JOINING OF Cu TO SS304 BY MICROWAVE HYBRID HEATING WITH Ni AS INTERLAYER

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Abstract

Joining of dissimilar pure Copper (Cu) to Stainless Steel (SS304) is necessitated in many industrial applications such as heat exchangers and electrical contacts. Advantages of both the materials such as high electrical conductivity of copper and better corrosion resistance of SS304 can be harnessed by way of joining both the metals. However, joining to Cu to itself or other materials is a challenge since the input heat is dissipated rapidly. Most of the conventional welding methods such as arc and gas are incompetent and unconventional methods such as Explosion Welding, EBW, and Diffusion Bonding are very expensive.

In this study a new economical process of joining of dissimilar metals i.e. Cu to SS304 by microwave hybrid heating is investigated. Microwave joining is made possible by applying a powder (in this work, Nickel metal powder) as an interlayer and exposing to microwave surrounding the interlayer with a susceptor.

The interlayer of Ni powder having average size 200nm and 45μm was used. The microstructure of the joint was studied by optical microscope and scanning electron microscope. The joints formed with 200nm Ni powder were observed to have a defect free microstructure. The EDS and XRD analysis determine the formation of solid solution between Cu-Ni interface and an intermetallic compound at Fe-Ni interface. The diffusion of elements across the joint was further analyzed by EDS line scan. The hardness variation was studied by Vickers' micro-hardness. It can be concluded that smaller size Ni heats up faster in microwave and produce stronger joint of Cu to SS304 by microwave hybrid heating.

Introduction

Dissimilar material joining is gaining interest nowadays due to the application potentials in terms of flexibility, functionality and energy savings. Different industries such as chemical, nuclear, automobile, rail, aviation, electronics and power have requirements for dissimilar material joining. Many difficulties that occur during dissimilar joining are due to the difference in mechanical, thermal and electrical properties of the materials to be joined. Failures to join dissimilar combinations are due to the difference in thermal expansion coefficients, fusion zone (FZ) solidification or thermal fatigue. Bimetallic corrosion may also occur. Hence, it is difficult to fabricate dissimilar material combinations using conventional welding methods like Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), and Submerged Arc Welding (SAW) etc. There are other methods for making dissimilar joints such as explosive welding, laser welding, electron beam welding, diffusion bonding, brazing, soldering and friction welding. These methods follow stringent processing conditions, and are expensive and time consuming. Faster processing method is always the necessity of the industry owing to energy saving and improved productivity.

Microwaves are the part of the electro-magnetic spectrum having wavelength between 1m to 1mm for frequencies ranging from 300MHz to 300GHz. Faster and selective heating and energy saving are the well-known advantages of microwave processing [1]. The molecules interact with the microwaves and coverts the microwave energy to heat energy. Due to this, the materials heat up faster compared to conventional heating. On the other hand, in conventional heating the convection, conduction and radiation help in heating a sample from outside to inside. Microwave heating is used in the past for a number of applications such as heating fruits, beans, meat and cooking food. It is also used in other industries to dry paper, tobacco, leather, textiles, ceramics, cure adhesives, vulcanise rubber, waste management and etch semiconductors[2] and in processing of ceramics, polymers and metals[3].

It is a well-known fact that metals reflect back most of the incident microwaves and penetration depth is limited to some microns. But when metals are used in powdered form it will heat up when subjected to microwave due to its small particle size being nearly equal to the penetration depth [4],[5]. The heating metal powders by microwaves was first reported by Walkiewicz et al [6] of heating Mg, Fe upto 120°C and 768 °C respectively. Later Roy et al [7] in 1999 conducted sintering to obtain full density components from metal powders with the formation of finer microstructures. This had resulted in better properties at lower cost.

Joining by microwave hybrid heating of similar bulk metals have been done by some researchers [8]–[15]. Limited work on dissimilar metals has been reported i.e. Srinath et al [16] joined Stainless steel to mild steel and Bansal et al [17] joined Inconel718 to SS316L.

The joining of copper and stainless steel can be used in many applications like in heat exchangers where corrosive fluids are used. The high conductivity of copper is a boon and a bane when it is to be joined with other material. Hence many problems are to be surpassed when welding copper to stainless steel. Tungsten inert gas (TIG) welding of copper is a challenge due to its high conductivity since all the heat generated is dissipated towards the base metal very fast. Copper has low miscibility with iron and no intermetallic compounds are expected. With preheating, TIG welding of the Cu and SS sheet is possible but with non-homogeneous joints, owing to resolidification time[18]. The high cooling rates in TIG and Electron beam welding cause bulk cooling of the molten pool. The molten metal solidifies to form Fe rich spherulites embedded in ε-Cu matrix and Cu rich spherulites embedded in α-Fe matrix [18]. These phases will tend to transform to equilibrium microstructure on application of thermal stress during service life, thereby affecting the mechanical and corrosion properties of the joint [19]. Magnabosco et al [20] confirmed the formation of non-equilibrium phases which are rich in Cu and Fe with Fe–Cr–Ni phase. The porosities in the copper-rich phase is due to the shrinkage of copper from inside the steel globule and intergranular microfissures at the interface towards the stainless steel are reported.

Diffusion welding was used to join Cu to SS304 by Yilmaz et al [21]. Micro-voids are seen along the grain boundaries on the Cu side of the bond region and it also has microcracks. Fracture can be observed at the microvoids on the copper side rather than the interface of Cu to SS. It is also reported that there is a thick band of intermetallic compounds formation. This is the limitation of the diffusion bonding process that leads to reduced joint strength. Using the same diffusion bonding process with nickel as an interlayer Sabetghadam et al [22] reported voids at both interfaces, that were of corrugated pattern. Intermetallic compounds were formed and its extent increased with temperature.

Explosion welding of Cu and stainless steel enhanced the tensile shear strength and flexural strength of joints [23]. Intermetallic compounds are not formed at the interface but the hardness is increased due collision of two plates. This process faces the limitation of being expensive and the lack in joint configuration flexibility. Moreover, it can be applied

only to lap joint. Friction welding is another process used for joining copper to Stainless steel but this too is limited only to joining of cylindrical work piece. Sahin [24] reported that the tensile strength of joint to be proportionally dependent on friction time and friction pressure until a certain point (75 MPa) after which intermetallic compounds were observed to be formed at prolonged friction time.

By assembling a slope butt (scarf assembly) joint and focussing the laser on the steel side Yao et al [25] achieved joint of Cu to SS with good tensile strength. Defect free joints can be obtained when limited copper is dissolved in steel matrix.

Hence it can be observed that there is a need of a joining process that can give good metallurgical joint with flexibility in joint configurations. Joining of Copper to Stainless Steel using microwave hybrid heating followed by analysis of the joints are presented in the subsequent sections.

Materials and Methods

Stainless steel SS304 and pure copper plates were cut into small section 6mm x 7mm x 25mm. Pure Nickel powder of average size 45µm and 200nm was mixed with 20 wt% epoxy resin (bisphenol A diglycidyl ether) to form a slurry. The joint prepared was a simple lap joint with the prepared slurry in between as interlayer and clamped by a force ~15MPa as observed in previous work [26]. A graphite crucible is placed inside a multimode microwave oven with 2.45 GHz frequency and 3200W power rating with the power set to 40%. The sample is placed in top of graphite crucible and covered with graphite susceptor and microwave is set with a heating rate of 50°C per min.

Results and Discussion

The microstructure of the joints formed by 45µm and 200nm Ni powder were observed under optical microscope. Fig. 1(a,b) clearly shows that the thickness of the interlayer using 45 µm Ni (140-170µm) is larger than the interlayer formed by 200nm Ni powder (30-50µm). It also contains voids which are not observed for the smaller Ni powder. This difference in interlayer thickness is due to the large difference in size of the powder which also affects the heating rate.
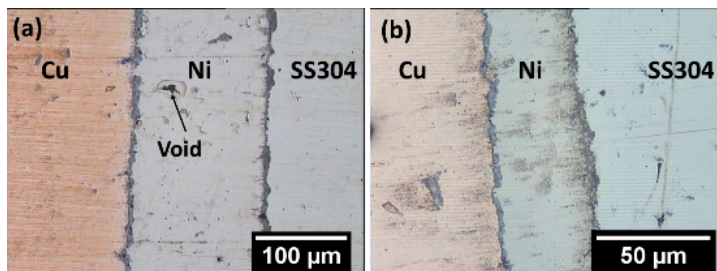

Fig. 1. Optical micrograph of the microwave joined Cu to SS034 samples (a)45 µm Ni (b) 200nm Ni powder

The experimental details are shown in Table 1. The 200nm Ni powder coupled with microwave at a soaking temperature of 900°C and 5min soaking time. Microwave uniformly heat the metal powder if its size is smaller than the skin depth[27]. So the heating of metal powder depends on the skin depth,

$$d = \sqrt{1/\pi f \, \mu_0 \mu' \sigma}$$

Where,
σ = electrical conductivity of a material (S/m)
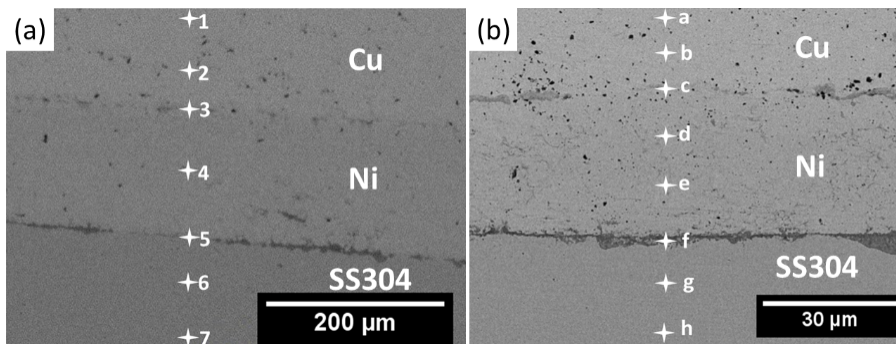f = frequency of the microwave (Hz),
$\mu_\circ$ = permeability of free space and
μ' = permeability (H/m).

Table 1. Experiment with varying temperature

Size of Ni	Soak time at 700 ºC		Soak time at 800 ºC		Soak time at 900 ºC		
	5min	10min	5min	10min	5min	10min	15min
45 μm	No joint	No joint	No joint	No joint	No joint	No joint	Good Joint
200nm	No joint	No joint	No joint	No joint	Good Joint	Good Joint	Good Joint

Thus 200nm Ni powder heat up faster by microwave hybrid heating than 45μm Ni powder. The SEM image of the joints representing the different points across them are shown in Fig.2. The elements present on all these points are represented in Table 2. From the EDS data, the diffusion of Cu and Fe across the interlayer is very prominent in addition to some diffusion of Ni and Cr. Since Ni and Cu are fully soluble [28] in each other and diffusion of Cu is high. The interlayer forms into a solid solution of Ni and Cu by substitution method. A reaction layer of $FeNi_3$ is formed between SS304 and the Ni interlayer. The higher diffusion of Cu and Fe for 200nm Nickel is due to the faster heating obtained by the smaller size of the powder particle. The XRD analysis of the joint cross-section verify the formation of $FeNi_3$ also represented in Fig 3.

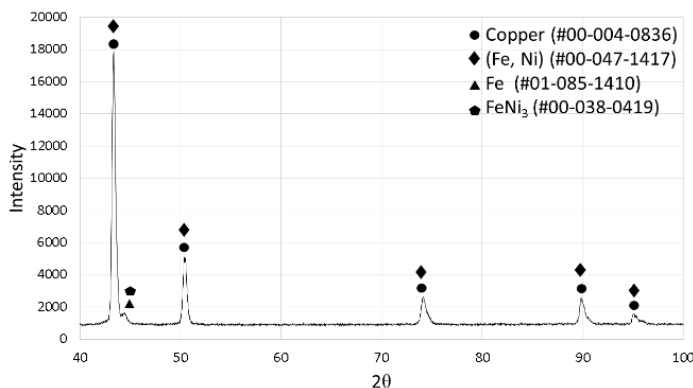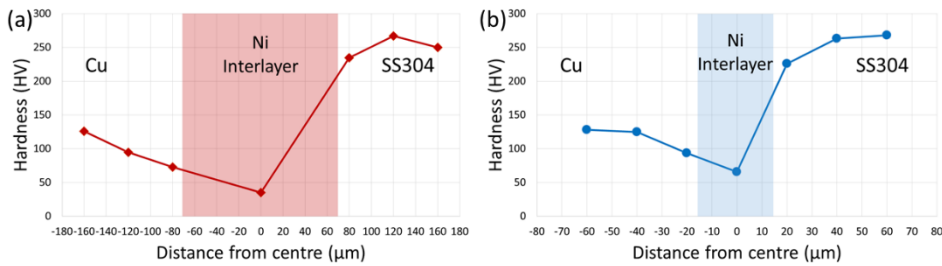**Fig 2.** The SEM image of (a)45 μm Ni and (b) 200nm Ni powder

Fig. 3. XRD analysis across the joint zone

Table 2. wt% of elements obtained by EDS of points shown in Fig 2

	Point	O	Cr	Fe	Ni	Cu	Probable compound
45 µm	1	1.333	0.794	2.144	2.430	93.299	Cu
	2	1.278	0.806	2.388	2.961	92.567	Cu
	3	1.367	1.088	2.730	26.939	67.875	Ni- Cu solid solution
	4	0.378	1.273	4.050	60.579	33.719	Ni- Cu solid solution
	5	5.027	5.114	18.994	39.760	31.106	$FeNi_3$ + Cu
	6	1.473	14.436	51.843	9.252	22.996	SS304
	7	0.653	15.197	53.531	8.850	21.769	SS304
200 nm	A	0.605	1.218	4.323	2.692	91.162	Cu
	B	0676	1.197	4.538	4.051	89.537	Cu
	C	2.689	1.414	4.989	19.949	70.958	Ni- Cu solid solution
	D	1.051	1.431	5.642	56.196	35.680	Ni- Cu solid solution
	E	2.951	1.763	10.683	53.302	31.301	Ni- Cu solid solution
	F	4.677	4.372	20.102	40.006	30.843	$FeNi_3$ + Cu
	G	1.572	14.786	50.177	6.901	26.564	SS304
	H	0.914	14.219	54.203	6.665	23.999	SS304

The Microhardness across the two types of joint obtained after soaking at 900°C for 15min was measured as represented in Fig 4. The hardness of the Ni-Cu solid solution is higher for 200nm powder than 45µm. The hardness of the heat affected zone is also higher for 200nm powder. With decrease in metal powder size the heating rate of the Ni interlayer increases and also reaches a higher temperature. All this is attributed due to total necking and melting of nano Ni powder. The lower hardness of 45µm is due to the partial fusion of the interlayer and presence of pores.

Fig. 4. Microhardness of the joint cross-section with joints formed using (a) 45μm size Ni powder and (b) 200nm size Ni powder

Conclusion

The following conclusion are made for the study of joining of Cu to SS304 by microwave hybrid heat using Ni metal powder:

1. The joining was successful by using both 45μm and 200nm Ni metal powder as interlayer
2. The 200nm Ni formed the joint faster than 45μm Ni.
3. The thickness of the interlayer formed by 200nm Ni is almost 3 times smaller than the   formed by 45μm.
4. The microhardness of the interlayer is higher for the 200nm Ni, with porosity in turn exhibiting higher strength.

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