JOURNAL OF MATERIALS SCIENCE 33 (1998) 1287–1292

Development of a new laser cladding process for manufacturing cutting and stamping dies

Y. P. HU, C. W. CHEN, K. MUKHERJEE
High Energy Laser Processing Laboratory, Department of Material Science and Mechanics, Michigan State University, East Lansing, MI 48824, USA
E-mail: mukherje@egr.msu.edu

An integrated powder delivery system is described, which can provide a highly stable, continuous, and accurate powder feeding rate, and deliver the alloy powders coaxially into the laser-generated molten pool to form high-quality cladding tracks. By combining such a powder feeding system and computer-aided design/computer aided machining system, complex, three-dimensional geometric patterns were deposited on AISI 1045 steel plate or roller via laser cladding for manufacturing cutting and stamping dies, and laminated metal matrix composites. The microstructures of cladding layers, interface, and heat-affected zone were characterized, and the microhardness of a transverse section of single cladding tracks was also measured. © *1998 Chapman & Hall*

1. Introduction

The aim of laser surface cladding is to deposit a coating material, with required properties, on to different metallic substrates in such a way as to produce a good metallurgical bonding with the substrate to improve surface properties such as wear resistance, corrosion resistance, and high-temperature oxidation resistance [1–6]. One essential criterion is to produce a minimum dilution of the cladded layer by the elements from the substrate or vice versa.

The quality of laser cladding tracks depends upon the processing variables, especially position, stability, continuity, and accuracy of the powder feeding. Even a small deviation of the powder flow rate, and the location of powder delivered with respect to the laser beam centre, will lead to a significant variation of the geometry, thickness, and smoothness of the cladding layer.

Lateral powder-feeding systems have been commonly used for laser surface alloying and cladding [7–9]. However, in terms of our laser cladding experience, such a feeding system has many drawbacks. First, it is difficult to align the location of the powder delivery with respect to the laser beam centre. This positioning is very critical, and a small deviation will greatly decrease the powder utilization efficiency, and lead to a poor quality of cladding tracks. With side powder feeding systems, preheating or premelting of the powder do not occur; as a result, cladding tracks are generally rough, and the thickness and width of tracks are not uniform. Second, a side-feeding system, once set up, might work reasonably well for a linear cladding track, i.e. x- or y-motion only, but does not work for complex geometric patterns requiring bi-directional motions. Typically, the inclination angle between the delivery tube and horizontal plane is $25°$–$35°$, and the distance from the delivery tube tip to the interaction zone is about 12–15 mm, so the distance from the laser nozzle tip to workpiece requires a clearance of at least 20 mm. This gap is so large that the shielding gas is not fully able to protect the cladding surface from oxidation. If the cover gas-flow rate is increased to overcome this problem, the powder is blown away. For these reasons, it is necessary to utilize a powder feeding system, which produces high stability, continuity, and accuracy of powder flow, while, avoiding oxidation, under an actual production condition.

Few authors have reported the detailed design of a nozzle which has a coaxial powder flow [10, 11]. One of these designs [10] utilizes a nozzle such that the powder stream interacts with the laser beam inside the nozzle. As a result, molten or partially molten particles are produced inside the nozzle. Because of that, the nozzle tip frequently wears out. In another design [11], a cone-shaped powder stream (its vertex lies on the specimen surface) interacts with the laser beam just on the surface of a substrate, and therefore the coaxial nozzle (equipped with water-cooling system) performs very well for laser surface alloying and cladding for on-line production. This paper describes the design of such a nozzle which is integrated with a fluidized-bed, metered delivery system along a computer-controlled laser and motion tables. Using this system, we present some results related to die manufacturing.

2. Experimental procedure

AISI 1045 steel plates and rollers were used as the substrates, and CPM 10V and CPM 15V alloy powders were used as the hard-facing materials. The substrate surfaces were ground before laser treatment. The chemical compositions of the substrate and the clad materials are listed in Table I.

TABLE I Chemical composition (wt%) of the substrate and clad materials

Materials	Fe	Cr	V	C	Mn	Mo	Si	Ni	S
1045 steel	Bal.	–	–	0.43–0.5	0.6–0.9	–	–	–	0.05
AISI 304L	Bal.	18.5	–	0.024	1.44	–	0.55	9.5	0.019
CPM 10V	Bal.	5.25	9.75	2.45	0.50	1.30	0.90	–	0.09
CPM 15V	Bal.	5.25	14.5	3.40	0.50	1.30	0.90	–	0.07

TABLE II Process parameters used for the laser cladding operations

Sample	Layers	Power (W)	Spot size (mm)	Traverse speed ($mm\,s^{-1}$)	Powder feed rate ($g\,s^{-1}$)	Overlapping percentage (%)
A	CPM 10V	2073	3.4	3.9	0.17	–
B	CPM 15V	2400	2.3	4.7	0.25	–
C	1st 304L	1914	1.8	3	0.12	25
	2nd CPM 10V	1326	1.8	4.9	0.08	50
	3rd 304L	1326	1.8	4.9	0.08	50
	4th CPM 10V	1326	1.8	4.9	0.08	50
D	CPM 10V	2073	1.8	3.9	0.17	–
E	CPM 10V	2073	2.3	3	0.17	–

A continuous-wave CO_2 laser was used as the energy source, and it was operated in TEM_{01*} mode. The laser-spot diameter, on the specimen surface, was varied from 1.8–3.4 mm. A precision powder injection system (METCO model 9MP) was used to deliver alloy powders into the laser-generated molten pool through a specially designed coaxial nozzle. Argon gas was used as the medium for powder transport and shielding. Coaxial cover gas flow rate was fixed at $1.27\,m^3\,h^{-1}$. A computer-aided design/computer-aided manufacturing (CAD/CAM) system was used for laser cladding experiments. Optical microstructural analysis, and microhardness tests were carried out to characterize the cladding layers, interface, and heat-affected zone (HAZ). The processing parameters of selected samples shown in this paper are listed in Table II, and the experimental setup is shown in Fig. 1.

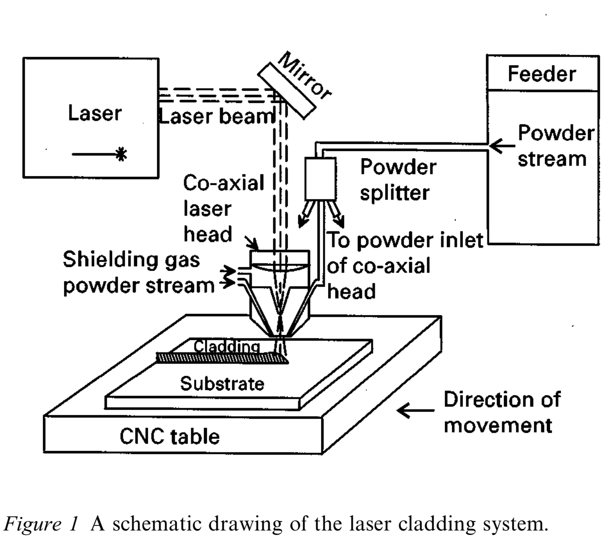

Figure 1 A schematic drawing of the laser cladding system.

3. Results and discussion

3.1. Design of an integrated powder feeding system

The integrated powder delivery system designed, includes a close-loop powder feeder, a powder splitter, and a coaxial nozzle, as shown in Fig. 2.

3.1.1. Powder feeder

A close-loop powder feeder (METCO Model 9MP) was used for providing a stable, continuous, and accurate powder feeding rate. It utilizes a weight-loss metering system as feedback for the powder feed rate. The powder feeder works on a fluidized-bed mechanism, in which various feed rates are obtained by adjusting the pressure difference between the hopper and the pickup shaft. This system is capable of consistently delivering alloy powder at rates as low as $0.07\,g\,s^{-1}$.

3.1.2. Powder splitter

The powder feeder transports the alloy powder, through a hose, to the powder splitter by using pressurized argon gas (called carrier gas). The powder stream is split into four streams of powder flow. These four streams are then carried through four tubes to the circumferential channel between the middle and the external nozzles.

3.1.3. Coaxial nozzle

Fig. 3 is a schematic diagram of the transverse section of our coaxial nozzle. The specifications of this design, however, were developed by researchers in the High Energy Laser Processing Laboratory (HELP), Michigan State University, based on our extensive preliminary investigations.

Figure 2 A view of an integrated powder feeding system.

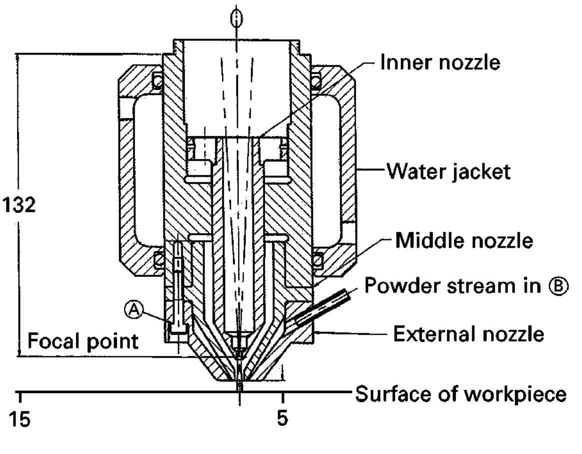

Figure 3 A schematic drawing of the transverse section of a coaxial nozzle. (A) 3 screw bolts, (B) 4 inlets. All dimensions in mm.

The coaxial nozzle consists of an inner nozzle, a middle nozzle, an external nozzle, and a water jacket for cooling. The inner nozzle has a channel, through which the focused laser beam passes, and a shielding gas flows. The positive pressure of this shielding gas prevents the particles from flowing up to the lens. As shown in Fig. 3, the local point of the laser beam is positioned at the tip of the inner nozzle to allow minimum opening for most effective protection of the lens. The shielding gas also protects the cladding layer from oxidation.

The middle and the external nozzles from a cone-shaped circumferential channel, with 27° cone angle,

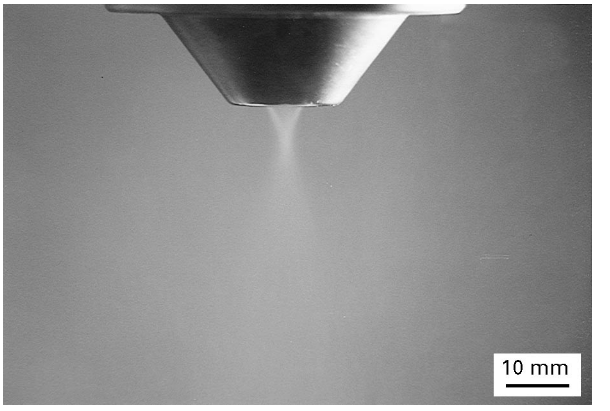

Figure 4 A view of cone-shaped powder stream.

where four parts of powder streams meet and converge to form a cone-shaped powder stream with the same central axis as the laser beam. Fig. 4 shows the nature of powder flow through the coaxial nozzle. This cone of powder finally interacts with the laser beam on the surface of a workpiece to form cladding tracks. As a result of precise deposition of the powder with respect to the centre of the laser beam, the powder utilization coefficient for our coaxial feeding system is up to about 80%. Further details about measuring the powder utilization coefficient may be found elsewhere [12]. Because the working distance, from the bottom surface of the coaxial nozzle to the specimen surface, is fixed at about 5 mm, spaces (each 5 mm thick) are inserted between the middle nozzle and the nozzle block for adjusting defocus distance, which controls the spot diameter on the work piece. Therefore, the range of spot diameter is between 1.8 and 3.4 mm.

During the laser cladding process, a considerable amount of laser radiation is reflected on to the bottom surface of the nozzle, which heats it to a relatively high temperature. Therefore, a circulating-water cooling system is necessary to prevent overheating of the nozzle. From our study, this nozzle, equipped with a cooling system, can work very well under continuous long-term use, for manufacturing patterned dies via laser clading.

3.2. Applications of the integrated powder-feeding system

This integrated powder-delivery system avoids all of the drawbacks of a lateral powder-feeding system. It can provide a highly stable, continuous, and accurate powder-feed rate, and deliver the powder stream precisely into the molten pool on the substrate to form high-quality cladding tracks. Also, this system allows deposition of complex geometric patterns on a flat, or a curved surface for different applications, such as fabrication of rotary cutting dies, repair of turbine blades, and rapid prototyping of forging dies. By adjusting the pressures of carrier gas, and the coaxial cover gas, the amount of preheating of powder can be controlled.

Fig. 5 shows an overview of a single cladding track on a AISI 1045 steel flat plate. The cladding track,

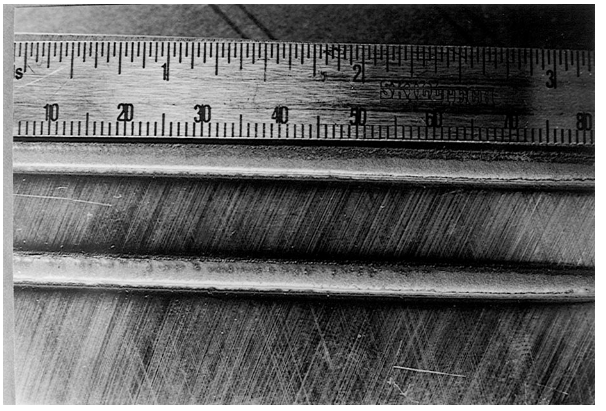

Figure 5 A view of single hard-facing cladding tracks with a smooth surface, uniform cladding thickness, and width (Sample A).

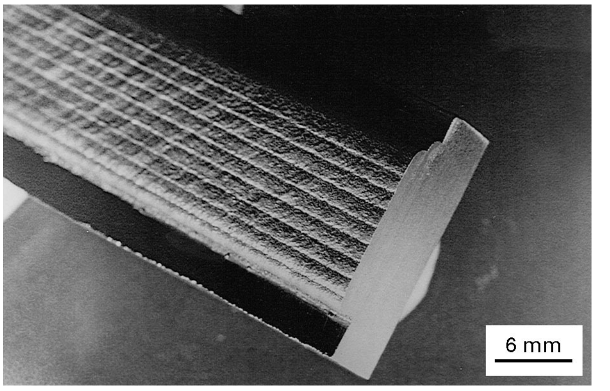

Figure 7 A top view of LMMC sample with smooth surface, no macroscopic cladding defects, and sharply discrete interface via laser cladding (Sample C).

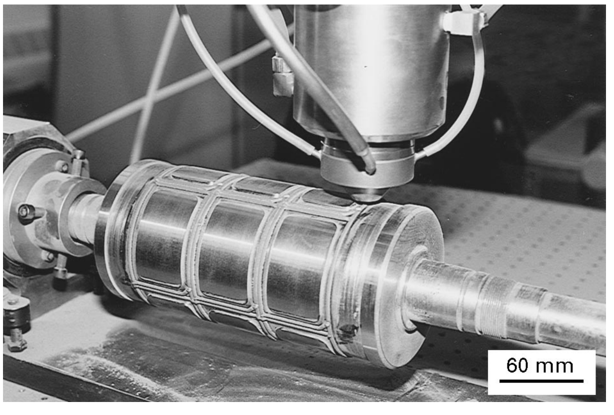

Figure 6 Hard-facing tracks, with complex geometric patterns, deposited on a steel roller for fabricating a rotary cutting die by the laser cladding process (Sample B).

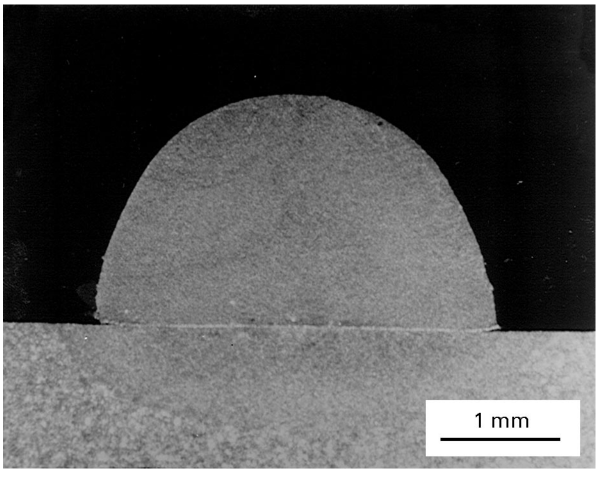

Figure 8 An optical micrograph of the cross-section of hard-facing tracks with no cladding defects (Sample D).

which is 80 mm long, 4 mm wide, and 1.5 mm high, is smooth in appearance, and upon testing, found to be metallurgically sound.

Fig. 6 displays a view of hard-facing tracks, with a relatively complex geometric pattern, on an AISI 1045 steel roller of 101.6 mm diameter. The cladding tracks (with smooth surface and no macroscopic cladding defects) are 1.8 mm high and 3 mm wide. The experimental result demonstrated that the curvature of a substrate can be accommodated, in this system, to produce a high-quality circumferential clad formation. Thus, this new process has opened a novel application field of laser-assisted die manufacturing, through which complex geometric patterns on steel substrates can be deposited for manufacturing cutting and/or stamping dies.

Fig. 7 is a view of a laminated metal matrix composite (LMMC) sample produced by our laser cladding process. The LMMC sample with a smooth surface, in which stainless steel 304L is used as one layer, and tool steel CPM 10V as the second layer, is free of porosity and cracks, and has smooth and discrete interfaces. The overlap between two adjacent tracks is about 50%. Two separate powder hoppers and metering systems (METCO Model 9MP) were used to automate fully the LMMC layers.

3.3. Microstructures

3.3.1. Microstructure of the cross-section of a single cladding track

Fig. 8 is an optimal micrograph of the cross-section of a single clad track. Typically, three zones in a good cladding track are observed: clad zone, interface zone, and heat-affected zone (HAZ). The clad zone is the rapidly solidified molten alloy. The interface zone is a transitional zone between the clad zone and the substrate. The heat-affected zone is produced by the laser energy transferred to the substrate. The clad track (Fig. 8) looks smooth, is free of porosity and macrocracks, and has a complete fusion bonding with the substrate, with a minimum dilution.

3.3.2. Vanadium carbides

Vanadium contents in CPM 10V and CPM 15V are up to about 10 and 15 wt%, respectively. Its major characteristic is the formation of highly wear-resistant carbides. Vanadium carbide is one of the hardest carbides found in high-speed steel. That is why highly wear-resistant tool steel CPM 15V was used to produce the cutting blades on AISI 1045 medium carbon steel roller by a laser cladding process. Fig. 9a shows that fine spherical vanadium carbide particles are

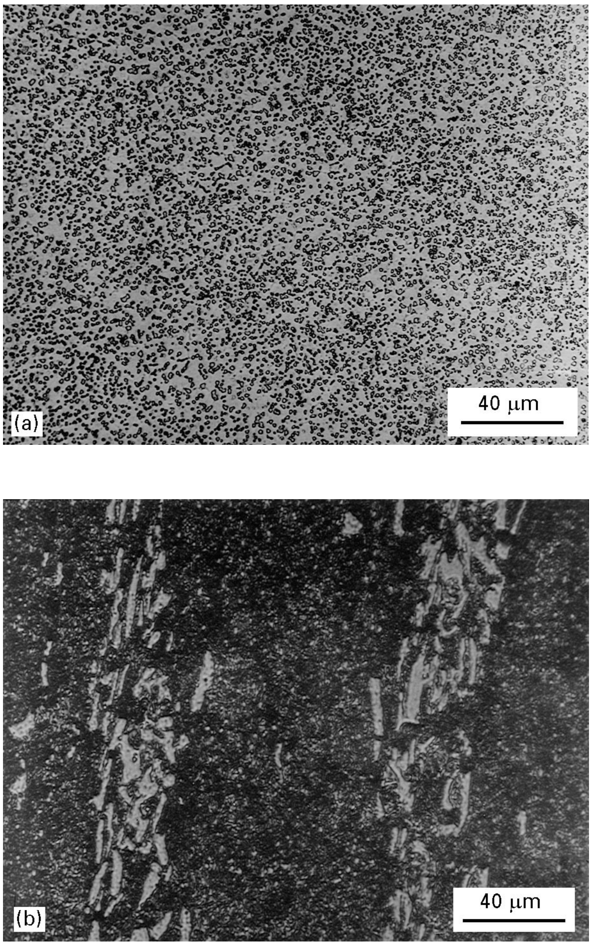

Figure 9 Overview of carbides in CPM 10V and D2 alloys. (a) Fine vanadium carbides uniformly dispersed in the matrix in CPM 10V tool steel (Sample E). (b) Segregation and blocky carbide morphology in D2 alloy.

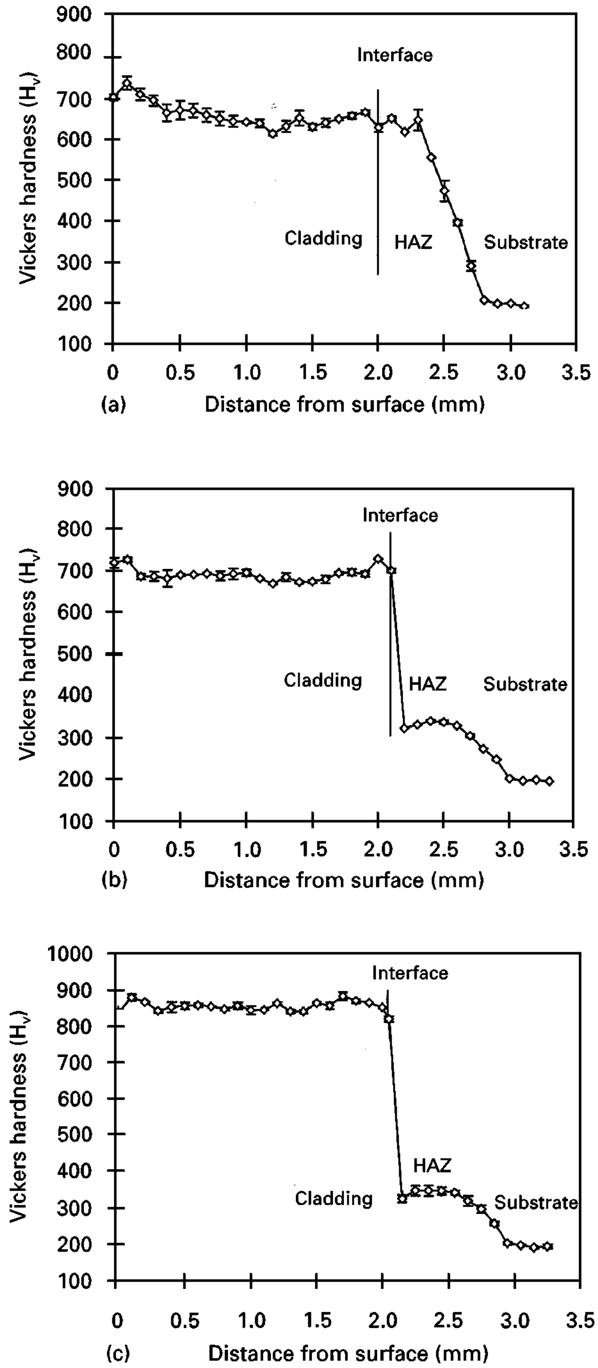

Figure 10 Microhardness profiles of sample E: (a) as-clad, (b) as-clad + tempering, (c) as-clad + tempering + liquid nitrogen treatment.

uniformly dispersed in the matrix, which consists of martensite and retained austenite. Segregation and blocky carbide morphology in D2 alloy, which is currently used in the die-making industry, is shown in Fig. 9b for comparison. Although we have not conducted any wear test, based on the comparison of microstructures, it is expected that wear-resistance of the cutting blades, which are made of CPM 15V by the laser cladding process, will be significantly improved.

3.4. Microhardness measurement

Fig. 10 shows Vickers hardness measured from the CPM 10V clad to the substrate under different treatment conditions. Fig. 10a shows that the hardness of the as-clad sample without any heat treatment is about 650 H_v, which is approximately equal to that of the conventional tool steel D2, after standard heat treatment.

Because retained austenite in high-alloy steels is very stable, it must be tempered above 500 °C, and transformed to martensite. Also, the tempering treatment can further increase the hardness of the steel by secondary hardening and the formation of hard martensite [13, 14]. For this reason, after the sample was double tempered at 540 °C for 15 min each, the hardness increased to about 700 H_v, as shown in Fig. 10b.

After the tempered sample was dipped in liquid nitrogen for 15 min, the hardness increased to 850 H_v due to transformation of the retained austenite to martensite, as shown in Fig. 10c. The high hardness and fine carbide particle distributions in cladding layers help prolong the service life of cutting dies in comparison to D2 alloy.

4. Conclusion

The integrated powder-feeding system, and processing parameters developed by us can be used for laser-assisted die manufacturing at a significantly reduced cost (cost-effective structural steel replacing an expensive tool steel die block, and minimum machining required after laser cladding) and improved quality. This system is also suited for deposition of patterned laminated MMC layers on a flat or a curved surface for various applications, such as fabrication of rotary cutting dies, repair of turbine blades, and rapid prototyping of forging dies.

Laser-clad hard-facing tracks, with relatively complex geometric patterns, produced on a steel roller, were found to be smooth and metallurgically sound. The thickness and width of the cladding tracks was very uniform, and could be controlled to within 50 μm by using the specially designed coaxial nozzle. Optical micrographs showed that hard-facing tracks are free of porosity and cracks, and have a complete fusion with the substrate. Optical micrographs also showed that fine vanadium carbide particles are uniformly dispersed in the matrix. This microstructure might significantly improve the wear-resistance of the cutting dies thus produced. A hardness of cladding tracks up to 650 H_v has been achieved without any post-cladding treatment, and the hardness increases to about 850 H_v after cooling to the liquid-nitrogen temperature, which causes transformation of the retained austenite to martensite.

Acknowledgement

This project was partially funded by the Composite Materials and Structures Center of Michigan State University, through the State of Michigan Research Excellent Fund.

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Received 27 November 1996
and accepted 23 October 1997