Plasma Cladding of Copper on Cylindrical SS 316L Surface

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1 Introduction

Cladding is a progressive technology for depositing material with the desired properties on a metal substrate. The main objective of this process is to improve the characteristics like hardness, wear resistance, corrosion resistance, conductivity, etc., or refurbishing of worn out parts. Cladding can be performed using various processes that perform overlay welding such as shield metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux cored arc welding (FCAW), cold spray method, plasma arc welding (PAW), laser beam welding (LBW) and electron beam welding (EBW) [1, 2]. Each process has its advantages and limitations when it comes to the characteristics of cladding. There are various problems associated with cladding reported in the literature including: (i) porosity due to atmospheric gases, (ii) inclusions of foreign particles, (iii) cracks due to thermal stresses induced during heating and cooling, and (iv) high dilution due to excessive heating [3]. Therefore, based on the application of the deposited clad a particular welding process is selected.

Copper is an interesting metal largely used for its properties of electrical and thermal conductivity, excellent corrosion resistance and management of heat [4]. It can help in diffusing the heat from local points to larger areas and recommended for fusion reactors, petroleum industries, crystallizers, etc. [5] However, it has poor strength, low hardness, and poor wear resistance at high temperature. Stainless steel offers its own unique properties such as high creep, stress to rupture and tensile strength at elevated temperatures. Stainless steel 316L is usually considered as the marine grade stainless steel, but it is not corrosive resistant to seawater. This combination of materials has many applications in fusion reactors and marine applications. In the present study, SS316L is considered as substrate material for providing high

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S. K. Natarajan et al. (eds.), *Recent Advances in Manufacturing, Automation, Design and Energy Technologies*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-16-4222-7_17

strength and copper as clad material to provide required thermal, electrical and corrosion resistant properties. However, coating of copper on stainless steel 316L is highly challenging as there is a distinct difference in the material properties of these two materials, including melting point, thermal conductivity, and thermal expansion.

For performing such cladding, there are two major categories of processes reported in the literature as fusion-based processes and cold coatings [6]. In conventional fusion-based cladding process, one of the metals is used as electrode, which directly absorbs the arc heat and melts to participate in cladding. This often results in excessive melting of the substrate and accumulation of Cu at the interface. Here, large amount of stresses will be developed at the interface due to difference in the coefficient of thermal expansion of both the metals. It causes the Cu to penetrate in SS and induce liquid embrittlement in stainless steel [7]. Laser and electron beam cladding are relatively new technologies having better control over the heat involved during deposition; however, it is challenging to process copper using these techniques due to its inherit property of being a reflective material. Theoretically, the absorptivity of copper for laser in the literature is about 25% which is quite different experimentally. For a wavelength of around 1 μm, the absorptivity reported about 3% at room temperature and 8 and 13% at elevated temperatures [8–11]. Reports present the successful deposition of copper on SS316L surface using cold spray method; however, it is limited to thin layer deposition where deposition of thick coating without porosity is still a challenge. Referring to the past literature, cladding of copper on cylindrical SS 316L surface is very limited and no efforts have been made to study it using plasma welding as a source. This fact motivated the authors for the work presented in this article.

In the present study, plasma welding source is used to confine the welding energy in a confined area. Plasma transferred arc is an effective method [12] for hard facing or cladding between arc welding processes with advantages such as very high-quality deposition, high energy concentration, narrow heat affected zone (HAZ), less weld distortion and some drawbacks, such as low deposition rates, overspray and high cost of equipment if compared with other conventional welding processes. The elevated plasma arc temperature enables the use of metallic wires to melt and deposit over the substrate. All most 100% wire can be deposited in the process which is about 70–80% in case of powder deposition [13].

2 Materials and Method

A substrate in the form of hollow pipe of stainless steel 316L having outer diameter 25 mm, length 130 mm and thickness 2 mm was used for all the experiments. The substrate was cleaned with acetone and polished with *A120* flap disks, later *600* grit sandpaper was used for a smooth finish and to do away with any foreign particles prior to deposition. Commercially available copper wire of 500 μm diameter was used as a feedstock material for deposition. The chemical composition of the deposition material and substrate is given in Table 1.

Table 1 Chemical compositions of the wire and substrate

	C	Si	Mn	P	Cr	Ni	Mo	Fe
Substrate (SS316L)	0.08	0.25	0.81	0.014	16.68	10.08	2.06	Bal
	Cu	Bi	Sb	Fe	As	Pb		
Clad material (Copper)	99.9	0.001	0.002	0.005	0.002	0.001		

2.1 Experimental Setup

A plasma welding source (make: EWM, Germany) was used as the energy source for the deposition. The welding torch was attached to a *3*-axis CNC machine having a travel accuracy of 0.01 mm in all the directions. An indigenously developed wire feeder was attached to the plasma welding torch to supply the required feed of deposition material. This wire feeder has a wire feeding range of 800–3200 mm/min. with an accuracy of ±3 mm. The angle for feeding the clad material was kept constant at 45° as referred from the previous literature [14]. The *CNC* machine, wire feeder and plasma parameters have been controlled by an integrated software through the computer. Two separate cylinders of argon gas were used. One of the argon cylinders was used for generating plasma and the other to provide a shielding atmosphere for the deposition. For shielding purpose, the gas flow rate was kept constant as 5 l/min throughout the experiments, and a gas flow rate of 0.4 l/min was used to generate plasma. An additional rotational axis attachment was mounted on the bed of CNC machine to hold and rotate the substrate pipe. The rotation of the additional axis was kept constant as one rotation per minute during the experiments. An additional argon cylinder is used to protect the deposited clad from further oxidation while solidification of the clad. Figure 1a shows the actual photographs of the arrangement prepared for experiments, and Fig. 1b presents the detailed view of the experimental setup. Clads were then deposited on the hollow pipe of stainless steel 316L substrate in an open atmosphere.

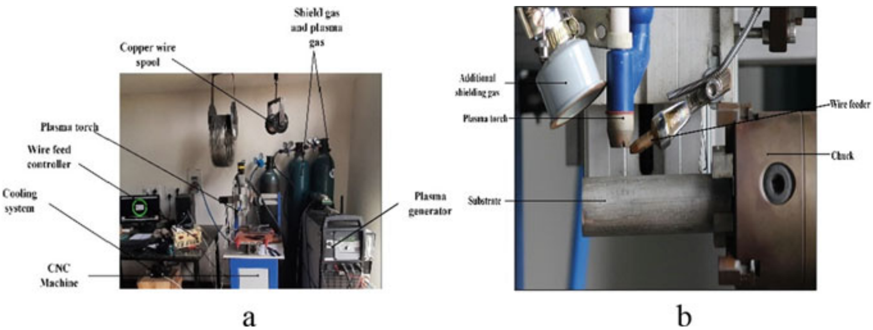

Fig. 1 **a** Plasma welding setup used for experimentations; **b** detailed view of arrangements

Table 2 Range of process parameters used for clad deposition

Parameter	Unit	Value
Plasma power (*P*)	Watt	625–875
Wire feed rate (*W*)	mm/min	3200–800
Travel speed (*V*)	mm/min	4–8

2.2 Experimental Details

Different combinations of processing parameters were used for preliminary experiments, post which main experiments were designed using the L_9 orthogonal array method. Table 2 presents the range of process parameters used for clad deposition. Argon gas was used for generating plasma as well as for shielding purpose to resist oxidation of copper clad and steel substrate during plasma cladding at elevated temperatures. The single track and multi-track were achieved by varying the process parameters, i.e., travel speed, wire feed rate and the power. The cross section of the cladding was investigated, and factors such as height of the clad, width of the clad, heat affected zone, geometric dilution and geometric shape were examined using AutoCAD software for geometrical investigations. Selected tracks were selected for further investigations for microscopy and micro-hardness measurement.

2.3 Clad Characterization

Cylindrical clad sample was sectioned into 5 $\times$ 5 mm and cut using wire EDM for high precision and low surface roughness. Utmost care was taken to maintain the standard metallurgical procedure. Analysis of clad geometry was done by visual observations, and the cross-section features were measured using a Zeiss inverted microscope. The samples were polished and etched with standard metallurgical procedure. The images were then processed on AutoCAD software for measurement of clad height and width. SEM analysis was carried out using TESCAN Vega 3. Micro-hardness was also measured at the load of 200 g for 10 s using Leica UHL VMHT micro-hardness tester. All the observations are discussed in the later section of this manuscript.

3 Results and Discussion

3.1 Geometrical Observations

Figure 2a–c presents the variety of clads deposited as a result of different combinations of processing parameters. The results are mainly due to the combinations of plasma power and wire feed rate which directly affects the welding heat input in the

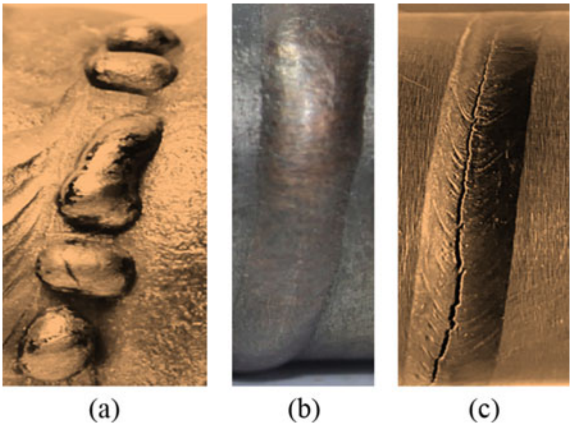

Fig. 2 A variety of clads deposited at different combination of processing parameters **a** discontinuous clad; **b** smooth clad; **c** clad with liquid embrittlement

substrate. The rotational speed of the pipe is kept constant for all the combinations at varying travel speed which helps in controlling the overlap distance to form multi-clad and form a smooth surface. Figure 2a shows poor combination of the plasma power and wire feed rate (P:625, W:800) producing discontinuous clad, whereas the combination of high plasma power and lower wire feed rate (P:875, W:800) resulted clad effect with liquid metal embrittlement shown in Fig. 2c. Figure 2b represents a good-quality smooth clad as a result of optimal parameters (P:750, W:800) measures clad width of 5.2 mm and clad height of 1.3 mm. This results in an aspect ratio of 4 (ratio of clad width to height). It has been reported in the previous literature that an aspect ratio above 4 is preferable for smooth and regular deposition [14]. The optimum combination of parameter was further used for multi-clad deposition to form a surface.

3.2 Effect of Overlapping Distance

The overlapping distance is the effect of travel speed which is governing the lead distance from the start point. The trials were made at various combinations of input variables. Figure 3a represents the clad formation of two successive layers at a travel speed of 8 mm/min. Figure 3b demonstrates the actual picture of smooth deposition with a combination of optimum parameters with a travel speed of 4 mm/min. This

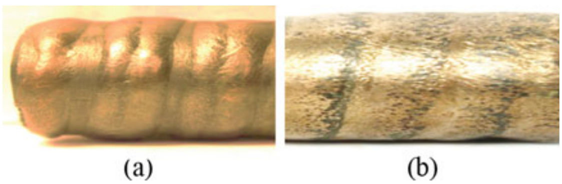

Fig. 3 Clad at various overlapping distances **a** double clads; **b** continuous clads

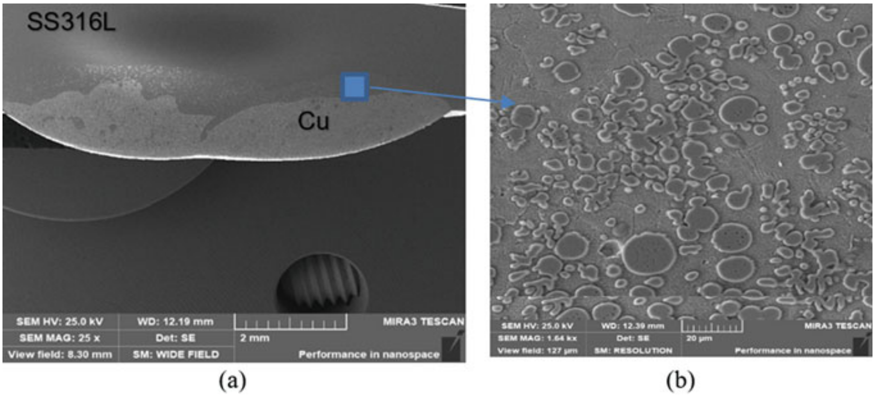

Fig. 4 SEM observation of Cu cladded on SS316L **a** double-clad representation; **b** micrograph at interface

clad was used for further examination using scanning electron microscopy to understand the bonding characteristics mechanism and the different phases present at the interface.

3.3 Microstructural Observations

Figure 4 reveals the SEM micrograph of selected clad which determines the joint strength between the two materials. The dilution between the two materials is optimum which provides enough strength to the joint, and the interfacial zone is thinner and cleaner. The interfacial zone is explained in Fig. 4b, where the mixing of Fe and Cu can be easily seen. Here, stainless steel is partially melted and is mixed with copper. This interfacial region depicts interesting phenomena for further studies. This clearly shows the possibility of using plasma welding equipment for the application of preparing Fe-Cu surface clads.

3.4 Micro-hardness Observations

For copper claddings, the cross-sectional micro-hardness versus distance from the cladding-substrate interface plots is shown in Fig. 5. The average of three values was taken for each value for better accuracy. It can be observed from the plot that in the substrate regions, the variation in micro-hardness is negligible beyond a distance of −0.3 mm from the interface. In the heat affected region, relatively higher micro-hardness values were measured for the sample. Lower hardness values were measured in the area between HAZ and unaffected substrate due to diffusion region to the HAZ.

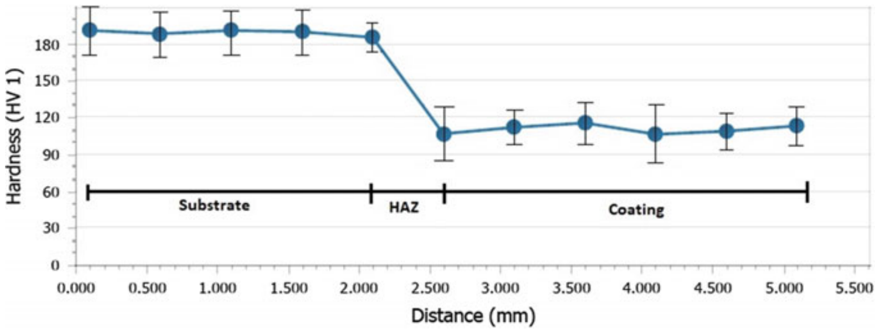

Fig. 5 Micro-hardness of surface layers of Cu-cladded SS316L pipe

The mean micro-hardness of the SS316L part was 198 HV, while the mean micro-hardness of the copper cladding part was 106 HV. The change in micro-hardness values shows the variation between substrate, HAZ and the coating region. There is a smooth transition in the hardness values from the substrate to the clad. The values of micro-hardness confirm the microstructure shown in Fig. 4, where clear separation between stainless steel and copper region is visible. However, a thin mixed Fe-Cu interfacial zone is visible at the interface which has no significant hard faces present in it.

4 Conclusions

In the present work, plasma welding is used for thick Cu cladding on stainless steel 316L pipe. The cylindrical cladding was prepared through autogenous setup presented in this study. The following conclusion can be drawn post-deposition:

1. Plasma overlay clads were successfully developed between Cu and stainless steel 316L pipe.
2. The parameters were optimized for single clad, and the optimized value was used for multi-clad deposition. A smooth and regular deposition was achieved as a result of the above work.
3. SEM images verdict sound deposition at optimum combination of parameters without much porosity even in the interface region.
4. Fe is precipitated and fused with Cu in the interfacial region. There is an accumulation of iron-rich phase present in copper.
5. The strong bonding of Cu and SS316L is evident through micro-hardness test. The mean micro-hardness of the SS316L part was 198 HV, while the mean micro-hardness of the copper part cladding was 106 HV.

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