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Developing New Applications Based on Laser Additive Manufacturing of WC Cermets and WC Forming Alloys

(Invited Paper)

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Abstract Laser additive manufacturing (LAM) of tungsten carbide metal matrix composites (MMCs) has been evaluated for surface modification of hot die forming tools，cutting edges，glass tooling，extrusion mandrels，and other abrasive wear applications. This work focuses on transitions from tool steels to MMCs through a single pass laser powder deposition operation. Issues related to the application of various metal powders and carbides used include surface hardness，porosity，cracking，and dilution. These issues along with factory results that were obtained during this project are discussed.

Key words laser technique；laser additive manufacturing；alloy

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1 Introduction

Manufacturing industries that form metal and glass can benefit from tools and dies that have better wear characteristics，thermal properties，and reduced chemical reactivity with the product being formed. Most tools and dies are made from H-13 or some other grade tool steel. These materials are relatively inexpensive，but exhibit numerous failure modes including heat checking，soldering，fatigue，chipping，cracking，loss of hardness，and corrosion. As the tools deteriorate，problems including poor mold release and surface imperfections arise，which result in part rejection and reduced process efficiency including increased energy consumption. Using higher performing materials could mitigate these problems，but fabricating tools from these materials would significantly increase their cost. In this investigation，the advantages of using some of these higher performing materials are being sought by cladding them onto the commonly used tool surfaces by using laser additive manufacturing (LAM).

LAM also offers a convenient means of producing a compliant transition from conventional carbon steels (e.g.，1018，1566，4140，and 4340) to higher performing materials (selected based on the application). LAM is a flexible and rapid manufacturing technique that directly deposits metal powder into a molten metal pool produced by laser interaction with the underlying metal surface thereby forming a clad or laminate layer on the metal surface[1]. The advantages of LAM over other manufacturing techniques for tool modification include the minimal heat affected zone，high solidification rate resulting in fine grain size，minimal segregation，minimal second phase coarsening，high density coating，and minimal mixing of the cladding with the base material (dilution). Other advantages include near-net shape，good surface durability and finish，efficient material use，and versatile part manufacturing or repair[2~5].

The paramount issue that arises in placing surface layers of high performance metals onto these steels is the nature of the bond with the steel and thermal stresses[2] at the interface. Since the desired surfacing materials might not always produce the best metallurgical interface and therefore not produce the most compatible mechanical properties with the substrate steel，the working surfaces of these steels were laser-deposited with a variety of metals to determine compatibility. Since different applications have varying and different material requirements，a variety of materials were selected for use in this study. LAM cladding with more conventional alloys (nickel and stainless steels alloys) onto the end of H-13 bars and plates of 4140，4340，and HSS 80 were performed during the initial investigations. Industrial tools have been clad with higher per-

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forming materials and delivered for testing in actual manufacturing operations (e. g., hot die forging and hot extrusion).

2 Evaluation Procedure

The LAM cladding experiments were conducted with Ni-based and Co-based super alloys on tool steel bars, carbon steel plates and actual industrial tools and dies. Inconel (625 and 718)[6], Stellite (6 and 21)[7~11], CCW+ , and NiTung60 (NT-60) were selected for their high-temperature wear and corrosion resistance properties[6~9]. All of these alloys produced a compliant metallurgical interface with the steel bars and plates. H-13 tool steel and 4140 carbon steel were selected since they represent the most common heat treatable alloys used in the tool and die industry. It was observed that these steel tools and specimens in the heat treated state exhibited little softening at the interface after the LAM cladding operation. The Inconel (625 and 718) and Stellite (6 and 21) were successfully deposited with no cracking, little porosity, and a good metallurgical interface, but were removed from the forging and die application testing due to low hardness and low wear resistance. The tool steel alloys M4, 10V, Rex 20, and Rex 121 also clad well and had great wear resistance but these alloys did not retain their properties at elevated temperatures. Several Co-based cermets were also evaluated but failed to produce good clads due to excessive porosity and cracking. In the end, two alloys, CCW+ , a Co-Cr alloy containing Mo and W, and NT-60 a Ni-based WC cermet, were selected for tooling applications. Table 1 gives the typical chemical compositions of some of the alloys that were deposited by LAM during this investigation.

Table 1 Typical chemical composition of some of the alloys evaluated for LAM cladding
(X indicates that the amounts of Si and B are proprietary)

	Inconel 625	IN718	Stellite 6	Stellite 21	CCW+	NT-60
C	0.4	0.03	1.2	0.26	0.15	
Cr	22.0	18.6	28.4	26.4	27	
Co	0.01	0.3	Bal	Bal.	Bal	
Nb/Ta	3.9	5.2			0.7	
W			5.3		4	
Mo	8.64	3.0	0.03	5.6	5.5	
Al	0.3	0.55			–	
Ti	0.3	0.97			–	
B		0.004			0.05	X
Zr					–	
Ni	Bal.	52.2	2.1	2.7	2.75	40
Mn		0.11	0.34	0.53	0.5	
Si	0.05	0.1		1.8	0.3	X
Fe	0.3	18.6	2.1	1.3	2	
N		0.005			–	
WC					–	60

The CCW+ while not having exceptional wear resistance was selected since it retains its properties at elevated temperature (600 ℃) and precipitation hardens making it a good candidate for the hot die forging and extrusion mandrel applications. The NT-60 did not perform as well as CCW+ in the hot die forging application but is a better solution for where there is a need for the elevated temperature abrasion resistance, such as in the glass forming industry.

Each candidate alloy was LAM clad either to a section of carbon steel 12.5-mm-thick plate (4140 or HS-80) or to the end of H-13 tool steel 35-mm-diameter bars for the preliminary evaluations. The LAM clad steel plates and the H-13 bar were sectioned about 3 mm below the clad interface for metallurgical evaluation. The quality of each of these specimens was determined by microstructural evaluation consisting of Vickers micro-hardness measurements and optical microscopy of the interface. These specimens were inspected for cracking, lack of fusion and porosity. Included with the initial evaluations, LAM clad material standard wear test specimens were also produced. Three 12-mm-thick plates of 4140 or 4340 steel, 25-mm width by 75-mm length were LAM clad for the wear test specimens for each material and condition. The standard technique for evaluation of these LAM clad materials included optical microscopy, micro hardness (Vickers), surface hardness (Rockwell C), wear testing (ASTM G65). Selected alloys were then applied to actual tools for field test evaluations that included hot die forging and hot extrusion.

3 LAM Cladding Results

Figure 1 is optical micrographs of LAM clads of the Carpenter Alloys CCW + and NT-60 on 4140 (hot rolled-annealed condition). As with the most of the alloys investigated, the LAM clads show no interfacial cracking, little porosity, and an abrupt transition in hardness at the interfaces. In Fig. 1(a), the faceted WC particles can be seen dispersed throughout the nickel matrix. The morphology of the WC particles indicates no melting and little dilution of the WC in the nickel matrix. The abrupt change in the microstructure and hardness at the interface also indicates limited dilution (mixing) of the clad with the substrate material. In the case of CCW +, there is an indication of hardening of the carbon steel plate as shown in Fig. 1(b) and with hardened H-13 as shown in Fig. 2. This maybe due to the diffusion carbon into the substrate material, further work is needed to study this observation.

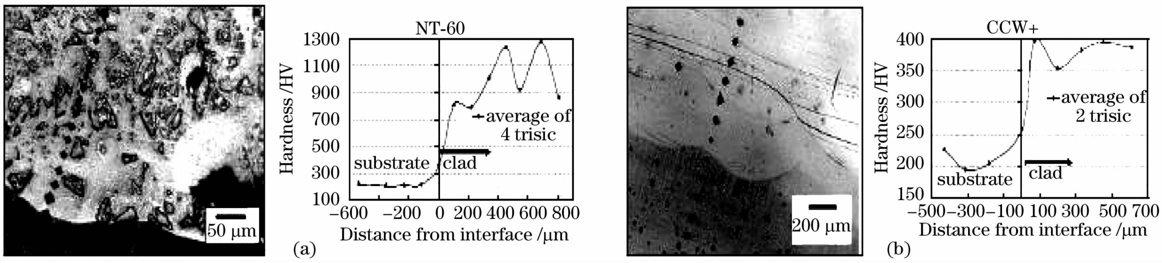

Fig. 1 Laser deposited samples on 4140 showing typical optical micrograph morphology of (a) NT-60, and (b) CCW + with the corresponding Vickers micro-hardness measurements

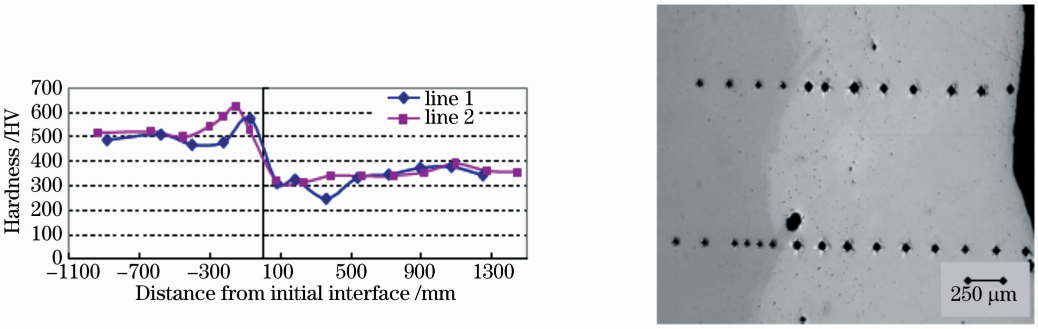

Fig. 2 Micro-hardness results of CCW + LAM clad on H-13. Note the slight increases in the H-13 hardness in prior to the interface

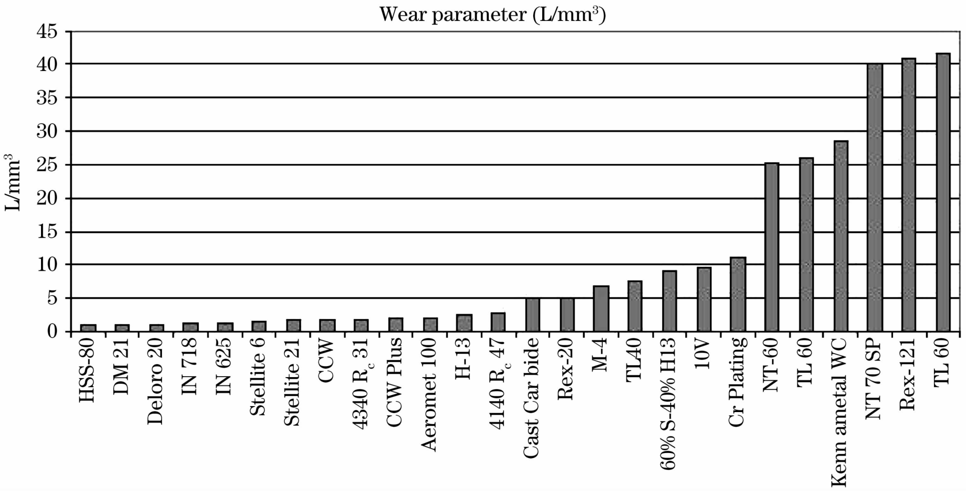

Fig. 3 ASTM G65 dry abrasion test results from LAM clad materials on 4140 carbon steel

Wear testing results are given in Fig. 3. The tool steels, hard chrome, and WC cermets gave the best wear results compared with the other alloys. A 4340 carbon steel heat-treated to a R_c 31 was used for calibration of the test and 4140 carbon steel heat treated to R_c 47 was used as a baseline. The Ni-based super alloys in the as-deposited condition all show higher volume loss than the calibration standard 4340 indicating low abrasive wear resistance. The Stellite alloys 6 and 21, CCW, CCW+, H-13, and AeroMet 100 in as-deposited condition all show abrasive wear resistance results similar to the heat-treated 4340 carbon steel. The tool steel alloys M4, 10V, and Rex 20 in as-deposited condition produced abrasive wear resistance results similar to the hard chrome plating. Rex 121, Technegenia TL60, Kennametal WC, and NT-60 (a Carpenter Cermet alloy) in as-deposited condition produced abrasive wear resistance 5 to 6 times higher than hard chrome plating. However, highly alloyed tool steels (i. e., Rex 121, Rex 20, and 10V) and the WC cermets (including TL-60 and Kenametal WC) also exhibit severe cracking and porosity in the as-deposited condition.

The LAM clad NT-60 in the as-deposited condition was cracking and porosity free giving. It appears that the NT-60 gives the best combination of wear resistance and toughness in the as-deposited condition. It should be noted here that pre-heating the substrate can mitigate cracking in some cases, however, the results obtain with NT-60 where obtained without pre-heating.

4 LAM Tooling Results

4.1 Hot Die Forging and Extrusion

Anvils (as shown in Fig.4) and extrusion punches (as shown in Fig. 5), were both LAM clad with CCW + and NT-60 and then inserted into actual industrial operations. The typical LAM processing parameters used during the cladding operations were laser power of 600 W, linear speed of 15 mm/s, layer thickness of 0.75 mm, and spacing width of 0.5 mm.

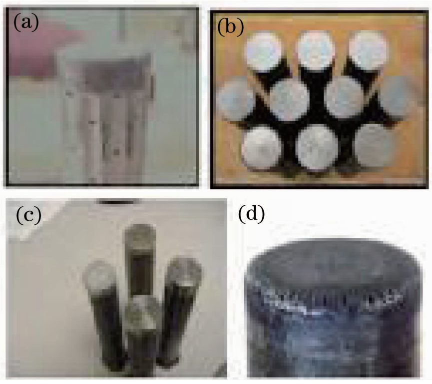

Fig.4 Photographs of H13 hot die forging anvils. (a) after use (~6000 cycles); (b) LAM clad; (c) clad and finished machined; (d) NT-60 clad anvil after ~10000 cycles

Fig.5 Extrusion punch tools LAM clad with (a) NT-60 and (b) CCW-plus

The distinct interface indicates limited dilution (mixing) of the Ni matrix with the H-13 substrate while maintaining a metallurgical bond. Forging trails with these tools have achieved cycles of up to 18000 for NT-60 and over 22000 CCW+ . Results from LAM CCW + clad extrusion punch trials showed a 60% improvement over unclad H-13 tool life. However, the tool was taken out of service before end of life.

4.2 Glass Forming Tooling

Tooling for the glass forming industry is also being evaluated. Several current alloys used by the glass industry were evaluated for LAM processing, however, only the Carpenter NT-60 produced porosity and crack free deposits. Further refinement of the NT-60 clad was needed to improve glass properties that are affected by the plunger surface characteristics (e. g., porosity, cracks, and finish), this included using finer size fraction carbides (< 45 μm) and less volume fraction WC (50%). Figure 6 is microstructures of normal NT-60 compared with the modified NT-50 version. Factory tests of these clad tools revealed that the matrix was too soft (resulting in degradation of finish over time), therefore a harder matrix has been applied and further factory test is scheduled for the first quarter 2010.

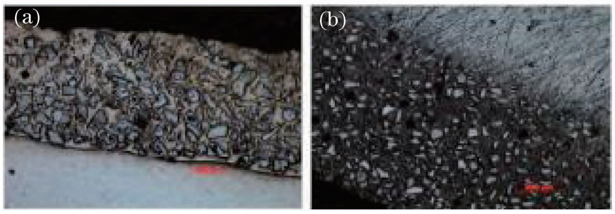

Fig.6 Optical micrographs of (a) NT-60 with standard sized carbides (~100 μm) and (b) NT-50 with fine carbides (<45 μm) and 50% volume faction carbides

4.3 Internal Bore Cladding for Plastic Injection Molding Barrels

Plastic injection molding barrels currently use cast tungsten carbide for abrasion resistance. Spirex Corp., Youngstown, OH has been exploring methods for improving the wear resistance and reducing cost in barrel manufacturing. Part of this investigation involved the selection of a superior wear resistant material. Several tungsten carbide compositions were evaluated with a variation of Carpenter's NT-60 producing a excellent laser clad with a wear resistance 5 times better than cast carbide when tested by ASTM-G65. The composition of this variation used the same Ni-Si-B matrix with a 70% volume fraction spherical tungsten carbide (NT-70SP). Process control was very important during this investigation. The process parameters developed for this project produced a microstructure with 70% volume fraction. Processing conditions that had excess energy input resulted in carbide dissolution as shown in Fig. 7. Figure 7(a) shows micrograph of the NT-70SP with high energy input, Fig. 7(b) revealing a high volume fraction tungsten carbide when laser cladding in an optimized processing condition. The key for this application is that the deposit is performed in one layer at about 1.5-mm thickness. Currently test samples of internal bore laser clad have been produced for both single and double bore barrels. Internal bore sections at a diameter of 60 mm have been clad to a depth of 150 mm. The actual barrels will be on the order of 2000-mm length with internal diameters from 50 mm to in excess of 120 mm. A test barrel for factory testing should be in place by the fourth quarter of 2009. Examples of clad single and double barrel test sections are shown in Fig. 8.

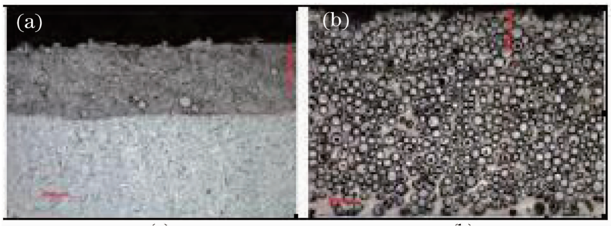

Fig. 7 (a) Optical micrograph of the NT-70SP with high energy input showing excessive carbide dissolution; (b) optical micrograph revealing a high volume fraction tungsten carbide when laser cladding in an optimized processing condition

The main issues for the transition of this technique into commercial manufacturing are system durability, clad quality, and build rate. Currently, the system has shown to be reliable for cladding durations of just over 3 h. Clad quality is a function of surface finish, carbide distribution, minimal dilution, and cracking. Currently, it has been shown that surface finish can be obtained with <0.2-mm clean up, high faction carbide present after cladding, about 5% dilution and no cracking (only after pre-heat of 462 ℃). A rate of 0.8-mm/s linear cladding has been obtained at 2000 W input with a Trumpf HD 3006L Nd:Yag laser with a 280-mm focus lens for a 70-mm-diameter bore for length up to 300 mm. Bore size down as small as 50-mm diameter is possible with barrel length up to 2 m being planned.

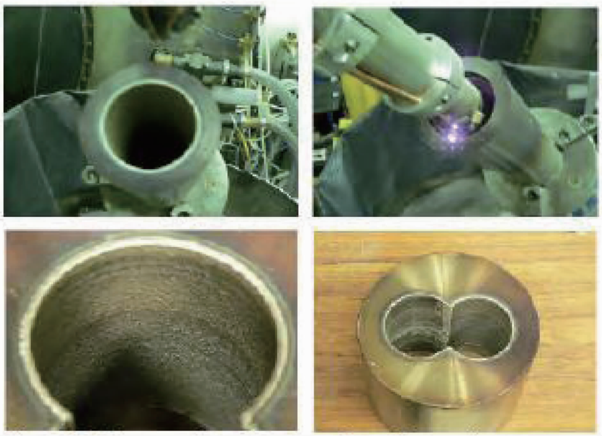

Fig. 8 Photographs of test sections for a 60-mm diameter single bore barrel (above) and a 60-mm twin bore barrel (below)

5 Summary

Commercial Inconel and Stellite alloys, M4 and other tool steels, stainless steel, and the Carpenter alloys CCW+, DM21, and NT-60 can be deposited successfully on H-13 with little dilution, good metallurgical interface, minimal porosity, and little thermal softening of the substrate. LAM of the alloys CCW+ and NT-60 on H-13 in hot die forging have produced a three times improvement in tool life. Up to 70% tungsten carbide has been deposited by LAM without cracking or significant porosity. Factory trials are scheduled for two applications being developed through LAM of tungsten carbide with a Ni-Si-B matrix.

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References

1 M. T. Ensz, M. L. Griffith. Critical issues for functionally graded material deposition by laser engineered net shaping (LENSTM) [C]. *Proc. of the* 2002 *Int. Conf. on Metal Powder Deposition for Rapid Manufacturing*, San Antonio, TX, April 8-10, 2002. Ed. by MPIF. 195～202

2 B. L. Wang, Y. W. Mai, X. H. Zhang. Functionally graded materials under severe thermal environments [J]. *J. Am. Ceram. Soc.*, 2005, **88**(3):683～690

3 R. Villar. Laser cladding [J]. *International Journal of Powder Metallurgy*, 2001, **37**(2):29～48

4 A. C. Costello, S. K. Koduri, J. W. Sears. Optimization of laser powder deposition for 316L stainless steel [J]. *Proc. of ICALEO* 03, 2003, October 13～16, 144～152

5 G. Bao, H. Cai. Delamination cracking in functionally graded coating/metal substrate systems [J]. *Acta Mater*, 1997, **45**(3): 1055～1066

6 V. Shankar, K. Bhanu Sankara Rao, S. L. Mannan. Microstructure and mechanical properties of Inconel 625 superalloy [J]. *Journal of Nuclear Materials*, 2001, **288**(2-3):222～232

7 V. Kuzucu, M. Ceylan, H. Celik *et al.*. Microstructure and phase analyses of Stellite 6 plus 6 wt.-% Mo alloy [J]. *Journal of Materials Processing Technology*, 1997, **69**(1-3):257～263

8 J. C. Shin, J. M. Doh, J. K. Yoon *et al.*. Effect of Mo on the microstructure and wear resistance of Co-base Stellite hardfacing alloys [J]. *Surface and Coatings Technology*, 2003, **166**(2-3): 117～126

9 A. Hidouci, J. M. Palletier, F. Dacoin *et al.*. Microstructural and mechanical characteristics of laser coatings [J]. *Surface and Coatings Technology*, 2000, **123**(1):17～23

10 S. Niederhauser, B. Karlsson. Mechanical properties of laser cladded steel [J]. *Materials Science and Technology*, 2003, **19**(11):1611～1616

11 S. Sun, Y. Durandet, M. Brandt. Parametric investigation of pulsed Nd:YAG laser cladding of Stellite 6 on stainless steel [J]. *Surface and Coatings Technology*, 2005, **194**(2-3):225～231