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DIRECT MANUFACTURING OF NET-SHAPE FUNCTIONAL COMPONENTS/ TEST-PIECES FOR AEROSPACE, AUTOMOTIVE AND OTHER APPLICATIONS

Paper #1403

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Abstract

Laser consolidation (LC) is a novel computer-aided manufacturing process being developed by the Industrial Materials Institute of National Research Council of Canada (NRC-IMI). This rapid manufacturing process produces net-shape functional metallic parts layer-by-layer directly from a CAD model by using a laser beam to melt the injected powder and re-solidifying it on the substrate or previous layer. As an alternative to the conventional machining process, this novel manufacturing process builds net-shape functional parts or features on an existing part by adding instead of removing materials. In this paper, laser consolidation of various high performance materials (such as Ni-alloys, tool steels, etc.) will be demonstrated to manufacture functional components or test-pieces (such as shell-based mold inserts, impeller, intersected multi-hexagon tube, goblet shape, etc.) for potential aerospace, automotive and other applications. In the paper, dimensional accuracy of various laser-consolidated test-pieces will be measured and compared with CAD models. In addition, an example will be given on laser consolidation to build complex cold spray nozzles that are difficult to make otherwise and significantly improve the performance.

Keywords: laser technique, materials, laser direct manufacturing, laser consolidation, net-shape, rapid manufacturing, green manufacturing

Introduction

Laser cladding based free-form fabrication is an emerging computer-aided manufacturing technology that uses a laser beam to melt injected powder (or wire) to form a solid, functional component layer by layer. This one-step computer-aided manufacturing process does not require any mould or die, and therefore provides the flexibility to quickly change the design of the components. As a result, the lead-time to produce functional parts could be reduced significantly. As opposed to the conventional machining process, this new technology builds

complete parts or features on an existing component by adding rather than removing materials. The parts built by the laser deposition process are metallurgically sound, free of porosity or cracks. Research work has been reported by various institutions using laser cladding based free-form fabrication technology on various alloys and steels [1-4]. Although the technology has a great potential for many industrial applications, concerns about the surface finish and dimensional accuracy have been raised.

The Industrial Materials Institute of National Research Council of Canada (NRC-IMI) has been developing laser consolidation process that takes the laser cladding based free-form fabrication technology to a new level enabling production of net-shape functional components that are difficult or even impossible to produce using conventional manufacturing technologies [5]. The surface finish of laser-consolidated components or test-pieces are comparable or better than as-cast components. Although research work has been conducted on laser consolidation of various industrial materials (such as Ni-alloys, Co-alloys, Ti-alloys, Al-alloys, stainless steels and tool steels) [5-10] and its potential for various industrial applications [11-15], relatively less information was generated on dimensional accuracy of the laser-consolidated components or test-pieces.

In this paper, laser consolidation of several functional net-shape test-pieces is introduced, the surface finish and dimensional accuracy of these test-pieces are described, and the potential applications of the process for manufacturing net-shape functional components are discussed.

Experimental Details

The laser consolidation (LC) process requires a substrate (new base or on existing component) onto which a part is built (Figure 1). A focused laser beam is irradiated on the substrate to create a molten pool, while metallic powder through a nozzle is injected simultaneously into the pool. A numerically

controlled (NC) motion system (3 to 5 axes) is used to control the relative movement between the laser beam and the substrate. The laser beam and the

Figure 1: Illustration of laser consolidation process.

powder feed nozzle are moved following a CAD model through a pre-designed laser path, creating a bead of molten material on the substrate, which solidifies rapidly to form the first layer. The second layer is deposited on the top of the first layer. By repeating this process, a solid thin walled structure is built. When the laser path is designed properly to guide the laser beam movement, a complex shaped part can be built directly from a CAD model without any mould or die.

The laser consolidation work presented in this paper was conducted using a proprietary LC system developed by NRC-IMI. A 500W or 1 kW Lasag Nd:YAG laser coupled to a fiber-optic processing head was used for the experiments. The laser was operated in a pulse mode with an average power ranging from 20 to 300 W. A Sultz-Metco 9MP powder feeder was used to simultaneously deliver metallic powder into the melt pool through a nozzle with the powder feed rate ranging from 1 to 30 g/min. A 4- or 5-axis CNC motion system was used for the laser consolidation work, while processing was conducted in a glove box, in which the oxygen content was maintained below 50 ppm during the process.

Chemical compositions of three alloy powders used in this paper, Ni-base IN-625 and IN-718 alloys, and H13 tool steel, are listed in Table 1. Annealed A36 mild steel plates (0.29% C, 1.0% Mn, 0.2% Cu and Fe) with a thickness of 12.7 mm were used as the base material for laser consolidation of IN-625, IN-718 and H13 materials. Except mentioned otherwise, the substrate plates were machined and ground to a consistent

surface finish for the laser consolidation of different alloy powders.

Table 1: Chemical compositions of alloy powders (wt.%)

Alloy	C	Ni	Fe	Cr	Mo	Ta+Nb	V
IN-625	0.03	Bal.	-	22.0	9.0	3.7	-
IN-718	0.05	Bal.	17.0	19.0	3.0	5.0	-
H13	0.42	-	Bal.	5.04	1.33	-	1.06

Results and Discussion

Impellers

Laser consolidation is a material addition process that can directly build functional features on an existing component to form integrated structure without the need of welding or brazing. For example, laser consolidation can be use to build net-shape functional components on pre-machined substrate. An impeller shape (Figure 2) was selected to demonstrate the capability of laser consolidation process using 5-axis motion. The impeller has a diameter of about 77 mm and height of about 26 mm. There are 9 long blades and 9 short blades uniformly distributed.

Figure 2: A CAD model of an impeller to be manufactured using laser consolidation process.

A profiled substrate was pre-machined using a CNC lathe (Figure 3) and was mounted on a 5-axis motion system using a simply designed fixture. Laser consolidation of IN-718 alloy was performed to build blades on the pre-machined base using the 5-axis motion system. Laser consolidation can be performed to complete building up a blade and then another one. However, the completed blade(s) will interfere with the laser beam and powder flow when building other blades. In order to avoid the interference issue, laser consolidation was conducted to build one layer at a time for each blade.

Figure 3: A profiled substrate was pre-machined using a CNC lathe.

Due to the impeller shape, large tilt-rotation movement is required for building each blade. Initial investigation indicated that the 5-axis motion system originally used for the project has serious dimensional accuracy and repeatability issues. The position error between two consecutive 90° tilt movement can be as large as 0.025" (0.635 mm) and even a lot more during the process. Due to the motion system problem, the laser-consolidated blades were melted down or double walls were formed during the laser consolidation process.

Figure 4: IN-718 impellers with laser-consolidated blades built on pre-machined substrate (Left one with as-consolidated surface and the right one after sand blasting).

After changing to another 5-axis CNC motion system, laser consolidation was successfully conducted to build blades on the pre-machined substrate to form an integrated impeller. Figure 4 shows an IN-718 impeller (left) with its blades directly built up on a pre-machine substrate using LC

process. The surface finish of the as-consolidated IN-718 blades is about 1.6 μm along horizontal direction and about 2.94 μm along vertical direction. After sand blasting, laser-consolidated blades and pre-machined substrate show consistent surface finish (Figure 4, right side).

The mechanical properties of laser-consolidated IN-718 are comparable to that of wrought IN-718. After standard heat treatment, the yield and tensile strengths of the LC IN-718 are about 1085 MPa and 1238 MPa, and the elongation is about 21 %, while heat-treated wrought IN-718 has the yield and tensile strengths of 1050 MPa and 1280 MPa, and elongation of 22%, respectively [10].

It is evident that this novel process produces high quality, fairly complex shapes directly from a CAD model with good surface finishes in as-consolidated condition or after sand blasting. The bond between the LC features and the existing component is metallurgically sound, without crack and porosity. Compared to conventional welding process, the heat input from LC process to the substrate is minimal, resulting in a very small heat affected zone (several tens micrometers). By using the LC process, more unique features can be added to the gas turbine components to provide additional functionality, and to reduce manufacturing time and cost.

Shell-based Mold Inserts

The laser consolidation research and development was performed to develop the process to build functional shell structures for parts and molds, and to investigate backfill methods to enhance the shell structures for rapid tooling applications. A unique backfill material was developed, which has good compression strength and thermal conductivity, and its thermal expansion is comparable to the laser-consolidated shell. The backfilled shell structure can operate at relatively high working temperatures (above 350°C). By using the backfill method, complex cooling channels and heating elements can be embedded into a mold at desired locations to improve the functionality and productivity of the mold. The possibility of using the laser-consolidated shell structure to make mold inserts was also demonstrated.

Figure 5: Cross-section showing laser-consolidated IN-625 shell-based molds embedded with cooling channels for demonstration.

Figure 5 shows a cross-section of a laser-consolidated IN-625 shell-based mold showing the internal cooling channels, while Figure 6 shows a multi-piece mold inserts with embedded cooling channels.

Figure 6: Laser-consolidated multi-piece mold inserts embedded with cooling channels for demonstration.

The surface finish of the as-consolidated IN-625 test-piece is about $R_a = 1.5\text{--}1.8\text{ }\mu\text{m}$. The LC IN-625 alloy shows good tensile properties [5]. Along the horizontal direction (perpendicular to the build direction), the yield and tensile strengths of the LC IN-625 material are 518 MPa and 797 MPa respectively, while the elongation is about 31%. When testing along the vertical direction (parallel to the build direction), both the yield and the tensile strengths are slightly lower to 477 MPa and 744 MPa respectively, while the percentage elongation increases significantly to 48%. The yield strength and the tensile strength of the LC IN-625 along both directions are significantly higher than the cast and comparable to the wrought material, although the elongation along the horizontal direction is slightly lower [5].

Cold Spray Nozzles

Cold spray (or gas-dynamic spray) is a relatively new coating technology that addresses many of the limitations of conventional thermal spray processes. It is a solid-state coating process in which small solid particles are accelerated to velocities between 300 m/s and 1200 m/s by a supersonic or sub-supersonic jet flow, and are subsequently deposited onto a surface by impinging upon a substrate [16, 17]. Coating formation in the cold spray process is mainly due to the high kinetic energy of the solid-state particles, in contrast to conventional thermal spray processes, in which coating formation depends on both thermal and kinetic energies. Because of relatively low operation temperature, cold spray is ideally suitable for depositing oxygen-sensitive materials, temperature-sensitive materials and/or phase-sensitive materials. Cold-spray coatings generally have low oxide content and low thermal stress and retain the microstructure (e.g. nano-phase or amorphous structure) of the feed powder material. Thus, it provides a promising technique for many applications unachievable with existing practices.

In cold spray, the supersonic or sub-supersonic jet flow is generated through a converging-diverging de Laval type nozzle. Particles are usually injected axially into the gas flow at the inlet of the nozzle (upstream of the nozzle throat) [18, 19]. There are many potential applications for cold spray coatings, for example, wear resistant, corrosion resistant, high thermal/electrical conduction, thermal barrier, thermal sink, etc. In some applications, cold spray offers unique advantages over other techniques but the uniformity of coating thickness is an important consideration.

Figure 7: Typical thickness profiles of cross section of a single track cold spray coating produced using round-shaped and rectangular-shaped nozzles

Currently, the most commonly used cold spray nozzle has a round shape in the cross section. Round nozzles are easy for manufacturing, but the thickness of a single-track coating is not uniform. The cross-section of

such a single-track deposit is usually triangular (Figure 7). Another type of commonly used cold spray nozzle has a rectangular cross section. Although the thickness uniformity of a single-track coating deposited using such nozzles is better than using round-shaped nozzles, it is still not satisfactory for certain demanding applications requiring uniform thin coatings.

To improve the cross-section thickness uniformity of single-track cold spray coatings, the following new nozzle design concepts are proposed: the cross-section shapes along the divergent section and at the nozzle exit are designed to have a generally dumbbell shape such that solid particles within the nozzle are more uniformly distributed. There can be many designs for the nozzle cross-section shapes/dimensions based on such concepts. In this paper, three shapes have been examined which are shown in Figure 8 with the anticipated cross-section shape of single-track coating.

Figure 8: Proposed nozzle cross section shapes for uniform thickness

Although the novel nozzle design offers unique advantages to improve the coating uniformity, it creates a challenge for the existing manufacturing technology to make them. After considerable evaluation of alternative manufacturing technologies, laser consolidation was selected as the most promising method for making these functional cold spray nozzles.

Figure 9: Laser-consolidated IN-625 cold spray nozzles with different cross sectional shapes (#1, #2 and #3).

Figure 10: Three laser-consolidated IN-625 cold spray nozzles with a length from 175 mm to 193 mm.

Laser consolidation of IN-625 was successfully used to build cold spray nozzles with newly designed shapes. Figure 9 shows laser-consolidated cold spray nozzles with three different cross-sectional shapes, while Figure 10 shows three completed laser-consolidated nozzles with a length from 175 mm to 193 mm.

Table 2: Outside dimensions of as-consolidated IN-625 nozzles (mm)

Nozzle #1						
Elevation	X	CAD	Deviation	Y	CAD	Deviation
Top	8.78	8.72	0.06	5.38	5.12	0.26
40	6.46	6.65	-0.19	5.22	5.18	0.04
Base	5.1	4.34	0.76	5.1	4.34	0.76
Nozzle #2						
Elevation	X	CAD	Deviation	Y	CAD	Deviation
Top	7.12	7.22	-0.1	5.61	5.32	0.29
40	6.48	6.65	-0.17	5.2	5.18	0.02
Base	5.09	4.34	0.75	5.09	4.34	0.75
Nozzle #3						
Elevation	X	CAD	Deviation	Y	CAD	Deviation
Top	7.78	7.52	0.26	5.43	4.82	0.61
55	6.88	6.59	0.29	4.71	4.02	0.69
Base	N/A	N/A	N/A	N/A	N/A	N/A

The outside dimensions were measured using calliper and compared with CAD data (Table 2). It is obvious that the laser consolidation process successfully produced non-conventional IN-625 nozzles with good dimensional accuracy.

Cold spray experiments were performed using the newly designed nozzles. Two different sets of deposition conditions were used: (a) a single-track one-layer Al coating deposited on Zn-coated steel plate, and (b) a single-track multi-layer Al-4047 coating deposited on Al-6061 plate.

Figure 11 compares the cross-section profiles of single-track coating deposited using conventional round nozzle, rectangular nozzle and the newly developed laser-consolidated nozzle #3. The coating sprayed using the nozzle has much better uniformity in thickness than the coating sprayed using the round nozzle. Although the rectangular nozzle produced more uniform coating thickness than using the round nozzle, it is still not as uniform as the coating sprayed using the new nozzle.

Figure 11: Comparison of cross-section thickness profiles of single-track coating deposited using different nozzle cross-section shapes: round nozzle, rectangular nozzle and LC nozzle #3.

Figure 12: Cross-section profiles of one-layer and two-layer coatings sprayed by round nozzle, and two-layer coating sprayed by innovative LC nozzle #3.

Figure 12 shows the cross-section profiles of single-track two-layer coating cold-sprayed using the conventional round nozzle and the new laser-consolidated nozzle #3. The thickness uniformity of the two-layer coating sprayed using round nozzle is worse than that of one-layer coating sprayed by the same

nozzle. On the other hand, two-layer coating sprayed using the LC nozzle #3 shows excellent thickness uniformity.

The laser-consolidated new nozzles in combination with our previously developed downstream powder feeding cold spray system with symmetrically located multi-powder injectors [20] show great potential to produce low-cost cold spray coatings with excellent thickness uniformity.

Intersected Multi-hexgon Tube

Laser consolidation of IN-718 was recently investigated to manufacture tubes with a cross-section of “honey comb” pattern. The intersected multi-hexgon tube has the outside dimension of 27.94 mm x 26.92 mm (1.1” x 1.06”) with the smallest internal circle of the hexagon measuring 4.4 mm, a wall thickness of 0.72 mm and a height of about 256.54 mm (10.1”).

Figure 13 illustrates a cross-section of an as-consolidated IN-718 “honey comb” tube, which reveals very uniform wall thickness, while Figure 14 shows the entire laser-consolidated IN-718 “honey comb” tube with a height of about 256 mm. It is obvious that the as-consolidated IN-718 tube demonstrated smooth surface finish (R_a = about 1.6 – 2.9 μm).

Figure 13: Cross-section of a laser-consolidated IN-718 “honey comb” tube.

Figure 14: A laser-consolidated IN-718 “honey comb” tube with a height of about 256 mm.

Dimensional accuracy of the as-consolidated IN-718 “honey comb” tube was measured using height gauge. The height of four sides of the tube was measured as 256.57 mm (10.101”), 256.54 mm (10.100”), 256.54 mm (10.100”) and 256.54 mm (10.100”), respectively, with a difference of 0.03 mm (0.001”), while the wall thickness was measured as 0.72 mm (0.0285”). Table 3 lists the measured length and width of the tube along X-axis and Y-axis at different height positions. The laser-consolidated IN-718 “honey comb” tube shows very consistent data: the deviation between measured length and the CAD data is in a range of -0.319 mm to -0.357 mm, while the deviation along width is only in a range of -0.079 mm to -0.090 mm.

Table 3: Outside dimensions of as-consolidated IN-718 “honey comb” tube

Height Position (mm)	Length (mm) (x-axis of build)			Width (mm) (y-axis of build)		
	CAD	Meas.	Diff.	CAD	Meas.	Diff.
12.7	28.665	28.321	-0.344	27.116	27.026	-0.090
25.4	28.665	28.334	-0.331	27.116	27.026	-0.090
50.8	28.665	28.321	-0.344	27.116	27.026	-0.090
76.2	28.665	28.321	-0.344	27.116	27.038	-0.078
101.6	28.665	28.346	-0.319	27.116	27.026	-0.090
127	28.665	28.321	-0.344	27.116	27.038	-0.078
152.4	28.665	28.321	-0.344	27.116	27.026	-0.090
177.8	28.665	28.321	-0.344	27.116	27.038	-0.078
203.2	28.665	28.321	-0.344	27.116	27.026	-0.090
228.6	28.665	28.308	-0.357	27.116	27.026	-0.090
254	28.665	28.308	-0.357	27.116	27.026	-0.090

It is obvious that the laser consolidation process can successfully manufacture functional net-shape long “honey comb” tube with small opening and thin wall

thickness, which is otherwise not easy to manufacture using conventional methods.

Axial Symmetric Shapes

Hourglass Shape

Another demonstration piece is an hourglass shape made from H13 tool steel. The hourglass shape requires a maximum outside diameter of about 44 mm and a height of about 76 mm. The maximum inclination angle of the sample is about 48° from vertical.

Figure 15: (a) A laser-consolidated hourglass shape made from H13; (b) measurement elevations.

Laser consolidation was investigated to build the hourglass shape from H13 powder using a 5-axis motion system. Figure 15a shows an as-consolidated H13 hourglass shape. It is evident that the as-consolidated shape shows reasonably good surface finish.

The outside radius of the LC H13 hourglass was measured using a profile projector at seven elevations (Figure 15b). The maximum deviation of the LC H13 sample compared to the CAD model is about 0.3 mm, while the minimum deviation is 0 mm (Table 4).

Table 4: Outer radius measurements of LC H13 hourglass shape (mm)

Elevation	CAD	Measured	Difference
Top	21.92	22.104	0.184
63.5	20.76	20.952	0.192
50.8	14.97	15.263	0.293
38.1	4.32	4.449	0.129
25.4	14.97	15.141	0.171
12.7	20.76	20.783	0.023
Base	21.92	21.92	0.000

The LC H13 tool steel shows excellent mechanical properties (Table 5). The average yield and tensile strengths of the as-consolidated H13 along vertical direction are about 1288 MPa and 2064 MPa

respectively, while the elongation is about 6% and the elastic modulus is about 216 GPa. Along the horizontal direction, the LC H13 shows significantly higher yield strength (1564 MPa) than along the vertical direction, while the tensile strength, elastic modulus and elongation of LC H13 are comparable for both directions. Compared to the conventional cast or wrought material, the LC H13 tool steel shows substantially higher tensile and yield strengths than annealed condition and comparable to the hardened wrought H13. However, the elongation of as-consolidated H13 material is about 5-6%, which is lower than the hardened wrought H13. A tempering treatment may be used to improve the elongation of the LC H13 material if required.

Table 5: Tensile properties of LC H13 tool steel.

Material Conditions		$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	δ (%)
As-consolidated	Vertical	1288±54	2064±51	6.0±2.2
	Horizontal	1564±24	2033±38	5.0±2.8
Cast (annealed)[21]		370	670	Lower than wrought H13
Wrought (annealed) [22]		510	676	28
Wrought (Heat-treated) [23]		1290	1495	15
Wrought (heat treated) [23]		1570	1960	13

Goblet Shape

The LC H13 sample with goblet shape is about 88 mm in height and about 54 mm in maximum diameter. The maximum inclination angle of the sample is about 60° from vertical. As a rapid manufacturing process, laser consolidation process successfully built the shape directly from H13 powder (Figure 16a).

Figure 16: (a) A laser-consolidated goblet shape made from H13; (b) measurement elevations.

The outside radius of the LC H13 goblet was measured using profile projector at 10 elevations (Figure 16b). The deviation of the LC H13 sample to

the CAD model is in the range of 0.06 – 0.68 mm (Table 6).

Table 6: Outer radius measurements of LC H13 goblet shape (mm)

Elevation	CAD	Measured	Difference
Top	20.50	20.720	0.220
80	5.37	5.662	0.292
70	4.32	4.486	0.166
60	4.32	4.486	0.166
50	10.09	10.771	0.681
40	22.56	22.884	0.324
30	26.69	26.767	0.077
20	26.22	26.277	0.057
10	23.56	23.619	0.055
Base	19.61	19.869	0.259

Ball with Two End Tubes

The LC H13 ball with two end tubes is about 89 mm in height and about 52 mm in maximum diameter. The maximum inclination angle of the sample is about 59° from vertical (Figure 17a).

Figure 17: (a) A laser-consolidated ball with two end tubes made from H13; (b) measurement elevations.

The outside radius of the LC H13 ball was measured using profile projector at 8 elevations (Figure 17b). The maximum deviation of the LC H13 sample compared to the CAD model is about 0.32 mm (Table 7).

Table 7: Outer radius measurements of LC H13 ball with two end tubes (mm)

Elevation	CAD	Measured	Difference
Top	6.86	6.799	-0.061
76.2	7.00	7.000	0.000
63.5	17.56	17.699	0.139
50.8	25.12	25.110	-0.010
38.1	25.12	25.125	0.005
25.4	17.56	17.880	0.320
12.7	7.00	7.095	0.095
Base	6.86	6.842	-0.018

Mold Insert with Conical Top

The LC IN-625 mold insert with a conical top is about 51.111 mm in height and about 43.992 mm in maximum diameter. The maximum inclination angle of the sample is about 60° from vertical (Figure 18a).

Figure 18: (a) A laser-consolidated IN-625 insert with conical top; (b) measurement elevations.

The outside radius of the LC IN-625 insert was measured using profile projector at 5 elevations (Figure 18b). The maximum deviation of the LC IN-625 sample compared to the CAD model is about 0.41 mm (Table 8).

Table 8: Outer radius measurements of LC IN-625 insert with conical top (mm)

Elevation	CAD	Measured	Difference
Top (51.1)	0	0	0
38.1	13.1420	12.7330	0.4089
25.4	17.6809	17.5336	0.1473
12.7	18.2423	18.1864	0.0559
Base	21.8745	21.9964	-0.1219

Conclusions

- The laser-consolidated IN-625, IN-718 and H13 components and test-pieces demonstrated good surface finish, dimensional accuracy, and excellent mechanical properties.
- Compared to other laser cladding based free-form fabrication processes that only produce near-net-shape components, the laser consolidation process provides a unique capability to build net-shape functional components or features on existing components that are difficult or even impossible to produce using conventional manufacturing processes.
- Laser consolidation is a green manufacturing technology that directly builds the required shapes with minimal machining. It also significantly simplifies the tooling requirements. This computer aided manufacturing process is expected to make a huge impact on

manufacturing in a wide range of industries in the near future.

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References

- [1] Keicher, D.M., Miller, W.D., Smugeresky J.E. & Romero, J.A., Laser Engineering Net Shaping (LENS™): Beyond Rapid Prototyping to Direct Fabrication. Proceedings of the 1998 TMS Annual Meeting, San Antonio, USA, 1998, 369-377.
- [2] Mazumder, J., Choi, J., Nagarathnam, K., Koch, J. & Hetzner, D., Direct Metal Deposition of H13 Tool Steel for 3-D Components. JOM, 49, 1997, 55-60.
- [3] Lewis, G. K. & Schlienger, E., Practical Considerations and Capabilities for Laser Assisted Direct Metal Deposition. Materials and Design, 21, 2000, 417-423.
- [4] Wu, X. and Mei, J., Near Net Manufacturing of Components Using Direct Laser Fabrication Technology. Journal of Materials Processing Technology, 135, 2003, 266-270.
- [5] Xue, L. & Islam, M.U., Free-Form Laser Consolidation for Producing Metallurgically Sound and Functional Components. Journal of Laser Applications, 12(4), 2000, 160-165.
- [6] Xue, L., Chen, J.-Y. & Islam, M.U., Functional Properties of Laser Consolidated Wear Resistant Stellite 6 Alloy. Powder Metallurgy Alloys and Particulate Materials for Industrial Applications, ed. by David E. Alman and Joseph W. Newkirk, 2000, 65-74.
- [7] Xue, L., Chen, J.-Y., Islam, M.U., Pritchard, J., Manente, D. & Rush, S., Laser Consolidation of IN-738 Alloy for Repairing Cast IN-738 Gas Turbine Blades. Proceedings of 20th ASM Heat Treating

Society Conference, St.-Louis, Missouri, USA, 2000, 1063-1071.

[8] Xue, L., Chen, J.-Y. & Theriault, A., Laser Consolidation of Ti-6Al-4V Alloy for the Manufacturing of Net-Shape Functional Components. Proceedings of 21st International Congress on Applications of Laser & Electro-Optics (ICALEO 2002), Scottsdale, Arizona, USA, 2002, 168-179.

[9] Xue, L., Chen, J.-Y. & Theriault, A., Laser Consolidation of Al 4047 Alloy. Proceedings of ICALEO 2005, Miami, Florida, USA, 2005, 344-351.

[10] Xue, L., Chen, J.-Y., Wang, S-H., Li, Y., Laser consolidation of Waspalloy and IN-718 alloys for making net-shape functional parts for gas turbine applications. Proceedings of ICALEO 2008, Temecula, California, USA, 2008, 255-263.

[11] Xue, L., Theriault, A., Chen, J., Islam, M.U., Wieczorek, A. & Draper, G., Laser Consolidation of CPM-9V Tool Steel for Manufacturing Rotary Cutting Dies. Proceedings of 10th International Symposium on Processing and Fabrication of Advanced Materials, Indianapolis, Indiana, USA, 2002, 361-376.

[12] Xue, L., Theriault, A., Rubinger, B. & Parry, D., Investigation of Laser Consolidation Process for Manufacturing Structural Components for Advanced Robotic Mechatronics System. Proceedings of the ICALEO 2003, Jacksonville, Florida, USA, 2003, 134-143.

[13] Xue, L., Theriault, A., Islam, M.U., Jones, M. & Wang, H.P., Laser Consolidation of Ti-6Al-4V Alloy to Build Functional Net-Shape Airfoils with Embedded Cooling Channels. Proceedings of the ICALEO 2004, San Francisco, California, USA, 2004, 34-40.

[14] Xue, L. & Purcell, C., Laser Consolidation of Net-Shape Shells for Flexensional Sonar Projectors. Proceedings of the ICALEO 2006, Scottsdale, Arizona, USA, 2006, 686-694.

[15] Xue, L., Li, Y., Van Daam, T. & Bampton, C., Investigation of Laser Consolidation for Manufacturing Functional Net-Shape Components for Potential Rocket Engine Applications. Proceedings of the ICALEO 2007, Orlando, Florida, USA, 2007, 161-169.

[16] A.P. Alkhimov, A.N. Papyrin, V.F. Kosarev, N.I. Nesterovich, and M.M. Shushpanov, "Gas-

dynamic Spraying Method for Applying a Coating", US Patent No. 5,302,414, April 12, 1994.

[17] R.C. Dykhuizen and M.F. Smith, "Gas Dynamic Principles of Cold Spray", *J. Therm. Spray Technol.*, 1998, 7(2), p 205-212.

[18] T. Schmidt, F. Gartner, H. Assadi, H. Kreye, "Development of a Generalized Parameter Window for Cold Spray Deposition", *Acta Mater.*, 2006, 54, p 729-742.

[19] T. Stoltenhoff, H. Kreye and H.J. Richter, "An Analysis of the Cold Spray Process and its Coatings", *J. Therm. Spray Technol.*, 2002, 11(4), p 542-550.

[20] Lijue Xue, Jimmy Jiang and Shadong Wang, "Cold Gas Dynamic Spray Apparatus, System and Method", United States Patent Application No. 12/654,064, filed December 9, 2009.

[21] Micronalloys, 2002, Information provided through an e-mail.

[22] <http://www.moldsteel.com>.

[23] ASM International, 1990, *Metals Handbook*, Vol. 1, pp.442.

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