Influence of Process Parameters in the Direct Metal Deposition of H13 Tool Steel on Copper Alloy Substrate

M. Khalid Imran, S. H. Masood* and Milan Brandt

Abstract— **Bi-metallic die of steel coated on high thermal conductive copper alloy is of great interest as mould material for the aluminium high pressure die casting industries. Direct Metal Deposition technique is widely used for laser cladding of steel on copper substrate. The characteristics of the deposited layer are strongly dependant on the DMD process parameters. Precise selection of the process parameters for a sound deposited layer is a great challenge in this stream. This paper investigates the influence of various process parameters such as laser power, feed rate, powder mass flow rate and focus size on the deposition process. Reflectivity, a common phenomenon associated with laser metal deposition on copper was the major obstructing factor considered in the experimental procedure. Based on these parametric investigations a suitable set of parameters are suggested for laser cladding of steel on copper substrate without high reflection that can potentially harm the machine.**

***Index Terms*— Direct Metal Deposition, Process Parameters, Porosity, Reflectivity.**

I. INTRODUCTION

Direct Metal Deposition (DMD) is a laser cladding process for fabricating fully functional metallic parts directly from CAD data, which involves the beam from a high power laser creating a melt pool on the surface of a solid substrate into which a metallic powder is injected [1]-[3]. DMD is one of the leading commercial processes for rapid fabrication of net shaped solid metallic parts, in situ alloying parts, parts with conformal /internal features and metal molds for injection molding and die casting.

Copper alloys have made significant inroads in the manufacturing of moulds for plastic injection moulding by providing shorter cycle time [4]. But copper moulds and inserts cannot be used directly in high pressure die casting of aluminium because there is a strong chemical affinity between copper alloys and molten aluminium. If H13 tool steel is deposited on high strength Copper alloys to produce bimetallic die, it can give superior heat transfer performance compared to traditional tool steel die for high pressure die casting applications [5]. But deposition of H13 tool steel on Copper is not an easy task due to very different material properties of these two materials. Moreover the high reflective characteristic of copper makes the process further complex. However to be succeeded in producing quality bimetallic structure of Steel on Cu, DMD process parameters like laser power, focus size, scanning speed and powder mass flow rate need to be controlled precisely.

Several studies have been carried out for laser cladding technologies which mainly focus on selecting appropriate materials to be processed, developing the process, general process parameter selection etc [6], [7]. Some other works describe the characteristics of steel deposited on steel substrate [8]. DMD processed tungsten and Inconel 718 on high strength copper substrate are studied as well [9]. Although these works provide with knowledge of various aspect of DMD process, some important factors such as reflectivity of copper, influences of process parameters in manufacturing 3D structure of steel on copper substrate have not been well understood. Therefore specific study of the scientific and technical aspects of Direct Metal Deposition of H13 Tool steel on copper alloys is in great demand for die casting and injection molding industries. These studies involve characterizing the influence of the various process parameters on the deposition process, finding out any type of difficulty associated with 3D manufacturing of bimetallic structure of these two materials using DMD and finally selection of a suitable set of process parameters that overcome the associated difficulty for a sound and functional structure.

This paper closely investigates the influence of various process parameters such as laser power, focus size, scanning speed and powder mass flow rate on the deposition process of H13 tool steel on Copper substrate. To find out the relationship between process parameters and cladding, two common characteristics in rapid prototyping, distribution of porosity and micro cracks in the layer have been investigated. Reflectivity, a common barrier associated with laser processing on copper was highly considered during the deposition process. In fact a set of process parameters has been suggested that overcome high reflection and can produce a good quality layer.

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II. EXPERIMENTAL PROCEDURE

A. *Laser Cladding Trials*

H13 tool steel was deposited using POM DMD 505 machine which is capable of producing maximum 5 kW CO_2 laser power on Copper substrate. Steel powder and high strength copper alloy (Moldmax) were supplied by Sulzer Metco (Australia) Pty Ltd. and Bohler Uddeholm (Australia) Pty Ltd. The size of the steel powder particles was 90-106 micrometer. For analysis purposes, bead which is a single track produced in a single shot with one set of process parameters was constructed. The chemical compositions of the materials are listed in Table I and II. Among the various process parameters, four most influential parameters, powder mass flow rate, feed rate, focus and laser power were selected for investigation.

With this research, the main intention was to select a set of parameters that is capable of sufficiently melting both the materials therefore, at the beginning; few trials were carried out by changing the parameters randomly. These trials are summarized in Table III and deposited beads are shown in Fig 1 (numbered 1 to 8).

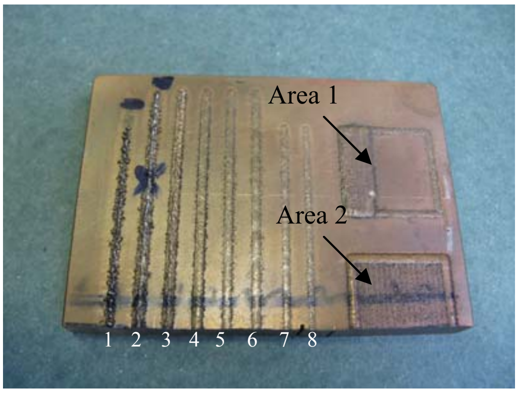

Figure 1: Beads produced with high power laser

After visual observation of the beads, one set of parameters with 3 kW laser power was selected for cladding a 25×25 mm square area shown in Fig 1 (area 1). The laser beam overlap was set at 50% and oxidation was avoided by an inert gas environment. Area 2 shown in Fig 1 was deposited with the same process parameters but tilted nozzle position.

Another series of experiments was conducted to examine the possibility of depositing steel powder using low power laser to avoid high reflection. Initially the nozzle was kept at tilting position for the safety purposes of the machine. The feed rate was fixed at 150 mm/min, while powder mass flow rate and focus size were in the range of 1.58 - 4.6 gm/min and (-) 18 – (+) 5 mm respectively. Two laser powers, 2 kW and 2.5 kW were used in these trials. These parametric combinations are listed in Table 4 and produced beads are shown in Fig 2 (numbered 1 to 13).

In these series of experiments a final set of experiment investigated the nature of reflection in large area deposition, therefore 15×15 mm area was deposited with 2 kW laser. Finally one 60×25 mm area was constructed with 2 kW laser in a single operation as shown in Fig 2 (area 1).

B. Metallurgical analysis

All the samples were cut transversely and polished with fine diamond polishing machine up to 1 micrometer to observe the porosity distribution of the deposited beads. The parts were etched using 2% nital to allow a precise microstructural view of the surfaces. All the SEM images were obtained using SUPRA 40 VP Scanning Electron Microscope manufactured by Carl Zeiss.

Table I: Chemical composition of Moldmax HH

Element	Be	Co + Ni	Cu
Chemical composition	1.9	0. 5	Balance

Table II: Chemical composition of H13 tool steel

Element	C	Mn	Si	Cr	Mo	V	Fe
Composition	0.35	0.4	1	5	1.5	1	Balance

Table III: Summary of the random trials

Laser power (W)	Powder mass flow rate (gm/min)	Focus size (mm)	Feed rate (mm/min)	Visual observation
1500	9.2	+20	500	No melting
2000	9.2	+20	500	No melting
2500	9.2	+20	500	No melting
4000	9.2	+20	250	Poor melting
5000	9.2	+20	250	Poor melting
5000	6.2	0	150	Poor melting
5000	3.15	-15	150	Poor melting
5000	1.58	-18	150	Better than previous one
5000	0.8	-18	150	Good melting
4000	0.8	-18	150	Good melting
3000	0.8	-18	150	Good melting

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Table IV: Summary of the trials to reduce reflection

Laser power (W)	Powder mass flow rate (gm/min)	Focus size (mm)	Nozzle angel (˚)	Visual observation
2000	4.6	-18	20	Very poor melting
2000	3.15	-18	20	Very poor melting
2000	1.58	-18	20	Poor melting
2000	1.58	-15	20	Poor melting
2000	1.58	-13	20	Poor melting
2000	1.58	-10	20	Poor melting
2000	1.58	-5	20	Good melting
2000	1.58	+5	20	Good melting
2500	2.3	+5	20	Good melting
2000	2.3	+5	15	Good melting
2000	2.3	+5	10	Good melting
2000	2.3	+5	5	Good melting
2500	2.3	+5	0	Good melting

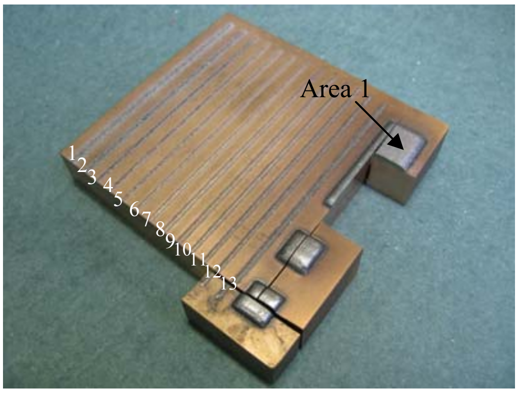

Figure 2: Beads produced with low power laser

III. RESULTS AND DISCUSSION

The first experiment considered beads on plate surface by melt fusion process to get a set of parameters that is capable of melting both the materials sufficiently. In the random trials, copper was thought to be melted with low energy, therefore the trials started with low power. But no bead was produced up to 2.5 kW laser power with high values of powder mass flow rate (9.2 g/min), feed rate (500 mm/min) and focus size (+20). It means the energy produced with the combination of these parameters was not able to melt the copper substrate. The high thermal conductivity of copper that transferred heat from the surface to the other part of the substrate made the melting further difficult. As a result, laser power was increased gradually with decreasing feed rate for higher intensity of energy to create a melt pool.

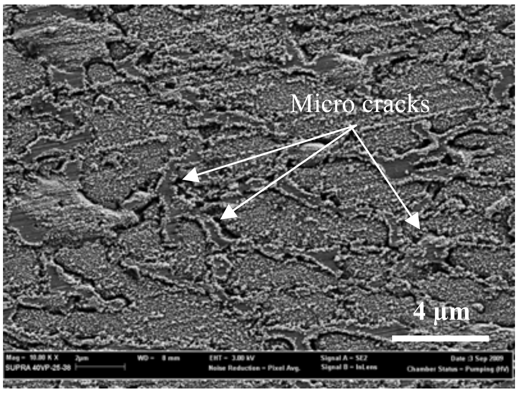

Figure 3: SEM image of the bead produced with laser power 5 kW, powder mass flow rate 3.15 gm/min, focus -15 and feed rate 150 mm/min.

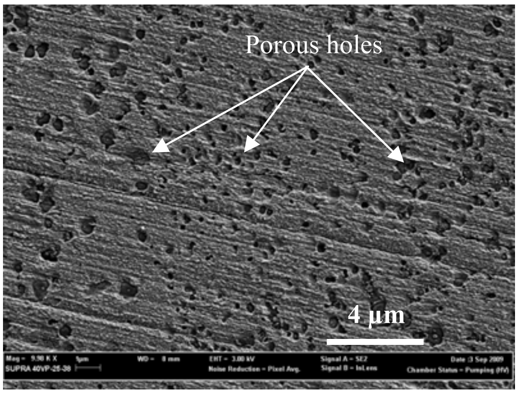

Figure 4: SEM image of the bead produced with laser power 5 kW, powder mass flow rate 1.58 gm/min, focus -18 and feed rate 150 mm/min.

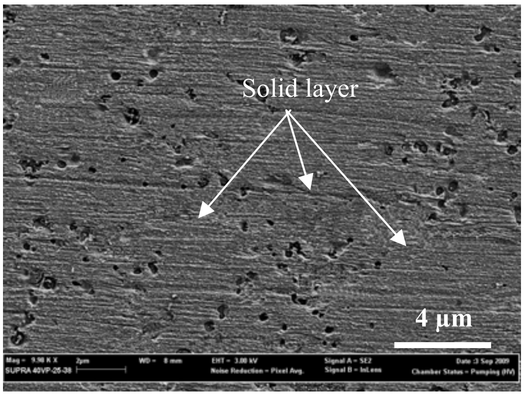

Figure 5: SEM image of the bead produced with laser power 5 kW, powder mass flow rate 0.8 g/min, focus -18 and feed rate 150 mm/min.

The first bead was produced at 4 kW laser power and 250 mm/min feed rate though melting of the materials was poor as shown in Fig 1 bead 1. The quality didn't improve even at maximum 5 kW power with all other parameters constant (bead 2 Fig 1). These beads clearly demonstrated the insufficient melting as lots of powder particles were present in the beads. High rate of powder mass flow rate lead the insufficient melting and presence of powder particles, hence it was reduced gradually. Focus size and feed rate were also reduced to increase the energy intensity when laser power was fixed at 5 kW. These reductions highly affected the deposition process as sound beads were visualized. The bead 4 in Fig 1 produced with powder mass flow rate 3.15 gm/min, focus -15 and feed rate 150 mm/min looked sound for further deposition. But the SEM image shown in Fig 3 depicts the presence of lot of micro cracks in the bead. These micro cracks are well described by Simchi [10] where he found that, at high laser energy input delamination of sintered layers and formation of large cracks are feasible. The image also shows insufficient melting due to the large powder mass flow rate. The bead quality improved with the reduction of powder mass flow rate. The SEM image shown in Fig 4 illustrates the microstructure of the bead produced with 1.58 gm/min. The microstructure shows presence of porous holes which reduces with the reduction of powder mass flow rate (Fig 5) when all other parameters are fixed. At high intensity of laser, delamination of laser processed layer due to thermal stresses, formation of gas pores during solidification, porosity formation due to material shrinkage and balling effects have been well studied [10] and lead the process towards reduced power. The beads produced with 4 kW laser power show reduced porous holes when beads produced with 3 kW laser power show almost porous free microstructure in Fig 6 and Fig 7 respectively. Though the microstructure shows low level of porosity, this set of parameters with 3 kW laser power was not suitable for large area deposition (Fig 1 area 1) as in this case, reflection from the substrate hit back on the nozzle and burnt it (Fig 8).

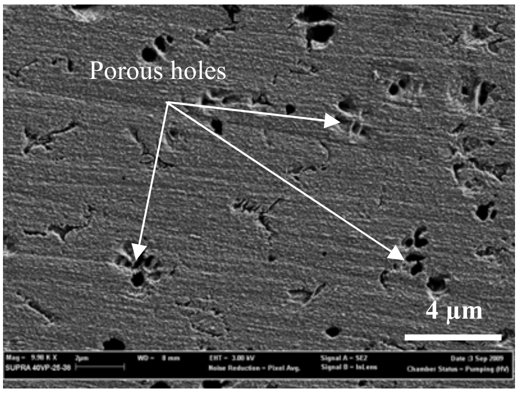

Figure 6: SEM image of the bead produced with laser power 4 kW, powder mass flow rate 0.8 g/min, focus -18 and feed rate 150 mm/min.

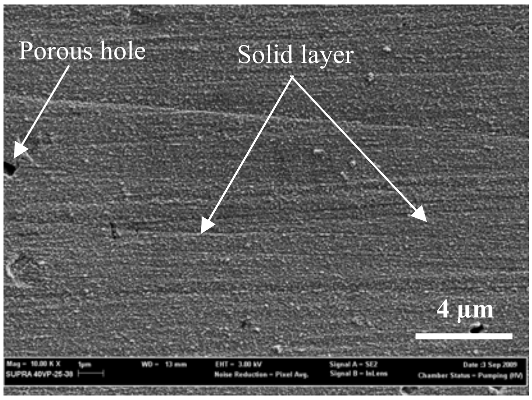

Figure 7: SEM image of the bead produced with laser power 3 kW, powder mass flow rate 0.8 g/min, focus -18 and feed rate 150 mm/min.

Making the substrate surface rough, tilting the nozzle head and reducing the laser power could be three ways to overcome the reflection. If the substrate surface is highly rough, it can leave potential defects at the interface [11, 12] and as a result the surface couldn't be made rough too much. In this experiment sand blasting was done to some extent, which was not capable of restricting the reflection completely. At the tilted position of the nozzle, reflection was high enough to burn the nozzle back plate and feedback tube of the machine (Fig 9) during large area deposition (Fig 1 area 2). Further tilting of the nozzle could potentially damage some other part as tilting the nozzle was not causing actual reduction of reflection rather driving reflection to some other place than the nozzle tip. Moreover while reading the CAD model for 3D deposition of complex shaped products, DMD machine doesn't operate from the tilting position. During CAD model reading, it creates its own tool path from the vertical position of the nozzle relative to the substrate. As a result, the laser power needed further reduction to avoid these consequences.

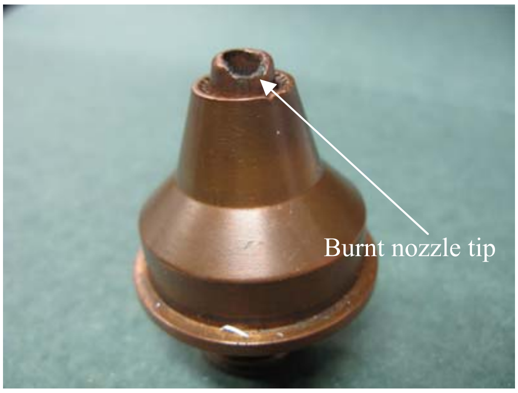

Figure 8: Burnt nozzle due to reflected heat at 3 kW laser power.

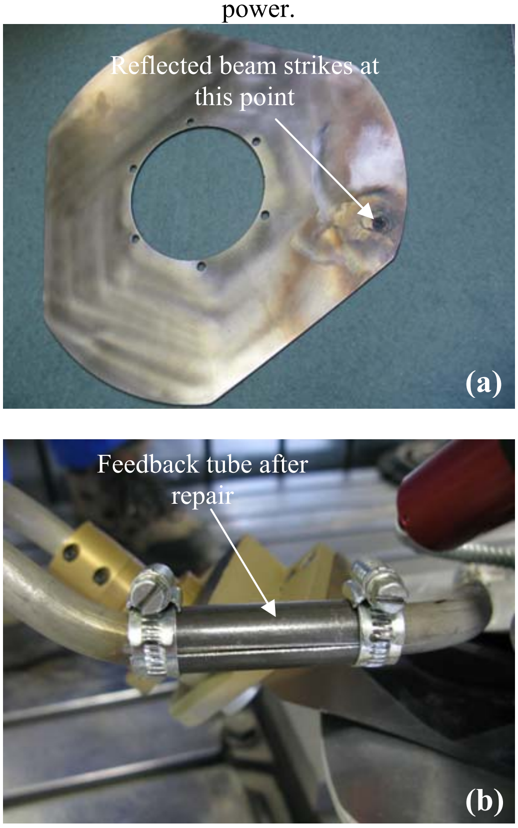

Figure 9: Burnt during large area deposition with 3 kW laser power and tilted nozzle (a) back plate and (b) feed back tube.

When the laser power was reduced to 2 kW, the bead produced with high level of powder mass flow rate was very poor with all the other parameters fixed (Fig 2 bead 1). The nozzle was kept tilted from the beginning to avoid any unexpected consequences. The bead quality didn't change much with the decrease of powder mass flow rate (Fig 2 beads 2 and 3) as incomplete melting could be visualized. The bead quality improved considerably with the decrease of focus size (Fig 2 beads 4-7). The melting was much better when the focus was changed from negative to positive (+5) with the same set of process parameters (Fig 10). The beads produced with 2.5 kW laser also showed sufficient melting (Fig 2 bead 9). But this power could be unfavourable in terms of reflection and was not used for large area deposition. Shifting the nozzle gradually to its vertical position didn't show any reflection to damage the machine. The 60×25 mm area constructed without any reflected beam (Fig 2 area 1) further verified the possibility of large area deposition with this set of process parameters.

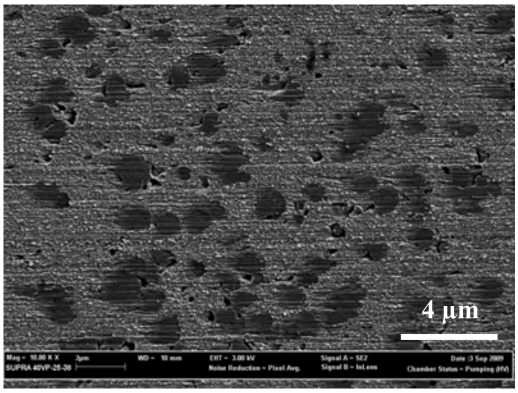

Figure 10: SEM image of the bead produced with laser power 2 kW, powder mass flow rate 1.58 g/min, focus -18 and feed rate 150 mm/min.

IV. CONCLUSION

The effect of processing parameters on the direct metal deposition of steel on copper was investigated. Based on the experimental trials, values of different parameters have been established for sound deposition of steel powder. From the achieved results, the following conclusions can be provided-

1) Though high intensity of energy is needed for DMD deposition of steel on copper substrate due to the higher thermal conductivity of copper alloys, high laser power (up to 3 kW) is not suitable as it reflects tremendous heat to cause damage to the machine. As a result 2 kW laser power is recommended for this application.
2) Low feed rate (150 mm/min) is applicable for all range of laser power as high feed rate (i.e. more than 150) cannot produce sufficient intensity of heat to create a complete melt pool on the substrate for sound bead.
3) Powder mass flow rate more than 1.58 gm/min is not recommended for any laser power as significant quantity of powder was not melted even at the maximum power.
4) Small focus size is suitable for low power laser when high power laser requires large focus size to create complete melt pool. Again negative focus is required for large laser power and positive focus is required for low (below 3kW) laser power.

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