Parametric Investigation of Diode and CO2 Laser in Direct Metal Deposition of H13 Tool Steel on Copper Substrate

M. Khalid Imran*, Syed Masood, Milan Brandt, Sudip Bhattacharya and Jyotirmoy Mazumder

***Abstract*—** In the present investigation, H13 tool steel has been deposited on copper alloy substrate using both CO2 and diode laser. A detailed parametric analysis has been carried out in order to find out optimum processing zone for coating defect free H13 tool steel on copper alloy substrate. Followed by parametric optimization, the microstructure and microhardness of the deposited clads have been evaluated. SEM micrographs revealed dendritic microstructure in both clads. However, the microhardness of CO2 laser deposited clad was much higher compared to diode laser deposited clad.

***Keywords*—** CO2 laser, Diode laser, Direct Metal Deposition, Microstructure, Microhardness, Porosity.

I. Introduction

DURING solidification of the casting part in high pressure die casting (HPDC), heat is transferred from the molten metal to the cooling channel by conduction through the mold material. Hence thermal conductivity of the mold material is the primary governing factor in the cooling process and thus in the production rate. Bi-metallic mold of copper and copper alloys, coated with protective layer of H13 tool steel (TS) has received considerable interest as a die material in the high pressure die casting industries of light metal alloys due to the high thermal conductivity of copper [1-6]. In liquid state, iron and copper are immiscible and form several intermetalics when solidified, while nickel and copper form complete solid solutions at all compositions. . Therefore a buffer layer of nickel can be used as a bonding agent between copper and tool steel. However manufacturing bi-metallic structure of H13 TS and copper is difficult due to the very different physical properties of these two materials. Some researchers have investigated this possibility by different approaches with varying degrees of success. Beal et al. [7] and Pogson et al. [8] have reported development of molds by manufacturing H13/Cu structure using selective laser sintering (SLS) and direct metal laser remelting (DMLR) respectively. These involved manufacturing 3D structures by using laser beam to sinter or melt the mixture of H13/Cu powder. Both SLS and DMLR involve many different steps, consequently, dimensional control of the final part is difficult. Additionally, finished parts are usually not fully dense resulting in, lower strength than a machined part. Also, in the case of DMLR, complex metallurgical interactions can occur if different powder types are used, as powders are fully melted and allowed to mix freely within the melt pool. Clark et al. [1-5] tried to manufacture a bimetallic tooling using thermal arc spray process and concluded that this process could deposit steel layers up to a certain thickness but due to high porosity of the layer, it resulted in poor surface finishing. Protective H13 tool steel layers on copper mold, deposited by laser aided direct metal deposition (DMD), can overcome this problem.

Direct metal deposition (DMD) is a laser cladding process for fabricating fully functional metallic parts directly from CAD data. The process involves a high power laser beam as a source of heat to create a melt pool on the surface of a solid substrate, into which a metallic powder is injected through an integrated powder delivery system [9, 10]. The heat from the laser and the latent heat taken from the molten pool melts the powder and when solidified, creates a fully dense and metallurgically bonded bead on the substrate. By overlapping the beads, usually by 50%, a continuous layer is produced and, subsequently, depositing in a layer by layer fashion builds the predetermined shape of the component. Among the various material deposition processes used to improve properties of the surfaces, DMD is an attractive alternative due to high input energy, low distortion, avoidance of undesirable phase transformations and minimum dilution between the substrate and the coating. Furthermore, faster processing speed, very high heating/cooling rate (105 K/s), high solidification velocity (up to a maximum of 30 m/s) and formation of an exotic composition/microstructure, and even metastable phases during laser processing [11] make DMD a plausible candidate in the materials cladding industry. DMD has been successfully used for rapid fabrication of net shaped solid metallic parts, in situ alloying of parts, parts with conformal/internal features and metal molds for injection molding and die casting. Though DMD can be easily applied for coating many metals, this surface treatment is limited for copper, due to the high reflectivity of copper to laser beam during laser cladding. Specifically, copper is more reflective at the infrared output wavelengths of CO2 (10.6 µm) which results in lower process

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efficiency for this type of laser [12]. In response to the need for a more optimal source for this application, a high power diode laser can be used. Typically, higher power diode lasers provide output in the near infrared, most commonly at either 808 nm or 975nm which is better absorbed by copper than CO2 laser. In the past, both CO2 and diode lasers have been studied extensively in laser cladding of various alloys [11, 13-17]. Though these lasers have been successfully applied for different metals and alloys, a parametric comparison between CO2 and diode lasers to clad H13 tool steel on copper alloys has not been extensively investigated.

In the present study, a parametric comparison between CO_2 and diode lasers to clad H13 tool steel on copper alloy has been investigated. Among various process parameters, three most influential parameters (laser power, powder mass flow rate and feed rate) have been considered in this experiment. By investigating the parametric comparison, the optimal processing zone for both types of lasers to develop a defect-free clad with improved properties has been established. Also, following the parametric comparison, detailed microstructural characterization of the fabricated layers has been carried out.

II. Experimental Work

Commercially available gas atomized H13 tool steel powder was used in this investigation. The powder size distribution was between 90-120 µm diameters. The substrate was an Ampcolloy 940 rolled block with dimensions of 80 mm × 50 mm × 30 mm. The chemical compositions of the powder and substrate material are given in Table I. A buffer layer of nickel was deposited in between the substrate and the H13 tool steel clad. Among various DMD process parameters, laser power, powder mass flow rate and laser scanning speed significantly influence the microstructure and mechanical properties of the deposited clad. Therefore, a statistical design of experiments (DOE) based on L9 orthogonal array of Taguchi method using these parameters was employed in this experiment to assess the performance of two different types of lasers. Table II and III summarize the detailed orthogonal array of Taguchi matrix with parametric combinations for CO_2 and diode lasers respectively.

TABLE I
Chemical Compositions of H13 Tool Steel and Ampcolloy 940

Materials	H13 tool steel	Ampcolloy 940
Elements (%)	0.35 C, 0.4 Mn, 1 Si, 1 V, 1.5 Mo, 5 Cr, 90.75 Fe	2.5 Ni, 0.7 Si, 0.4 Cr, 96.4 Cu

Laser depositions were made using POM DMD machines at Precision Optical Manufacturing (POM) Inc. using both diode and CO2 lasers. Both lasers were capable of producing maximum 4000 kW power. A laser beam diameter of 2.0 mm was used for both lasers in all the depositions. To prevent oxidation during laser processing, the entire process was carried out using Helium and Argon as shrouding environment. These gases also worked as powder carrier gas. For CO2, a combination of the following processing parameters- laser power 2.5, 2.75 and 3.0 kW, laser scanning speed 100, 300 and 500 mm/min and powder mass flow rate 5, 7.5 and 10 gm/min were used to form the L9 orthogonal array of Taguchi matrix. On the other hand, for diode laser, laser power was reduced to 1.25, 1.50 and 1.75 kW and the laser scanning speed was increased to 500, 700 and 900 mm/min, while keeping the powder mass flow rate same value as in the CO2 laser for the L9 orthogonal array of Taguchi matrix. Nine different blocks of dimensions 20 mm × 20 mm was deposited using each type of lasers. The thickness of each block was different and varied according to the processing condition.

TABLE II
Design of Experiment for CO_2 Laser Based on L9 Orthogonal Array of Taguchi Matrix

Run order	Laser power (kW)	Powder mass flow rate (gm/min)	Laser scanning speed (mm/min)	Porosity area fraction (%)
R1	2.5	5.0	100	-
R2	2.5	7.5	300	5.78
R3	2.5	10.0	500	3.1
R4	2.75	5.0	300	1.52
R5	2.75	7.5	500	0.45
R6	2.75	10.0	100	-
R7	3.0	5.0	500	0.36
R8	3.0	7.5	100	-
R9	3.0	10.0	300	14.74

TABLE III
Design of Experiment for Diode Laser Based on L9 Orthogonal Array of Taguchi Matrix

Run order	Laser power (kW)	Powder mass flow rate (gm/min)	Laser scanning speed (mm/min)	Porosity area fraction (%)
L1	1.2	5.0	500	6.3
L2	1.2	7.5	700	8.2
L3	1.2	10.0	900	-
L4	1.5	5.0	700	0.8
L5	1.5	7.5	900	1.4
L6	1.5	10.0	500	-
L7	1.7	5.0	900	3.5
L8	1.7	7.5	500	-
L9	1.7	10.0	700	-

Following fabrication, a detailed porosity analysis of the cross section of the fabricated blocks was conducted using optical microscopy and image analysis software (ImageJ) to establish the optimum processing zone for the development of a defect free clad with improved properties. Once the parameters were established, the microstructures of the cross sections of the as deposited specimens prepared using the optimized parameters were characterised using optical microscopy (Nikon™) and scanning electron microscopy (Philips™, XL30 FEG SEM). The specimens were etched using a mixture of 10 ml HNO_3, 15 ml HCl and 10 ml CH_3COOH for the optical and scanning electron microscopy. A Vickers microhardness tester (Clark, CM-400 AT) using

300 gm load and 15 s dwell time was used to measure the hardness of clads from the top surface to the copper base.

III. Results and Discussion

In the present section, a detailed parametric investigation of both CO_2 and diode lasers have been presented to establish the optimum processing zone for the development of a defect free microstructure with improved properties of the clad. Following parametric investigation, detailed microstructural characterization along with microhardness of the clad, fabricated using the optimum processing parameters is also presented.

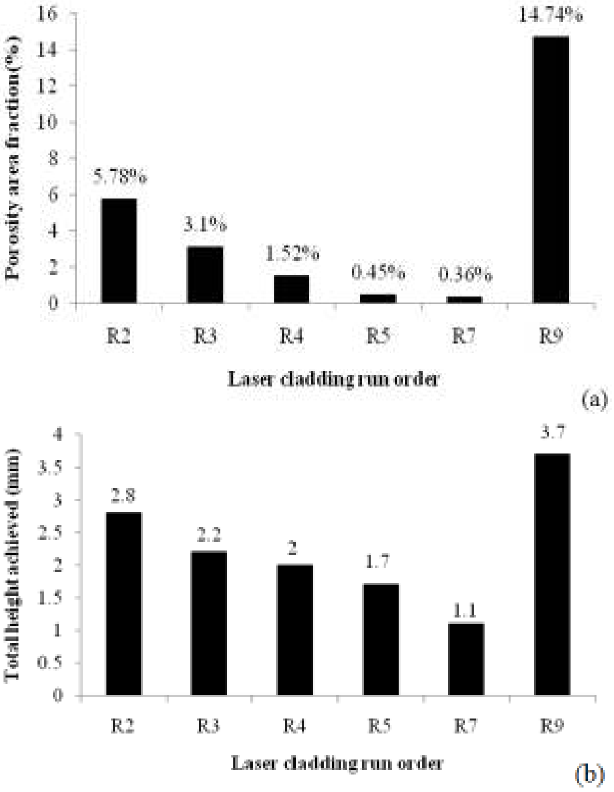

Fig. 1: (a) Quantitative analysis of porous areas in CO_2 laser produced clads and (b) total height achieved for five layers of clads with different parametric combinations.

A. Parametric Investigation

1. CO2 Laser

The primary goal of the design of experiment was to optimize the laser deposition parameters to deposit Nickel as buffer layer, followed by deposition of H13 tool steel with minimum porosity. Therefore the porosity analysis of the blocks produced with the parametric combinations as per the L9 Taguchi matrix was carried out. Previous work by the author and other researchers have revealed that if CO_2 laser is used to clad H13 tool steel on copper alloy substrate, laser power should be limited within 2.5-3.0 kW since laser power in excess of 3 kW reflects tremendous heat to damage machine and laser power less than 2.5 kW cannot provide sufficiently strong clad [12, 18]. It was observed that all parametric combinations shown in Table II couldn't produce defect free clads on the copper substrate. R1, R6 and R8 parametric combinations in Table II burnt the powder and were unable to deposit buffer layers of Nickel. This suggested that low laser scanning speed (less than 100 mm/min) was not suitable to clad on copper substrate. Due to low scanning speed, the heat intensity became high and burnt the powder rather than melting it. Other parametric combinations selected in this investigation produced samples, but with varying layer thicknesses and degrees of porosity in the deposits. Fig. 1 (a) shows the porosity analysis of clads produced with these parametric combinations. It can be seen from Fig. 1 that the minimum porosity area fraction was observed in the sample R7 that was produced with maximum power (3.0 kW), minimum powder mass flow rate (5.0 gm/min) and maximum laser scanning speed (500 mm/min). The porosity area fraction was within the acceptable limit (<1%) in the sample R5 as well that was produced with medium power (2.75 kW), medium powder mass flow rate (7.5 gm/min) and maximum laser scanning speed (500 mm/min). Moreover this set of parametric combination provided better deposition rate compared to the R7 combination while depositing same number of layers (two layers of nickel followed by three layers of H13 tool steel (Fig. 1 (b)). Fig. 1 (b) also reveals that the deposition rate was more for R2, R3, R4 and R9 samples. Since the levels of porosity area fraction were higher in these samples, these parametric combinations were not suitable for the deposition process. Thus, considering porosity and deposition rate, R5 combination is recommended for the deposition of H13 tool steel with buffer layers of nickel on copper alloy substrate using CO_2 laser.

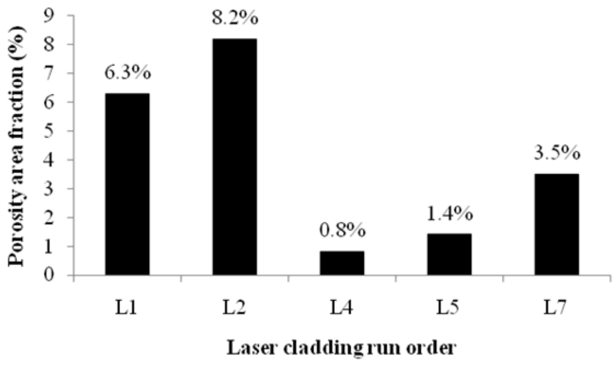

Fig. 2: Quantitative analysis of porous areas in diode laser produced clads with different parametric combinations.

2. Diode Laser

Because of the small infrared output wavelengths, diode laser is largely absorbed by most of the reflective metals. As copper is a highly reflective metal, diode laser has got much potential to clad on copper substrate. Even then, to date, deposition of metal on copper substrate using diode laser has not been reported in the open literature. Since absorption is higher for diode laser, in this set of experiment, laser power was reduced and laser scanning speed was increased compared to CO_2 laser to reduce the heat intensity. High intensity of heat from laser also required placement of a heat sink under the substrate to remove extra heat from the surface. These conditions were selected from some preliminary experiments where using low laser scanning speed (below 500 mm/min) produced excessive heat to burn the powder. Unlike CO_2 laser, optimization of deposition parameters was done in two steps with diode laser. In the first series of trials, nickel was deposited on copper substrate based on L9 Taguchi matrix shown in Table III. Afterwards, H13 tool steel was deposited on nickel buffer layer using different parameters. However, an initial visual observation of clads deposited as per Taguchi matrix in Table III was able to identify limits of the parameters beyond which deposition of nickel was obviously unaccepted. In essence, during deposition of nickel, the higher powder mass flow rate (10 gm/min) with any other parametric combinations (L3, L6 and L9) resulted in excessive powder being introduced to the system. Thus, the powder was not completely melted to produce sufficient bond to the substrate. Also high power laser (1.75 kW) combined with low laser scanning speed (500 mm/min) resulted in excessive heat being introduced to the system and burnt the powder rather than melting (L8). All other parametric combinations in Table III produced nickel clads but with varying degrees of porosity defects. Fig. 2 shows the porosity analysis of clads produced with these parametric combinations. From Fig. 2 it is evident that clads produced with low power laser exhibited high percentage of porosity (L1 and L2). The probable reason was that with low power energy the heat was not sufficient enough to successfully melt the powder and bond it to the substrate. In contrast, when the power was increased to maximum value (1.75 kW) heat intensity was high so it to burnt the powder instead of melting (L7). Minimum porosity area fraction was found in the clad produced with medium laser power (1.5 kW), low powder mass flow rate (5.0 gm/min) and medium laser scanning speed (700 mm/min).

Although, the results of these initial experiments of nickel deposition were encouraging, significant obstacle was identified during deposition of H13 tool steel on nickel buffer layer. The L4 parametric combination was unable to deposit quality clad of H13 tool steel on nickel. The laser power appeared to be excessively high since, instead of melting, it burnt the H13powder and produced black slugs. Initially when nickel was deposited on copper, due to high thermal conductivity, copper could transfer heat from the surface to other part to resist high concentration of heat but while deposition on buffer layer, nickel certainly could not transfer heat as quickly as copper and allowed heat to be concentrated on the surface. In this case, laser power was reduced gradually to decrease the heat intensity. Nevertheless, quality of the clad did not improve much until the laser power was reduced to 1.0 kW. Finally 800 watts laser power with 5.0 gm/min powder mass flow rate and 700 mm/min laser scanning speed produced the best quality H13 tool steel clad on nickel buffer layer, though few micro cracks were visible in the clad (Fig. 3).

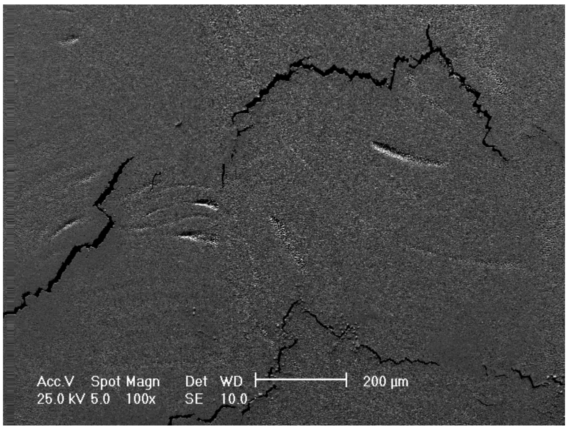

Fig. 3: SEM micrographs showing micro cracks in the diode laser deposited H13 tool steel clad.

B. Microstructure and Microhardness of the clad

Microstructural homogeneity is a pre-requisite for the superior mechanical properties of the laser deposited clads. Therefore, microstructure of two clads produced by using optimum processing parameters of both CO2 and diode lasers were investigated. Fig. 4 shows the scanning electron micrographs (SEM) of the cross section of clads at different locations. Metallographic inspection of the surface microstructure revealed dendritic structure in the clad. SEM image shows that in the nickel clad, the microstructure consists of columnar dendrites, most of which appear almost parallel to the buildup direction of deposits. The microstructure becomes fine and disoriented in the H13 tool steel clad deposited with CO_2 laser. The microstructure appears as columnar dendritic in the H13 tool steel clad when deposited with diode laser. The growth morphology of the dendritic microstructures can be determined by their solidification conditions. The substrate acts as a heat sink in laser deposition process. Therefore, during the rapid melting and solidification in the laser deposition process, mainstream of the heat is always transferred from melted materials to bulk substrate. This directional solidification forms columnar dendritic microstructure parallel to the heat transfer direction in the nickel layers since it was adjacent to the substrate. In contrast, as the deposition thickness increases, far away from the bulk substrate, the directional solidification becomes weak and leads to the formation of disoriented microstructure in the clads [19]. Nevertheless, columnar dendrites were observed in H13 tool steel, deposited with diode laser. Formation of columnar dendrites in this clad is mainly because of the heat sink used under the substrate which assisted the directional heat flow from clad to substrate during diode laser deposition. From Fig. 4, it is also noticeable that in the nickel layer, the growth morphology of a portion of the columnar dendrites is not completely perpendicular to the substrate. Dinda et al. [9] reported that during laser deposition, cooling mostly occurs via substrate and partially via the adjacent solidified deposit layer that grew from the trailing end of the laser melt pool. As a result, the resultant heat flow direction changes to an angle between 45°-90° instead of being perpendicular to the substrate and so does the growth direction of the dendrites.

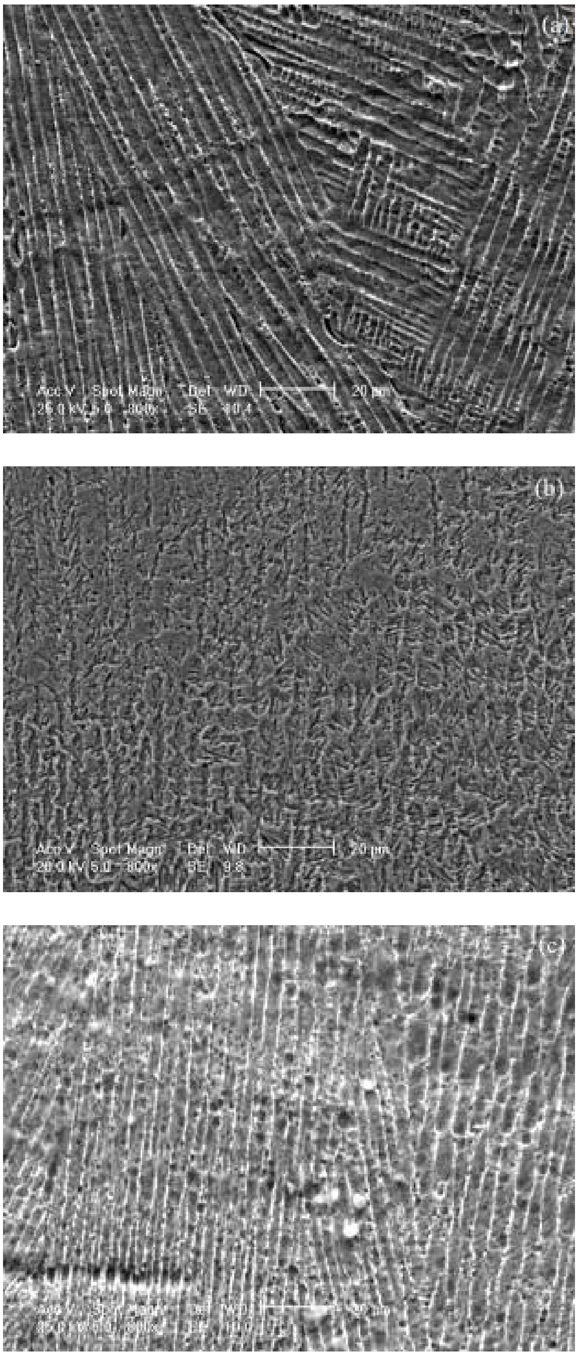

Fig. 4: SEM micrographs showing microstructure of different clads (a) CO_2 laser deposited nickel (b) CO_2 laser deposited H13 tool steel and (c) diode laser deposited H13 tool steel.

Fig. 5 presents the measurements of microhardness on cross sections of both CO_2 and diode laser deposited clads. The microhardness analysis of the CO_2 laser deposited clad showed that the average microhardness was above 600 VHN in H13 tool steel clad, around 200 VHN in nickel layer. The microhardness value was however, found to be lower in the clad deposited with diode laser. In this sample, the average microhardness was just above 200 VHN in H13 tool steel and around 150 VHN in nickel layer. The reduction of hardness in the diode laser clads were most probably due to the micro cracks present in the clad. It was revealed from microhardness measurements that the microhardness was not uniform throughout the substrate. Significantly lower hardness values, in copper substrate adjacent to the interface known as heat affected zone (HAZ) were observed. Degradation of hardness in HAZ is attributed to the grain coarsening effect during laser cladding. However, the hardness in the HAZ was higher in diode laser sample compared to the CO_2 laser sample. Also the depth of HAZ was less in diode laser clad compared to that of CO_2 laser.

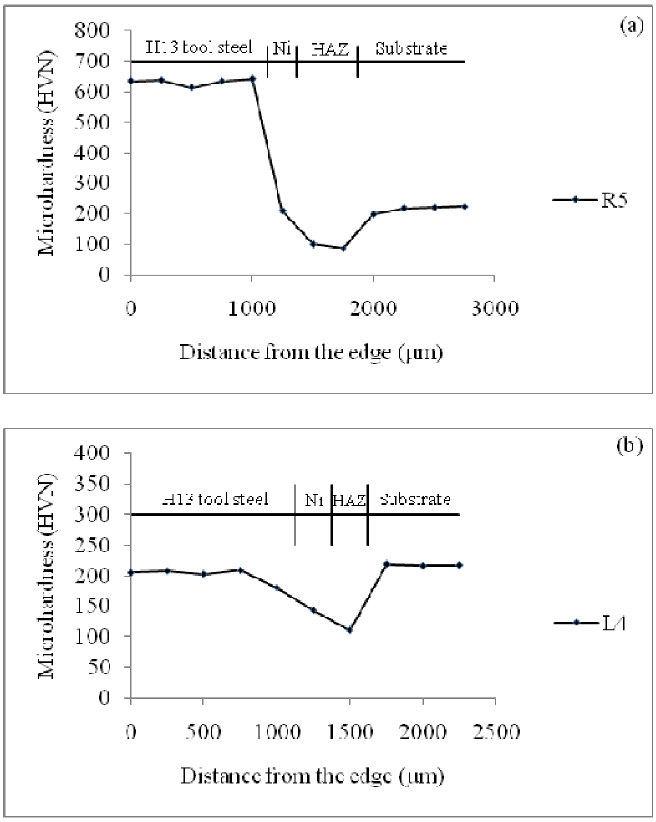

Fig. 5: Microhardness on cross sections of (a) CO_2 and (b) diode laser deposited clads

IV. Conclusion

A series of H13 tool steel clad with buffer layer of nickel on copper alloy substrate has been successfully deposited using both CO2 and diode lasers. Optimum DMD processing parametric zones for both lasers have been suggested through experimental investigations. Though CO2 laser deposited clads were completely free from relevant defects like crack, bonding error or porosity, diode laser deposited clads showed some micro cracks. The microstructure of as-deposited nickel clads consisted of columnar dendrites, most of which grew in a direction perpendicular to the substrate. However, the microstructure was fine and disoriented in the H13 tool steel clad deposited with CO2 laser whereas the microstructure was columnar dendritic in the diode laser deposited H13 tool steel clad. Hardness of CO_2 laser deposited clads was much higher compared to diode laser deposited clads.

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REFERENCES

[1] M. T. A. Rasgado, L. D. Clark, S. Hinduja, “Boundary element stress analysis for copper-based dies in pressure die casting”, *Computers & Structures*, 84 (2006), pp. 254–267.

[2] M. T. A. Rasgado, L. D. Clark, S. Hinduja, “Bi-metallic dies for rapid die casting”, *Journal of Materials Processing Technology*, 175 (2006), pp. 109–116.

[3] L. D. Clark, M. T. A. Rasgado, K. Davey, S. Hinduja, “Experimental investigation into the thermal behavior of copper-alloyed dies in pressure die casting”, *Transactions of the ASME*, 128 (2006), pp. 844-859.

[4] M. T. A. Rasgado, K. Davey, “Thermal models for copper-alloyed dies in pressure die casting”’ *Applied Mathematical Modeling*, 33/1 (2009), pp. 61-80.

[5] M. T. A. Rasgado, K. Davey, L. D. Clark, S. Hinduja, “Boundary element stress analysis for bi-metallic dies in pressure die casting”. *Journal of Materials Processing Technology,* 175 (2006), pp. 117–122.

[6] M. K. Imran, S. H. Masood, M. Brandt, “Microstructural investigation of direct metal deposition of h13 steel on high strength copper substrate”. *Proceedings of the World Congress on Engineering (WCE),* 1 (2009), pp. 704-708.

[7] V.E. Beal, P. Erasenthiran, N. Hopkinson, P. Dickens, C. H. Ahrens, “The effect of scanning strategy on laser fusion of functionally graded H13/Cu materials”. *International Journal of Advanced Manufacturing Technology,* **30**/(9-10) (2006), pp. 844-852.

[8] S. F. P. Pogson, W. O’Neill, C. J. Sutcliffe, “The direct metal laser remelting of copper and tool steel powders”. *Materials Science and Engineering A,* 386 (2004), pp. 453-459.

[9] G. P. Dinda, A. K. Dasgupta, J. Mazumder, “Laser aided direct metal deposition of Inconel 625 superalloy: Microstructural evolution and thermal stability”. *Materials Science and Engineering A,* 509 (2009), pp. 98–104.

[10] J. Mazumder, J. Choi, A. Schifferer, “Direct materials deposition: designed macro and microstructure”. *Materials Research and Innovation,* 3 (1999), pp. 118-131.

[11] J. D. Majumder, L. Li, “Studies on direct laser cladding of SiC dispersed AISI 316L stainless steel”. *Metallurgical and Materials Transactions A,* 40A (2009), pp. 3001-3008.

[12] M. K. Imran, S. H. Masood, M. Brandt, “Influence of process parameters in the direct metal deposition of H13 tool steel on copper alloy substrate”. *Proceedings of the World Congress on Engineering (WCE-2010),* London, U.K., 30 June-2 July 2010

[13] D. Srivastava, I. T. H. Chang, M. H. Loretto, “The effect of process parameters and heat treatment on the microstructure of direct laser fabricated TiAl alloy samples”. *Intermetallics,* 9 (2001), pp. 1003-1013.

[14] J. D. Majumder, A. Pinkerton, Z. Liu, I. Manna, L. Li, “Diode laser assisted surface nitriding of Ti-6Al-4V: Properties of the nitrided surface”. *Applied Surface Science,* 247 (2005), pp. 320-327.

[15] J. D. Majumder, A. Kumar, L. Li, “Direct laser cladding of SiC dispersed AISI 316L stainless steel”. *Tribology International,* 42 (2009), pp. 750-753.

[16] W. H. Syed, A. J. Pinkerton, L. Li, “Multiple-layer laser deposition of steel components using gas- and water-atomised powders: the differences and the mechanisms leading to them”. *Applied Surface Science,* 247 (2005), pp. 268-276.

[17] D. Srivastava, I. T. H. Chang, M. H. Loretto, “The optimisation of processing parameters and characterisation of microstructure of direct laser fabricated TiAl alloy components”. *Materials and Design,* 21 (2000), pp. 425-433.

[18] M. K. Imran, S. H. Masood, M. Brandt, “Effect of selected DMD process parameters on mechanical and microstructural property of cladded H13 tool steel on copper alloy substrate”. *Proceedings of the 6th Australasian Congress on Applied Mechanics,* paper no 1065, 12-15 December 2010, Perth, Australia.

[19] F. Liu, C. Liu, S. Chen, X. Tao, Y. Zhang, “Laser cladding Ni–Co duplex coating on copper substrate”. *Optics and Lasers in Engineering,* 48 (2010), pp. 792–799.