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Characterization of Metallurgical and Mechanical Properties of Commercially Pure Copper and AISI 304 Dissimilar Weldments

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Abstract

This research work presents mechanical and metallurgical investigations on commercially pure copper and austenitic stainless steel AISI 304 dissimilar joints produced by shielded metal arc welding. The effect of three different electrodes: Inconel (ENiCrMo3), Monel (ENiCu7) and stainless Steel (E316L) on this bimetallic combination were evaluated. Mechanical and metallurgical investigations were carried out on the welded joints. Various microstructures like equiaxed, columnar, cellular dendritic and delta ferrites were observed in the various zones of the weldments. Vickers microhardness plots showed that the CP-copper HAZ had the least hardness. Minimum strength requirement was met by joints produced by all the electrodes. Due to grain coarsening effect in the heat affected zone of CP copper all the weldments fractured in this region. SEM tensile fractographs revealed ductile modes of fracture in all weldments. Joint with ENiCrMo3 electrode showed the maximum strength and that with ENiCu7 electrode showed the least strength.

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Keywords: Shielded metal arc welding; CP-copper; AISI 304; dissimilar weldments.

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1. Introduction

Welding of dissimilar metals is of high priority in industries as it helps in achieving certain service requirements and cost savings by replacing the expensive materials with cheap ones. Primary requirement to have metallurgical bond between two dissimilar metals is the mutual solubility between them. Selection of an electrode material which is soluble with both the base materials is one of the major challenges in dissimilar welding. Dissimilar material welding is difficult compared to similar materials owing to the difference in their chemical and thermal properties as reported by Devendranath et al. (2012). The difference in chemical composition of the materials to be joined causes solubility problems. The thermal expansion coefficient mismatch of the two materials to be welded could result in failure of the joint due to thermal fatigue. The difference in thermal conductivity and melting point of the materials to be joined causes melting of one material before the other one melts and it causes lack of fusion defects. In such case material with higher thermal conductivity should be preheated prior to welding as performed by Sajjad et al. (2012) in their research on GTAW of AISI 304-CP Copper.

Austenitic stainless steel AISI 304 is a commonly used grade of stainless steel. One of the prime problems of AISI 304 is the poor heat dissipation during high temperature service leading to formation of undesirable phases which adversely affects their properties. By joining copper, which has good thermal conductivity with stainless steel heat dissipation can be improved. This in turn prevents the formation of undesirable phases like the sigma phase and chromium carbide precipitation.

The selection of compatible filler material plays a crucial role in fusion welding of CP-copper and stainless steel. Inappropriate filler materials can lead to defects like hot cracking, porosity, lack of fusion, shrinkage, decreasing tensile strength as indicated by Sajjad et al. (2012). Dissimilar metal welding involving copper and stainless steel 304 finds application in the field of food processing, vessel industries to utilize high strength and corrosion resistance of stainless steel with high electrical and thermal conductivity of copper as pointed out by Durgutlu et al. (2005). AISI 304- CP copper joint could have potential application in the field of heat transfer devices as mentioned by Magnabosco et al. (2006). However studies on the performance of such weldments are not common.

Velu et al. (2013) suggested that Nickel based electrodes are better than bronze electrode in joining copper (UNSC11000) and alloy steel by Shielded Metal Arc welding SMAW. Defects like hot cracking and porosities were encountered when bronze electrode was used. Improved mechanical properties combined with good solid solubility with copper and iron makes nickel based electrodes a favorable candidate. Mai and Spowage (2004) were not successful in achieving complete metallurgical bond between laser welded copper and steel owing to high reflectivity and conductivity of Copper. Yao et al. (2009) succeeded in achieving a complete metallurgical bond by employing special scarf joint butt design and laser beam focusing on steel side. Authors suggested that amount of copper dissolved in molten steel should be limited to produce a defect free joint.

Magnabosco et al. (2006) in their studies on Electron Beam welding of copper to austenitic stainless steels analyzed that microstructure of the joint was found to be characterized by a mixture of two non equilibrium phases, one rich in copper and the other rich in austenite with Fe, Cr and Ni. They reported that this was due to low solubility between iron and copper in the solid state. Steel globules and dendrites embedded in a copper matrix and areas of austenite matrix containing globules of copper were found in the microstructure due to different melting temperatures and steep concentration gradients. Defects like voids due to some of the problems like shrinkage of copper trapped inside the solidified steel and micro fissures due to embrittlement resulting from the copper grain boundary wetting and thermal stresses were found in the weld.

From the literature available, various researchers have attempted to join stainless steel and copper using techniques like tungsten inert gas welding, laser and electron beam welding processes. It is evident from the literatures that these dissimilar joints posses a very challenging task even with high energy beam process like electron beam welding. Shielded Metal Arc Welding (SMAW) is one of the most economical and commonly used methods in industries and has its own advantages than the latest joining techniques. Also SMAW process is an on-site process unlike other methods and it can also be used for repair works.

Research works related to employing SMAW for joining copper and stainless steel is not available in the open literature. So an attempt was made to investigate the weldability of CP copper to Stainless steel dissimilar combination using SMAW. Also the effect of three different electrodes on the mechanical and metallurgical properties of dissimilar combination of AISI 304 with CP-copper was analyzed.

2. Experimental Procedures

2.1 Welding

The candidate materials AISI 304 and CP copper plates of thickness 3mm was cut to a dimension of 150 × 50 mm. The edge of the plates to be joined was machined to an angle of 30^0. Prior to welding the surfaces were thoroughly cleaned with emery sheet and acetone. Three different consumable electrodes Inconel (ENiCrMo3), Monel (ENiCu7) and Stainless Steel 316 (E316L) were used. The Chemical compositions of base and electrodes are shown in Table. 1. For accurate gripping and alignment of the parts to be welded a rigid fixture was made with a copper backing plate. Single V butt joint with an included angle of 60^0 with a root gap of 2.4 mm was employed .Copper was preheated to about 200^0 C for 5 minutes to minimize heat dissipation during welding owing to its high thermal conductivity . Two passes, a root and cap were done for all the joints. Process parameters used for welding are given in the Table. 2. The weldments were visually examined in the as welded condition for any visible defects. The as welded samples are shown in Fig. 1.

Table. 1 Chemical composition of base and filler materials.

	Chemical Composition (% by Weight)									
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe
AISI 304	0.04	1.70	0.48	0.016	0.005	19.55	8.23	0.3	0.7	68.98
Copper	-	-	-	0.001	0.002	-	0.002	-	99.99	0.002
ENiCrMo3	0.03	0.5	0.2	-	-	21.5	65	9.00	0.5	2.00
ENiCu7	0.1	3	1	0.02	0.015	-	62	-	30	1.00
E 316L	0.05	1.65	0.45	0.015	0.003	18.5	9.20	2.70	0.45	66.98

Table. 2 Process Parameters employed for the dissimilar welding of AISI 304 and CP-copper

Electrode	Current (A)	Voltage (V)	Electrode Dia. (mm)
E316L	111	31	3.2
ENiCu7	111	28	3.2
ENiCrMo3	110	29	3.2

2.2 Macro and Micro structure Examination

For the macro examination the samples were cut from the dissimilar joints which include 5 regions: weld, HAZ and base of both the parent metals. Cross sections of dissimilar weldments were metallographically prepared using special operating procedures owing to difficulty in preparation of microstructure samples of dissimilar joints. It includes polishing with SiC emery sheets from 220 to 1000 grit size followed by velvet cloth disc polishing with alumina and water. The parent and heat affected zone of AISI 304 and the weld metals of ENiCrMo-3, ENiCu7 and E316L is etched using acetic glyceregia (15 ml HCl +10 ml HNO_3 +10 ml CH_3COOH+ 2 drops of glycerol) and aqua regia (15ml HCl +5ml HNO_3). Marbles reagent (10 grams $CuSO_4$ +50 ml HCl + 50 ml water) was used for etching the parent and heat affected zone of copper. The etched samples were viewed in macroscope for macrostructure and examined in optical microscope for microstructural analysis at various zones of the weldments.

2.3 Tensile testing

Transverse tensile specimen of rectangular cross section was machined from the welded joint using wire electrical discharge machining. Tensile samples were prepared as per ASTM E8-11 standard. The gauge length of the specimen was 35 mm and with a cross section 6 mm x 3 mm. Three samples were tested for each weldment to ensure the repeatability. Tensile test was done using INSTRON 8801 universal testing machine at room temperature. A strain rate of 0.5 mm/min was applied during the tensile test. Analysis of the fractured surface morphology was done using a Scanning Electron Microscope (SEM). Two images were captured for each sample at 1500X and 6000X magnification.

2.4 Micro Hardness testing

The hardness test was done using Matsuzawa micro vickers hardness tester over the entire cross section covering all the 5 zones. A load of 200 g was applied on the CP-copper side and 500 g for the rest of the region with a dwell time of 10 seconds. The hardness is measured at every 0.25 mm at a distance of 1.25 mm from the weld root.

3. Results

3.1 Visual Examination

On visual examination of the welded sample it was observed that ENiCrMo3 weldment showed a bead of good quality (Fig. 1a). The weld with ENiCu7 is observed to be equally good with some spatter (Fig. 1b). In the case of E316L weld porosity was visible in the weld bead (Fig. 1c).

3.2 Macrostructure

From macrostructure examination of the weld cross section which is shown in the Fig. 2a-c it is found that the joints produced with ENiCrMo3 (Fig. 2a) had good side wall fusion and good penetration. In ENiCrMo3 weld, width of the weld zone stretch uniformly along both sides of the base metals which shows equal melting of both the base metals. The weldment made from ENiCu7 (Fig. 2b) also showed good side wall fusion with some acceptable root undercut. The fusion area and width are different for E316L joint (Fig. 2c) due to difference in solubility of the electrode with copper which resulted in poor side wall fusion.

Fig. 1. As welded sample of AISI 304- CP copper using three different filler materials, (a)ENiCrMo3, (b)ENiCu7 and (c)E316L

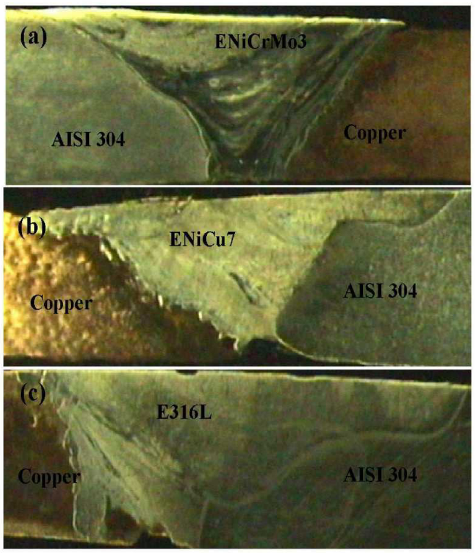

Fig. 2 Macrophotographs of dissimilar welded AISI 304 and CP Copper with three different filler materials, (a)ENiCrMo3, (b)ENiCu7 and (c)E316L

3.3 Microstructure

The microstructure of the base materials is shown in the Fig. 3. A mixture of fine and coarse grains was observed in the microstructure of copper as witnessed in Fig. 3a. Austenitic grain microstructure is observed in AISI 304 base region as shown in Fig. 3b.

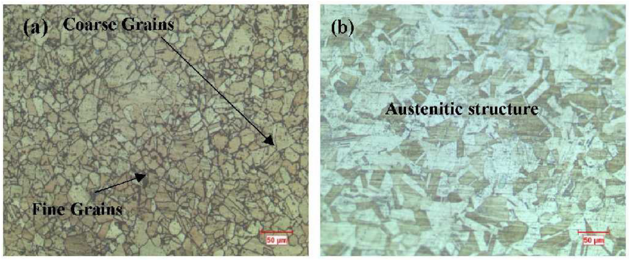

Fig. 3 Microstructure of the base materials at different magnification
(a)Cu 200x, (b)AISI 304 200x

The microstructure of joints made with ENiCrMo3 and ENiCu7 electrodes are shown in Fig. 4 and Fig. 5 respectively. A prominent unmixed zone as reported by Baeslack et al. (1979) is formed in the weld interface due to partial melting and recrystallization of small portion of base metal during welding. This exists as a laminar layer in ENiCrMo3 weld between AISI 304 base and the weld metal (Fig. 4f). Unmixed zones were also identified in the CP copper- ENiCu7 interface (Fig. 5a) and Copper- E316L interface (Fig. 6b).

Dendrite formation is observed in the weld metal which may be due to the diffusion of Ni, Cr, Cu and Fe resulting in formation of intermetallic compounds as reported by Devendranath et al. (2012). This formation is present in case of both ENiCrMo3 and ENiCu7 electrodes. Cellular grain structure was observed in the weld metal made with ENiCrMo3 and ENiCu7 electrode in the root region (Fig. 4d and Fig. 5b). The weld centre and the face region has predominantly equiaxed dendritic structure in ENicrMo3 (Fig. 4d-e) whereas, it is predominantly columnar structure along with meagre amount of equiaxed dendritic structure in ENiCu7 (Fig.5d-e). Similar weld microstructure is reported by David et al. (2003).

Microstructure at various zones of the weldment made with E316L electrode is shown in the Fig. 6. Copper globules were seen in the fusion zone in the Copper- E316L weld interface. This is in line with Yao et al. (2009). δ ferrite stringers was observed in austenitic grain boundaries of the AISI304-E316L interface(Fig. 6e-f) in line with Gill et al. (1979). The weld zone of E316L shows a cellular structure in the weld centre (Fig. 6c) and a primary dendritic structure in the weld root (Fig. 6d).

A coarse grain structure was observed in the heat affected zone (HAZ) of AISI 304 and CP copper near the fusion zone. Lengths of HAZ in all weldments are measured using clemex image analyser software. The length of the HAZ of CP copper and AISI 304 base was observed to be higher near the root of the weld compared to face in all the cases which is shown in Table 3. Weldment made with 316L has the maximum heat affected zone compared to the other two weldments.

3.4 Microhardness

The Cumulative micro hardness plots are depicted in Fig. 7. It is observed from the plots that the average hardness of weld zone with ENiCrMo3 electrode was higher (225 HV) than those of the base materials. A peak value is observed in interface AISI 304 and ENiCrMo3 may be due to the presence of precipitates. The peaks observed in the AISI 304 base region may be due to the presence of carbide precipitates. The hardness of the HAZ of copper is less compared to the copper base. In the case of ENiCu7 the average hardness of the weld zone (203 HV) is comparable with the hardness of AISI304 base material. Hardness value in the HAZ of copper was also found to be less than the CP copper. The average hardness value of 167 HV was obtained in the E316L weld.

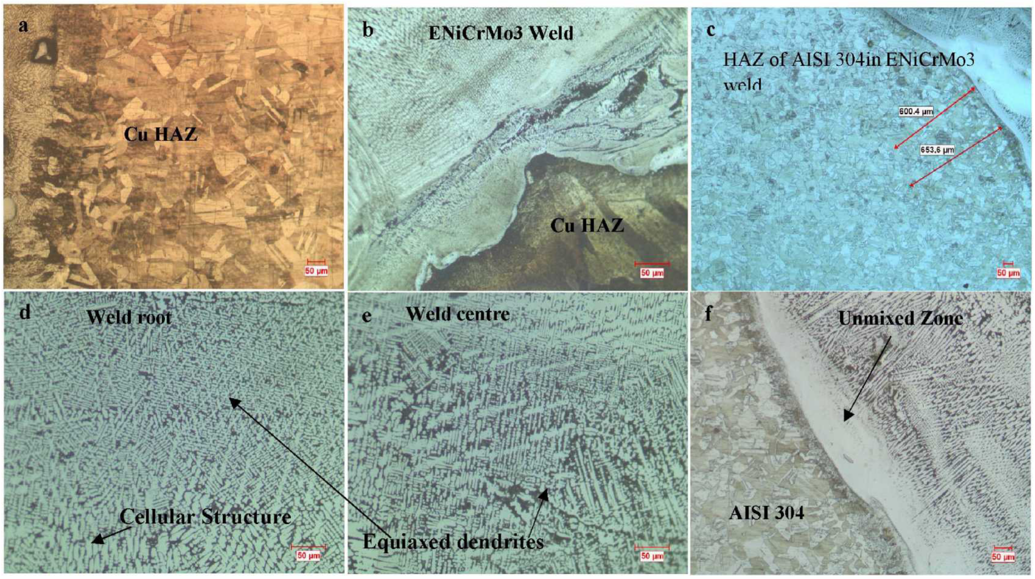

Fig. 4 Micro Structures at interfaces of Cu, AISI304 and weld region using ENiCrMo3 filler.

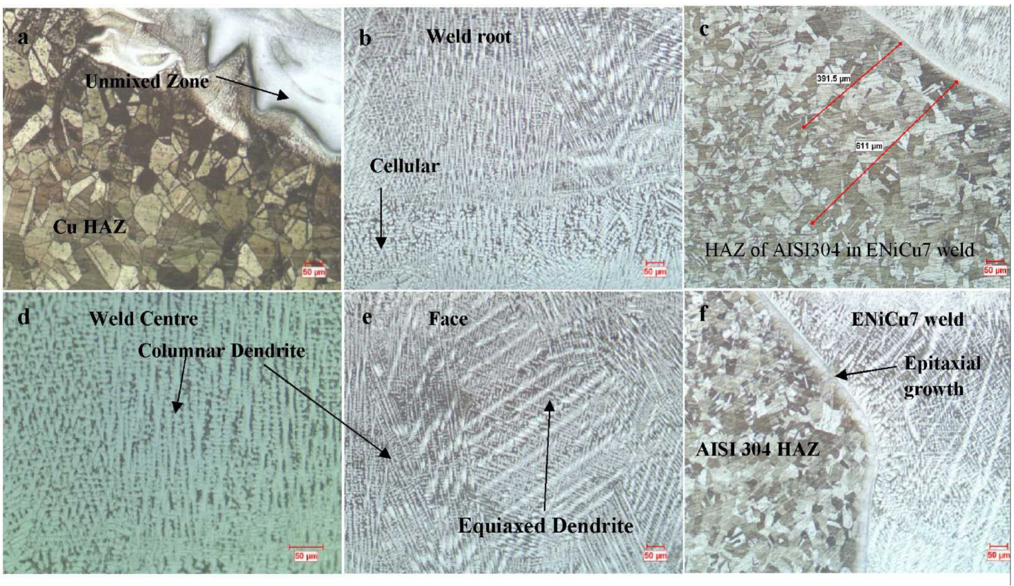

Fig. 5: Micro Structures at interfaces of Cu, AISI304 and weld region using ENiCu7 filler.

Table. 3 Length of HAZ of the Copper and AISI 304 when welded with three different filler materials.

Filler Material	HAZ of Copper	HAZ of AISI 304
ENiCrMo3	1258 µm	653.6 µm
ENiCu7	711.8 µm	918 µm
E316L	3193 µm	1318 µm

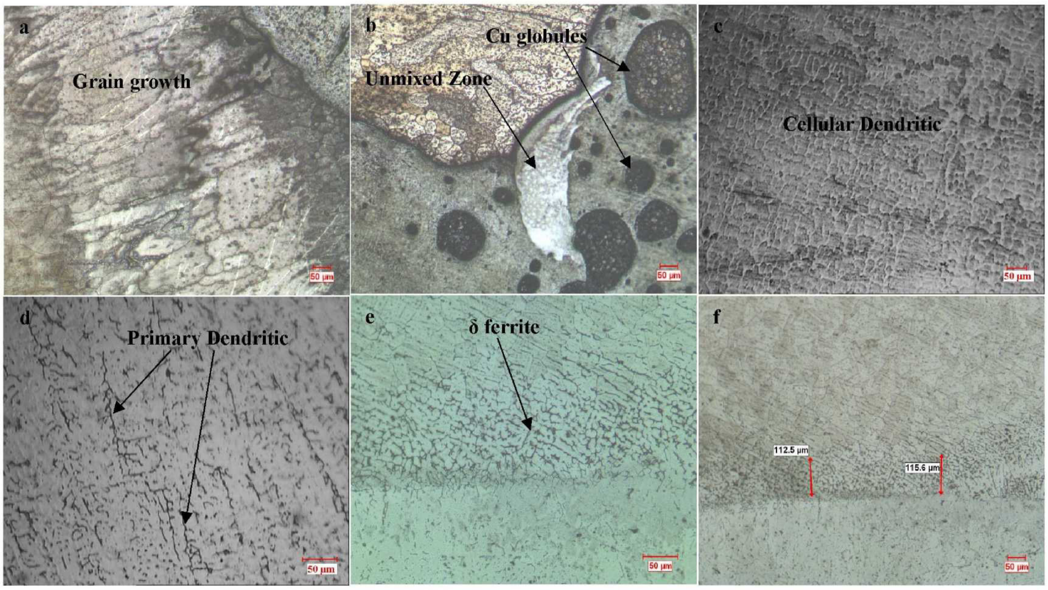

Fig. 6 Micro Structures at interfaces of Cu, AISI304 and weld region using E316L filler.

Hardness at the weld zone with E316L was found to be less than that of the AISI304 base. In all the weldments a drop in hardness values was witnessed from the weld zone to the HAZ of CP Copper.

3.5 Tensile Properties

The specimen for the tensile test is shown in Fig. (8a-c). The fractured specimens are shown in Fig. (8d-f). And their cumulative tensile properties are listed in Table. 4. Comparison of tensile strength and percentage of the dissimilar weldments and base materials are shown in Fig. (9a-b) respectively. For all the weldments fracture occurred in the heat affected zone of copper. The strength of the weldments was found to be 319, 258 and 273 MPa for ENiCrMo3, ENiCu7 and E316L electrodes respectively. SEM fractorgaphs for all the samples are shown in Fig. 10. It is observed from the SEM images that all the weldments has micro voids, dimples with fibrous network showing that the mode of failure is ductile.

4. Discussion

From the macrostructure analysis of weldments it was found that ENiCrMo3 showed good side wall fusion with full penetration compared to the other two weldments. The side wall fusion and penetration of ENiCu7 was comparatively better than the E316L.

From the microstructure analysis it was observed that for all the three specimens a well defined boundary exists. Unmixed zones formed by melting and recrystallization of base metal in the interfaces are due to the considerable difference in chemical composition of base metal and weld metal. For both ENiCrMo3 and ENiCu7 the cellular structure in the root region of the weld metal is due to the high heat concentration in the area. The change from cellular to equiaxed dendrite from weld root to weld face may be due to the increase in growth velocity towards the centre of the weld.

Copper globules observed in the interface of copper and E316L interface could be due to the steep concentration gradient and lesser melting point of copper compared to stainless steel. This makes stainless steel to solidify faster

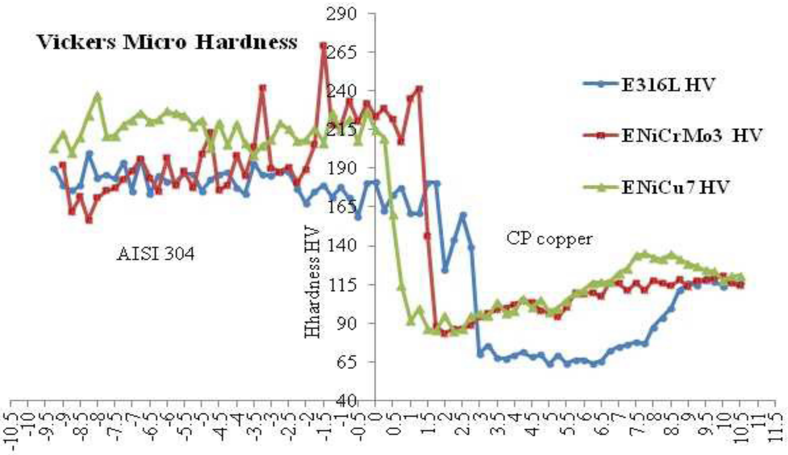

Fig. 7 Vicker's Microhardness for the dissimilar welded CP Copper and AISI 304 with three different filler materials

Table. 4 Cumulative mechanical properties of the dissimilar weldments

Electrode	Max. Load (N)	UTS (MPa)	% Elon at Break (%)	Max. Hardness at Weld (HV)	Fracture Zone	Mode of failure
ENiCrMo3	5238.94	319.5	7.81	241.4	HAZ of Cu	Ductile
ENiCu7	3633.73	258	7.43	226.6	HAZ of Cu	Ductile
E316L	4540.09	273	16.01	181.0	HAZ of Cu	Ductile

than copper in the molten pool. The presence of δ ferrite in the HAZ of AISI 304 is due to the weld pool solidification as primary ferrite which has eliminated the HAZ solidification cracking. The presence of δ ferrites in the E316L weld has resulted in eliminating the problems like micro fissuring and hot cracking. In addition to that, it also helps to increase the strength of the weldment.

The lesser length of HAZ in ENiCrMo3 and ENiCu7 electrode joints compared to E316L joint shows that parent metals of the former are less affected by heat of welding. Length of HAZ for this interface is observed to be very high compared to the HAZ of copper in other two joint interfaces.

Investigation of structure property relationship revealed the decrease in hardness in the HAZ of the weldments is due to the coarse grained structure. High temperature involved and slow cooling rate in SMAW process resulted in the formation of coarse grains. The higher hardness value attained in the HAZ of ENiCrMo3 and ENiCu7 weldments compared to E316L is due to less grain coarsening than in E316L weld.

The equiaxed structure predominant in the ENiCrMo3 weld gives higher strength (319 MPa) and hardness to the weldment compared to the other two. The lower strength (258 MPa) and hardness of the ENiCu7 weld is due to the domination of columnar structure over the equiaxed structure and also from the fractographs it is evident in few regions of the fractograph of ENiCu7 intergranular fracture pattern was observed. E316L weld attained a better strength (273 MPa) higher than ENiCu7. This may due to the presence of δ ferrite and cellular structure in weld interface. The fracture occurred in the HAZ of copper in the case of all the welds which shows that the weld have achieved a better strength than the copper base.

The fractographic analysis also shows ductile fracture mode characterized by fibrous network. Some precipitates are observed in the dimples of the fractured region. Numerous dimples in ENiCrMo3 and E316L fractograph indicates that the specimen have undergone a large plastic deformation before fracture. ENiCu7 shows less number of dimples which indicates less ductility of the material Due to the intergranular fracture this weld exhibited least ductility among the three. Ductility of copper is considerably reduced due to the formation of precipitates as observed in fractographs.

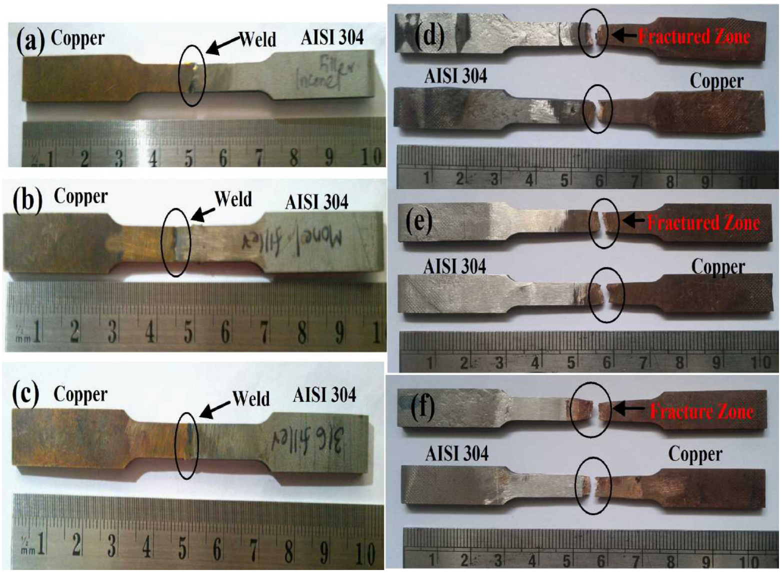

Fig.8 Tensile test on the dissimilar welded CP Copper and AISI 304 using three different filler materials. Figure shows the specimen before and after fracture. (a, d)ENiCrMo3, (b,e) ENiCu7 and (c,f) E316L.

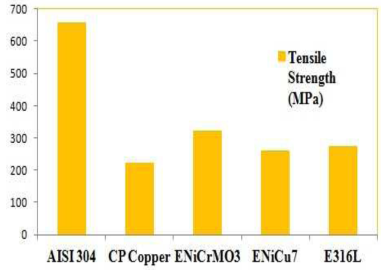

Fig. 9a Comparison of weldment strength with the base.

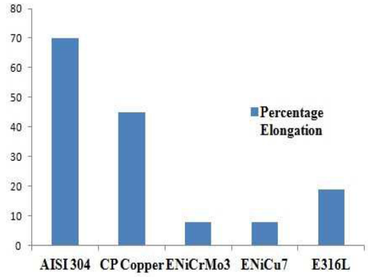

Fig. 9b Comparison of % Elongation of weldments with the base.

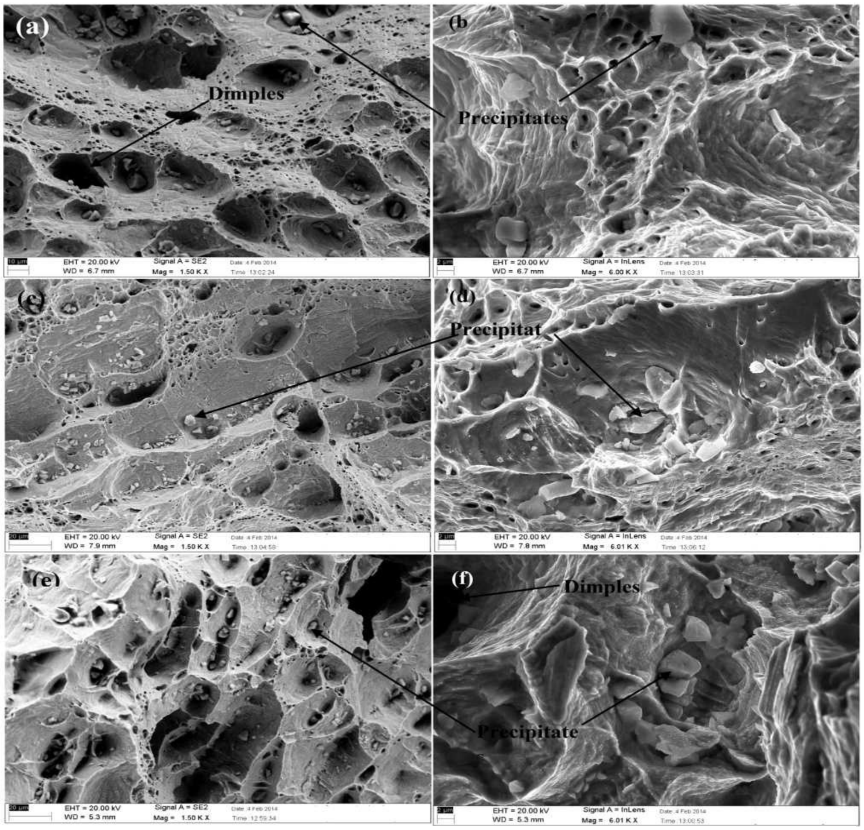

Fig. 10: Fractograph of the dissimilar SMA welded Copper and Stainless steel 304 using different filler material at two magnifications, (a,b) ENiCrMo3, (c,d) ENiCu7 and (e,f) E316L

5. Conclusion

On the basis of this investigation, the following conclusions can be drawn.

- All the three electrodes have produced weld joints which meets the minimum strength requirement of this dissimilar joint.
- The presence of equiaxed structure, high hardness in the ENiCrMo3 weld zone and complete fusion has resulted in the better strength in this weldment.
- Considerable strength and ductility was shown by the E316L weldment even though some defects like porosity and copper globules were observed in the weld interface of AISI 304 HAZ.
- Weld joint made of ENiCrMo3 showed the maximum strength followed by E316L andENiCu7.
- Failure has occurred in the HAZ of CP-copper in all the weldments.
- It can be concluded from the tensile fractographs that all the weldments has undergone ductile mode of failure.
- Ductility of all the welded joints was less than that of the copper base due to the grain growth. Percentage elongation (16.01%) observed in E316L was much higher compared to that of ENiCrMo3 (7.81 %).
- Inconel (ENiCrMo3) electrode has produced a weld joint with good fusion and better strength compared with the other electrodes and is found most suitable to join these bimetallic joints and is recommended for the industrial practice.

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