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Full Length Article

Experimental investigation on mechanical and microstructural properties of AISI 304 to Cu joints by CO_2 laser

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ABSTRACT

Aim of the present work is to investigate mechanical and metallurgical characteristics of continuous wave CO_2 laser welded dissimilar couple of AISI 304 stainless steel and commercially pure copper sheets in autogenous mode. Metallurgical analysis of the fusion zone has been done to understand the mixing and solidification behavior. Macroscopic examination has been carried out to observe the macro-segregation pattern of Cu, Fe and Cr rich phases in different zones, and the thickness of HAZ was found to be around 10 µm. The micro-channels formed from the steel side to weld pool describe that the copper solidifies first and provides the nucleation surface for the residual melt to grow. These tubular micro-channels formed may be due to carbide precipitation. The EDS analysis conforms the well mixing of SS and Cu inside the weld pool. The mechanical properties in terms of tensile stress found up to 201 MPa and the fracture are obtained outside the weld zone. Microhardness measurements over the fusion zone have been done to understand the keyhole growth and quenching, solidification sequence and stress distribution over the full area.

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1. Introduction

The increase in popularity of use of dissimilar metal couples in process industries has opened up a vast area of research, which includes process development, parameter optimization and material development. The academic engineering fraternity is largely focused on process development and optimization for welding parameters applied to commercially available metal and alloys being used as dissimilar couple. Welding processes are chosen depending upon properties of the dissimilar couple under consideration and the properties of the product being desired for specific application [1]. Dissimilar welding of incompatible couples results in intermediate alloys of myriad compositions. Different welding process offers different levels of control over alloying. Out of all welding processes available, as laser beam welding offers a small weld bead, narrow heat affected zone (HAZ) and high penetration draw more attention.

Stainless steel (SS)–Cu dissimilar couple is extensively used in nuclear power plants, steam turbine power plant, heavy electronics, switch gears etc., due to their complementary properties like high thermal and electrical conductivity of Cu and corrosion resistance of SS. Autogenous welding of this couple is challenging because of a miscibility gap in solid state. Addition of Ni as a filler material is the best solution because of infinite mutual solubility of Ni and Cu in liquid as well as solid state, and Fe and Ni are mutually soluble. But, in cases where addition of filler material is prohibited or not feasible, the only solution left is to undertake filler-less autogenous welding operation with a objective to obtain a sound microstructure. The mechanics of different phase separation and development of various features have been explained by various workers. Rowcliffe et al. [2] studied the feasibility of using an austenitic SS and precipitation harden (ph) Cu bonded by hot isostatic pressing. Their main focus was on the performance of the intermediate bi-layer in the radio neutron-rich active environment. They observed that the ph Cu exhibited anisotropic fracture toughness and poor cracking growth resistance in the direction parallel to bi-layer.

Chen et al. [3] characterized SS–Cu dissimilar joint made by continuous CO_2 laser welding. They studied the effect of energy input on the development of weld pool microstructure and interface. Their work attempted to improve upon the technique suggested by Yao et al. [4] to control the microstructure through dilution ratio altered by scarf geometry. They proposed to use minimum possible copper in the weld pool so that solidification cracking would not occur, giving better weld quality. Phanikumar et al. [5] also studied the

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mixing mechanism and dilution behavior of the copper in the melt. While it has been common knowledge that due to miscibility gap of Fe and Cu below the peritectoid point, the two segregate as pockets or bands in the fusion zone; researchers [3–5] observed that Fe and Cu segregate in an ordered manner. Fe droplets form Cu matrix or Cu droplets form in Fe matrix. Further, at higher resolution, this phenomenon repeats at micro scales. Hence, upon solidification, Fe–Cu would produce fractal repetitions because of miscibility gap. This may be taken up as a defect and can be addressed largely by addition of Ni. Alloying with Ni reduces the hot-shortness caused due to Cu, because Cu and Ni are fully soluble to each other. Suga et al. [6] explained the variation in tensile shear stress of dissimilar joint of austenitic stainless steel and pure copper by laser brazing with respect to different filler combinations like Cu–Si, Cu–Ni, Ni–Cu, Cu, Ni etc. and concluded that Ni–Cu type showed relatively high shear value compared to others.

Baghjari and AkbariMousavi [7] observed that the fusion zone microstructure and the HAZ microstructure are controlled by growth rate and temperature gradient across the fusion zone. Thus, this approach may be adopted to improve the microstructural texture of Fe–Cu based dissimilar welds. Fe in Cu or Cu in Fe segregation is essentially droplet shapes, which are conductive to offer crack resistance. Torkamany et al. [8] explained the microstructure and mechanical characteristics of weld fusion zone with effect of laser welding mode. The equiaxed grains and fine columnar dendrites form at the fusion boundary and grow toward the molten pool center.

The non-equilibrium copper rich phases highlight the problems in microstructural stability of joint. Different materials such as steel, copper, kovar alloy and aluminum are welded by Nd-YAG laser. All characteristics like mixing behavior, the microstructure, cracks, hardness and stress in the weld zone are investigated by Mai and Spowage [9]. Roy et al. [10] investigated the metallurgical and mechanical properties of Cu–SS 304 dissimilar weld by shielded arc welding method. They found phases like equiaxed, columnar, cellular dendrite structure, etc. in the weldment and observed fracture line at the HAZ of the copper side due to grain coarsening effect. Yao et al. [4] suggested the appearance of α and ε phase near the interface between intermixing zone and Cu plate increases the possibility of formation of intermetallics. Yan et al. [11] observed that the laser welding gives the smallest dendrite size in the weldment in comparison to TIG and hybrid welding. The solid solution zone near the interface and formation of different phased based on (Fe, Ni), (Fe, Cr, Ni) and (Fe, Cr) chemical system occur in diffusion bonding of SS 410 and copper with Ni interlayer. Gao et al. [12] explained the non-uniformity microstructure detect at the fusion zone and interface, which is improved by increasing the heat input in laser-arc hybrid welding. Sun and Ion [13] suggested the presence of δ-Fe in the weld zone due to insufficient time for phase transformation from $\delta \rightarrow \gamma$ in the laser welding. The martensitic HAZ in alloy and high-carbon or medium steels may be due to the result of high cooling rate in laser welds. The only precaution to avoid excessive hardness is preheating the metals. According to Hussain et al. [14], the austenitic phase begins to precipitate during cooling of weld zone, which is very less in laser welding.

The present experimental work focuses on some more explanations on the microstructure of SS–Cu dissimilar joint by CO_2 laser to get a bigger picture. A detailed study is performed on different phases in fusion zone, HAZ, interface as well as microhardness.

2. Experimental

2.1. Materials and laser welding

In the present work, two dissimilar metals sheets such as AISI 304 stainless steel and commercially pure copper (chemical compositions of the base metals are given in Table 1) are taken into the consideration for welding, and their mechanical and microstructural characteristics are investigated.

Table 1
Chemical composition of SS 304 and copper (mass fraction, %).

	Fe	Cu	Si	C	Cr	Mn	Ni
SS	74.11	–	0.29	–	17.75	0.72	7.13
Cu	–	99.63	0.37	–	–	–	–

Flats of AISI 304 SS and commercially pure copper are welded in butt configuration. The welding is carried out in a “3.5 kW CO_2 slab laser” continuous wave laser welding unit. The machine has a power output of 50–3500 W, wavelength of 10.6 µm. The beam used in the experiment was of a pure TEM00 mode with beam quality $k > 0.96$. Working conditions and different process parameters used for the laser welding are shown in Table 2. Helium is used as shielding gas with a flow rate of 20 lpm and fed through a 5 mm diameter nozzle at an angle of 45° in the trailing mode configuration. The nozzle stand-off distance was maintained at 3 mm. Gas post flow of 5 seconds was given to prevent oxidation of the hot weld regions and to maintain the cooling rate. Initial bead on plate (BOP) experiments are performed to identify the process parameters window by means of laser coupling observations. The top surfaces of the welded samples as shown in Fig. 1 captured by optical microscope at 40× demonstrate an appreciable welding from outside observation.

The welded samples were rectangular after welding. Hence, standard test specimen conforming to tensile test standard ASTM E8M-04 was prepared by removing extra material from the gauge length with the help of a wire EDM cutter. The scheme of cutting has been shown in Fig. 2. The portion discarded from the sides while preparing the dogbone shape samples (of the gauge length) was used for metallographic observation. The face being observed under microscope is a transverse section of the weld normal to the welding direction.

2.2. Characterization

The weld cross-sections are obtained by cutting with wire-EDM, and subsequent polishing. The metallurgical specimen was cleaned in an ultrasonic bath, and etched in 10% oxalic acid solution for 3 minutes at 3 Volts. Microstructure of the weld cross section was observed in a scanning electron microscope (Oxford, JEOL JSM 6084LV) and optical microscope (SEIWA). Vicker's microhardness measurements were carried out with a diamond tip indenter applying 200 gf load for 10 seconds dwell time. Tensile tests are performed on an Instron® 600KN UTM as per standard ASTM E8M-04.

Table 2
Welding parameters.

Welding parameters	Values
Laser power (kW)	3.0, 3.5
Scan speed (m/min)	2.0, 3.0
Position of laser beam	50 µm offset toward SS Beam
Diameter (mm)	0.18
Beam profile	Gaussian mode
Focal length (mm)	300
Laser beam angle	900
Gas flow rate (lpm)	20
Focal position	At the surface

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