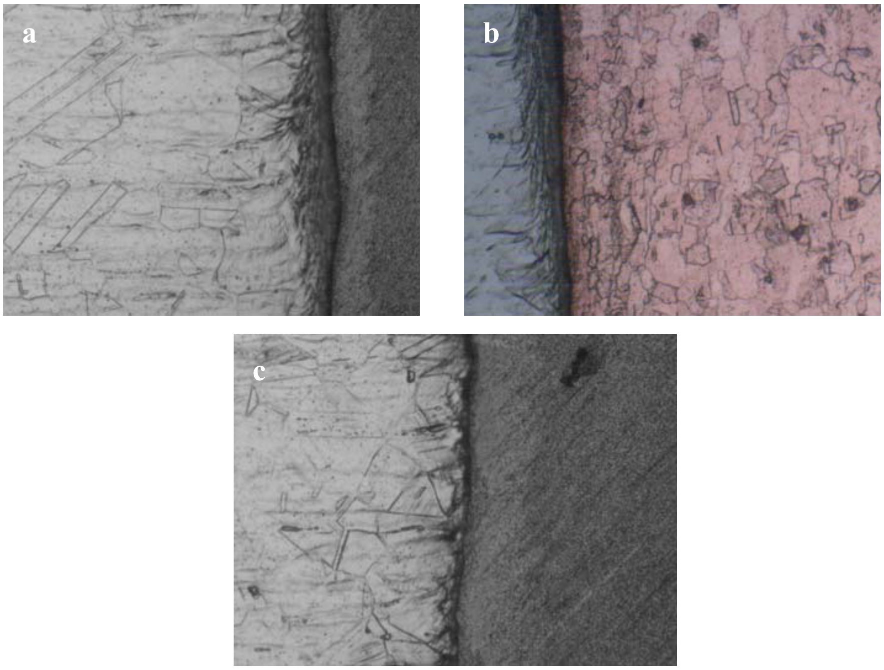

Fig.8. Optical microstructure of (a) HAZ of Austenitic Stainless Steel, (b) HAZ of Copper & (c) Weld zone

3.5 Atomic Force Microstructure

Atomic force microstructure (AFM) is used to study the surface morphology of friction welded joints in dissimilar materials. Atomic force microscopy (AFM) is a powerful technique that can provide direct spatial mapping of surface morphology with nanometer resolution. The optical images were captured by the integrated optical microscope of the AFM. The system was operated in tapping mode using commercial silicon probes. Topographic and phase images were obtained simultaneously using a resonance frequency of approximately 300 kHz for the probe oscillation and a free-oscillation amplitude of 62 nm ± 2 nm. The microstructure of interphase layer in dissimilar material is seen in atomic force microscopy.

Table 6. Roughness values in friction welded joint

Description	Roughness of Austenitic Stainless Steel	Roughness of Copper	Roughness of interphase
Amount of sampling	65536	65536	65536
Max	45.0797 nm	236.748 nm	246.931 nm
Min	0 nm	0 nm	0 nm
Peak-to-peak, Sy	45.0797 nm	236.748 nm	246.931 nm
Ten point height, Sz	22.6247 nm	111.755 nm	123.253 nm
Average	24.3959 nm	53.8834 nm	95.3568 nm
Average Roughness, Sa	5.04006 nm	11.8715 nm	17.9387 nm
Root Mean Square, Sq	6.05847 nm	14.8604 nm	23.2121 nm
Second moment	631.865	3124.25	9631.72
Surface skewness, Ssk	0.0733674	0.681236	0.40583
Coefficient of kurtosis, Ska	-0.418326	3.87967	2.42874
Entropy	7.84309	9.10953	9.73503
Redundance		-0.15587	-0.225748

From Fig. 9, it was found that there is no significant structural change in the interphase region when compared to the parent metal regions. The maximum roughness in the interphase zone has more or less same roughness with the copper. From the roughness graph, it was observed that the difference between average roughness of dissimilar material is very less and negligible in the interphase region. When studying roughness size the parent materials of stainless steel and copper are having peak in the range of 15-35nm and 30-90nm respectively and in welding zone, the peak of interphase region has increased upto the range of 60-130nm.

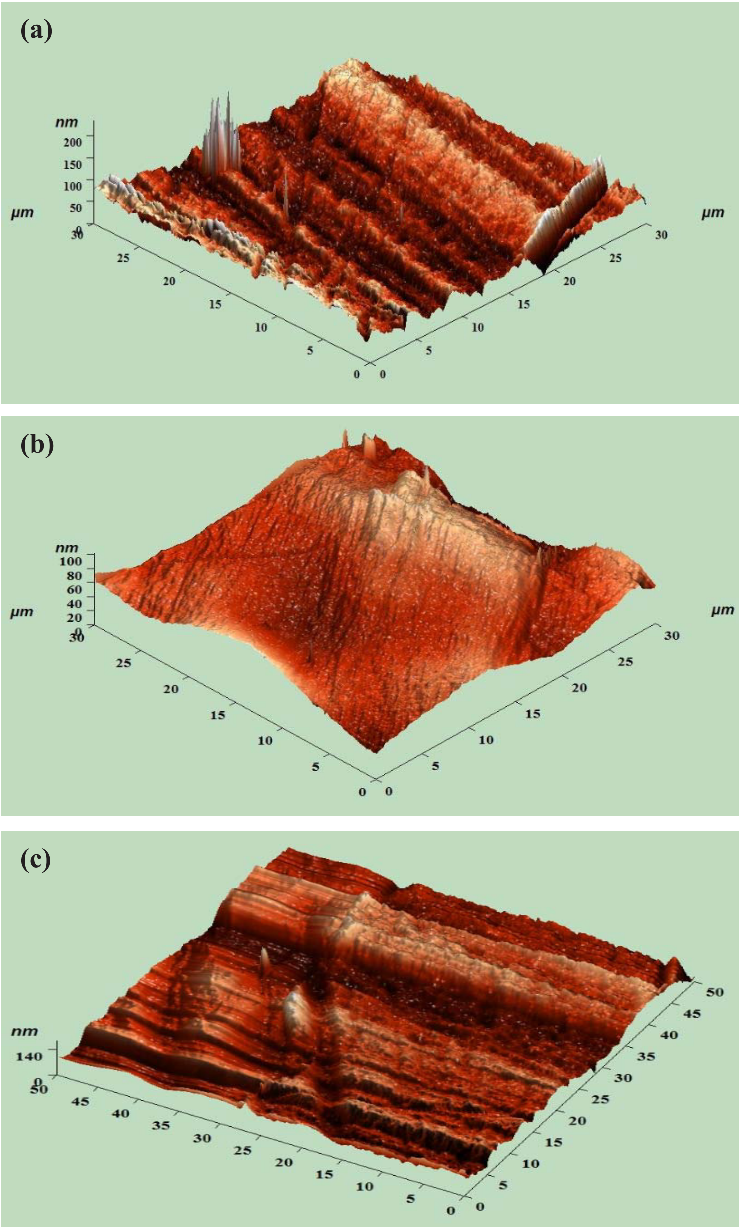

Fig.9. Atomic force microscopy of 3D image in (a) Copper, (b) Austenitic Stainless Steel, (c) Interface

3.6 EDX analysis of joints

Scanning electron microscopy (SEM) and Energy Dispersive Analysis of X-rays (EDAX) analysis were performed in order to investigate the phases that occur at the welding interface. Observations were realized with a 200 kV field effect scanning electron microscope coupled to energy dispersive analysis of X-rays (EDAX) analysis. The software allowed piloting the beam to scan along a surface or a line so as to obtain X-ray cartography or concentration profiles by elements [5,6]. SEM microstructure of the interface region in the friction-welded austenitic stainless steel and copper joint and EDAX analysis results are given in Fig.10, while distributions of elements within the determined location are shown in Table 7.

Table 7. EDAX analysis results according to SEM microstructure

Element	Weight %	Atomic %
O K	3.61	12.90
Si K	0.32	0.65
Cu K	96.07	86.45

EDAX analysis was carried out on the SEM image. The EDAX results confirm that austenitic stainless and copper joints contain some intermetallic compounds. Formation of these brittle intermetallic compounds degrades the strength of the joints.

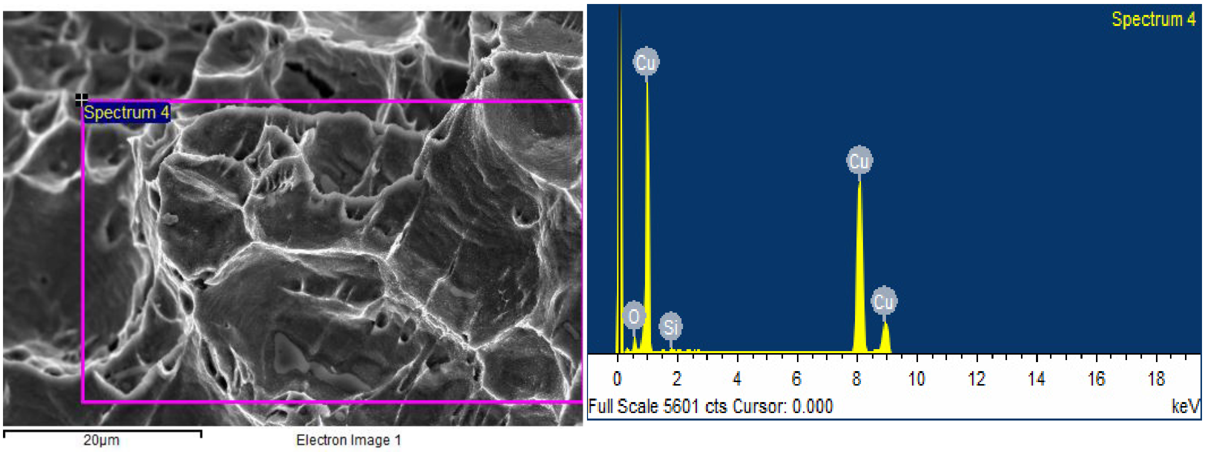

Fig.10. EDAX based on SEM microstructure

3. Conclusions

This study investigates some factors affecting the joint performance of friction-welded joint of austenitic stainless steel to copper and the various tests were carried out to evaluate the joint performance. Based on the results produced through mechanical and micro-structural analysis, the following conclusions were obtained.

- Friction welding has been used to successfully join with austenitic stainless steel and copper. The tensile strength values obtained on joints were varied with three different rotational speeds of 500 rpm, 1000 rpm and 2000 rpm. The bond strengths were comparable to parent material of copper. Strength of the joints obtained was good and ductility was reasonable in copper.
- The welded joint made with the austenitic stainless steel and copper was achieved in nearly all the conditions. The quality and the strength of the bond produced are varied. The use of higher friction pressure with low upset pressure increases the tensile strength of friction-welded joint whereas with lower friction pressure and high upset pressure results decrease in joint of dissimilar material.

- The highest tensile strength obtained in friction welded joint was 2.52% higher than parent material of copper whose tensile strength was 232 Mpa. Joint strength increased and reached a maximum, and then decreased again as the friction pressure increased. A longer friction time causes the excess formation of an intermetallic layer. However, some of the welds show poor strength depending on some alloying elements at the interface result of temperature rise and the existence of intermetallic layers.
- When studying roughness size, the peak of interphase region has increased upto the range of 60-130 nm which is more or less similar to the parent material of copper in the range of 30-90 nm.
- The hardness shows higher in parent metal than in HAZ of stainless steel material.

References

[1] Ananthapadmanaban.D, Seshagiri Rao.V, Nikhil Abraham, Prasad Rao.K, “A study of mechanical properties of friction welded mild steel to stainless steel joints”, Materials and Design 30 (2009) 2642-2646.
[2] Dunkerton SB. Toughness properties of friction welds in steels. Weld J 1986; 65(8):193s–202s.
[3] Jayabharath.K, Ashfaq.M, Venugopal.P, Achar.D.R.G, “Investigations on the continuous drive friction welding of sintered powder metallurgical (P/M) steel and wrought copper parts”, Materials Science and Engineering A, 454-455 (2007) 114-123.
[4] Mumin Sahin, “ Joining of stainless steel and copper materials with friction welding, Industrial Lubrication and Tribology, 61/6 (2009) 319–324
[5] Mumin Sahin, “Joining of stainless steel and aluminium materials by friction welding”, Int.J.Adv.Manuf Technology (2009). 41:487-497.
[6] Mumin Sahin, “Joining of aluminium and copper materials with friction welding”, Int J Adv Manuf Technol (2010) 49:527–534
[7] Radosław Winiczenko, Mieczysław Kaczorowski, “Friction welding of ductile iron with stainless steel”, Journal of Materials Processing Technology, Volume 213, Issue 3, March 2013, Pages 453-462
[8] Sathiya.P, Aravindan.S, Noorul Haq.A, “Effect of friction welding parameters on mechanical and metallurgical properties of ferritic stainless steel”, Int.J.Adv.Manuf Technology (2007). 31: 1076-1082.
[9] Sare Celik, Ismail Ersozlu, “Investigation of the mechanical properties and microstructure of friction welded joints between AISI 4140 and AISI 1050 steels, Materials and Design 30 (2009) 970–976
[10] Sathiya.P, Aravindan.S, Noorul Haq.A, “Some experimental investigations on friction welded stainless steel joints”, Materials and Design 29 (2008) 1099–1109