Laser Consolidation – A Novel One-Step Manufacturing Process for Making Net-Shape Functional Components

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ABSTRACT

Free-form laser consolidation is a novel manufacturing process that produces a functional complex part layer by layer directly from a CAD model without any moulds or dies. This process uses a laser beam to melt a controlled amount of injected powder on a base plate to deposit the first layer and on previous passes for the subsequent layers. As opposed to conventional machining processes, this computer-aided manufacturing (CAM) technology builds complete functional net-shape parts or features on an existing component by adding instead of removing material.

Laser consolidation of Ni-base IN-625 and IN-738 superalloys, Ti-base Ti-6Al-4V alloy, Co-base Stellite 6 alloy and Fe-base CPM-9V tool steel has been investigated. The laser consolidated (LC) materials are metallurgically sound, free of cracks or porosity. Due to the rapid solidification inherent to the process, excellent material properties are obtained. The as-consolidated Ti-6Al-4V material shows tensile and yield strengths comparable to the heat-treated wrought Ti-6Al-4V. The LC Stellite 6 is harder, stronger and even more ductile than the respective material produced by conventional casting or powder metallurgy method. The average stress rupture life of LC IN-738 specimens at given test condition is substantially longer than that of cast IN-738 baseline samples. Pin-on-disk wear tests demonstrate that the wear loss of the LC CPM-9V material is only about 1/3 compared to that of the heat treated D2 tool steel currently being used for many tool and die applications. The LC samples also show very good surface finish and dimensional accuracy. Surface finish of the order of 1~2 μm (Ra) is obtained on as-consolidated IN-625 samples. In this paper, laser consolidation process will be introduced, the functional properties of the laser-consolidated materials will be described, and the potential applications of the process will be discussed.

1.0 INTRODUCTION

The Integrated Manufacturing Technologies Institute of the National Research Council Canada (IMTI-NRC) is developing a novel process called "Laser Consolidation" to build functional net-shape components directly from metallic powder in one step [1-3]. The laser consolidation is a one-step computer-aided manufacturing process that does not require any moulds or dies, and therefore provides the flexibility to quickly change the design of the components. Thus, the lead-time to produce final parts could be reduced significantly. In

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addition, this computer-aided manufacturing process provides an excellent opportunity for manufacturing complex parts that are difficult to make by conventional manufacturing processes.

As opposed to the conventional machining process, this new technology builds complete parts or features on an existing component by adding rather than removing material. The parts built by the laser consolidation process are metallurgically sound, free of porosity or cracks. Due to the rapid solidification inherent to the process, excellent material properties are exhibited by the laser-consolidated materials, such as Ni-base superalloys, Co-alloys, Ti-alloys, stainless steels and tool steels [1-6].

In this paper, laser consolidation process is introduced, the functional properties of the laser-consolidated materials are described, and the potential applications of the process for manufacturing structural components are discussed.

2.0 PROCESS DESCRIPTION

The laser consolidation process requires a solid base 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 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 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.

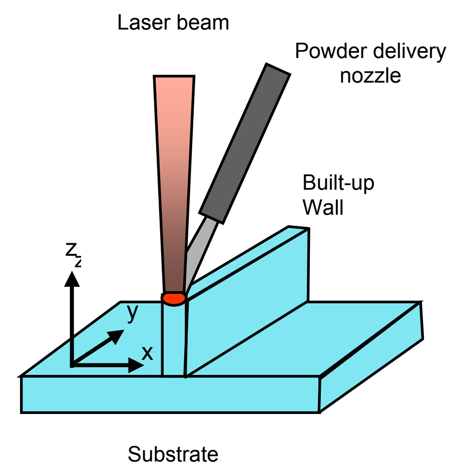


Figure 1: Laser consolidation process.

A Nd:YAG laser coupled to a fiber-optic processing head is used for the laser consolidation work presented in this paper. The laser is operated in a pulse mode with an average power ranging from 20 to 300 W. A powder feeder is 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. All laser consolidation work is conducted in a glove box and at room temperature, in which the oxygen content is maintained below 50 ppm during the process.

The functional properties of five typical laser- consolidated materials, Ni-base IN-625 and IN-738 alloys, Ti-base Ti-6Al-4V alloy, Co-base Stellite 6 alloy and Fe-base CPM-9V tool steel, are presented in this paper. The microstructures of the LC samples were examined metallurgically with an optical microscope as well as a scanning electron microscope (SEM). A Philips X'Pert X-ray diffraction system was used to identify the phases of the LC samples. A 100 kN Instron Mechanical Testing System was used to evaluate the tensile properties of the LC samples.

3.0 FUNCTIONAL PROPERTIES OF LC MATERIALS

3.1 IN-625 Alloy

IN-625 is a Ni-base solution hardening superalloy, containing 0.03 %C, 22% Cr, 9% Mo, 3.7 % Ta and Nb. Laser consolidation of IN-625 powder produces metallurgically sound components, free of cracks or porosity. Figure 2 shows three LC IN-625 samples, a hollow square, a hollow cylinder and a hollow cone. These samples were prepared for measurement of the surface roughness as well as the dimensional accuracy.

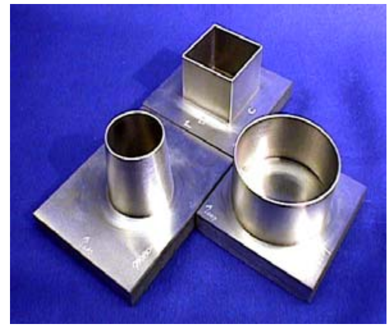
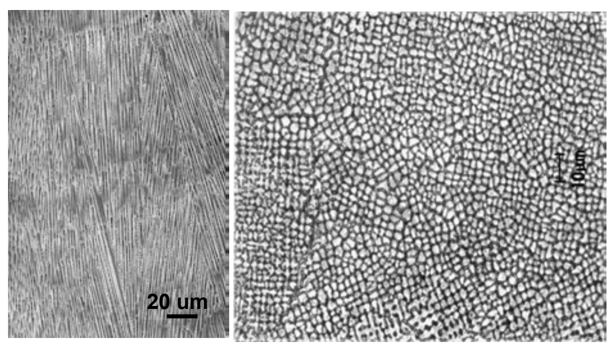


Figure 2: Three as-consolidated LC IN-625 samples.

It is evident that LC IN-625 samples show very good surface finish. Surface roughness measurement reveals that the average roughness (Ra) of the as-consolidated IN-625 samples is about 1.5 ~ 1.8 μm.

The LC samples have very good dimensional accuracy. For the 25 mm × 25 mm thin-wall square, the standard deviation in wall thickness and height is only about 0.025 mm and 0.038 mm respectively, while the wall parallelism is within the range of 0.050mm. The average squareness between walls is 90.00^o with a deviation of 0.02^o, while the average perpendicularity of square walls against the base plate is 89.92^o. For the cylinder, the standard deviation in the inner and outer diameters is within 0.050 mm. For both the thin-wall cylinder and the cone, the deviation in circularity is less than 0.050 mm, while the deviation in cylindricity and conicity is 0.086 mm and 0.069 mm respectively. It is notable that the measurement of the inclined angle for the built cone is 9.93^o compared to the required 10^o. These errors could be attributed to the repeatability errors in the motion system as well as the errors caused by the laser consolidation process itself. The source of these errors is under investigation.

The LC IN-625 material shows unique directionally solidified microstructure due to rapid solidification inherent to the process (Figure 3). The cross-sectional view along the vertical direction (build-up direction) shows that LC IN-625 has columnar grains growing almost parallel to the build direction (Figure 3a), while the horizontal cross section shows that the LC IN-625 consists of fine cells of around 2-3 μm in diameter (Figure 3b). The X-ray diffraction reveals that the LC IN-625 has the same γ phase as the IN-625 powder: a face-centered cubic structure with a lattice parameter of 3.59 Å. The directional solidification of LC IN-625 material is along the (100) crystallographic plane, which is the typical dendritic growth direction of face-centered cubic structure materials [7].



(a) (b)

Figure 3: Microstructure of LC IN-625 alloy (a) vertical cross-sectional view, and (b) horizontal cross-sectional view.

The LC IN-625 material exhibits very good mechanical properties (Table 1). Along the horizontal direction (perpendicular to the build direction), the yield strength ($\sigma_{0.2}$) and tensile strength (σ_{UTS}) 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 anisotropic behaviour of the tensile properties of the LC IN-625 alloy may be attributed to its directionally solidified microstructure. The yield strength and the tensile strength of the LC IN-625 along both directions are significantly higher than the cast IN-625 and comparable to the wrought material, although the elongation along the horizontal direction is slightly lower.

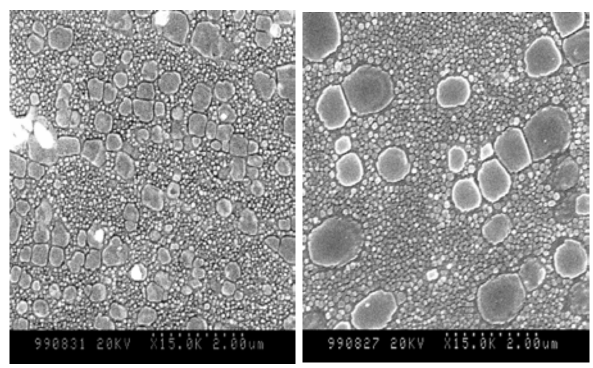
Table 1: Tensile properties of LC IN-625 alloy

Conditions		$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	δ (%)
LC IN-625	Horizontal	518±9	797±8	31±2
	Vertical	477±10	744±20	48±1
Cast IN-625 [8]		350	710	48
Wrought IN-625 [9]		490	855	50

3.2 IN-738 Alloy

IN-738 is a nickel-base γ'-precipitation hardening superalloy containing 16.1% Cr, 8.34% Co, 3.27% Al, 3.38% Ti and other alloying elements. It has an excellent creep strength and hot corrosion resistance and has been used for manufacturing gas turbine airfoils in hot section [10]. Similar to the LC IN-625, the LC IN-738 also shows directionally solidified microstructure: very fine columnar γ dendrites growing almost parallel to the building direction. XRD analysis reveals that the preferred orientation is along the (100) crystallographic plane.

Precipitation of γ' particles is the primary strengthening mechanism for the IN-738 superalloy. The as-consolidated IN-738 material does not have γ'-precipitates, while precipitated carbides are distributed uniformly along the interdendritic regions. After a standard heat treatment cycle (1120°C × 2 hrs/air cooling + 845°C × 24 hrs/air cooling), a significant amount of γ'-particles precipitated in the LC IN-738 matrix (Figure 4a). Compared to the cast IN-738 (Figure 4b), the heat-treated LC IN-738 shows the similar but finer bimodal γ' distribution: coarse particles in near cuboidal shape plus fine particles.



(a) LC IN-738 **(b) Airfoil IN-738**

Figure 4: Observation of γ' precipitates in airfoil and LC IN-738, ×15,000.

Table 2: Comparison of room temperature tensile properties of LC IN-738 with Cast IN-738 alloy

Material	Condition	σ_{UTS} (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)
LC IN-738	Vertical direction As-consolidated	1202 ±23	869 ±5	18 ±2
	Vertical direction Heat-treated	1269 ±35	869 ±19	17 ±2
	Horizontal direction As-consolidated	1084 ±23	880 ±14	6.7 ±1.7
Cast IN-738 [11]	Heat-treated	1100	915	5

The LC IN-738 material shows very good tensile properties (Table 2). Along the vertical direction, the tensile and the yield strength of the as-consolidated IN-738 is about 1202 MPa and 869 MPa respectively, while the elongation is about 18%. After the standard heat treatment (1120°C × 2 hrs/air-cooling + 845°C × 24 hrs/air-cooling), the tensile strength of the LC IN-738 slightly increases to about 1269 MPa, while its yield strength and elongation remain the same.

Along the horizontal direction, the as-consolidated IN-738 shows slightly higher yield strength (880 MPa), but relatively lower tensile strength (1084 MPa) and smaller elongation (6.7%), as compared to the vertical direction. It should be noted that the tensile test data are very consistent within each testing group (Table 2), which indicates that the laser consolidation process has an excellent reproducibility.

Compared to the tensile properties of heat treated cast IN-738, the heat-treated LC IN-738 along the vertical direction shows 15% higher tensile strength and 240% higher elongation, although its yield strength is slightly reduced by about 5%.

Table 3: Stress rupture life tested at 1010°C (1850°F) and 55 MPa (8 ksi)

Sample No.	LC IN-738	LC IN-738/Cast IN-738	Cast IN-738 Baseline
#1	515 hrs.	123 hrs.	206 hrs.
#2	236 hrs.	175 hrs.	116 hrs.
#3	485 hrs.	128 hrs.	187 hrs.
#4	455 hrs.	-	-
Average	**423 hrs.**	**142 hrs.**	**170 hrs.**

The LC IN-738 material shows excellent stress rupture life (Table 3). Under the test condition (1010°C and 55 MPa), the average stress rupture life of LC IN-738 material is about 423 hours, which is more than double the life of the cast IN-738 baseline (170 hours). The excellent stress rupture life of the LC IN-738 may be attributed to its directionally solidified microstructure, uniform γ' particle precipitation, and fine and uniform carbide distribution.

The stress rupture life of LC IN-738/cast IN-738 specimens ranged from 123 to 175 hours with an average value of 142 hours, which falls within the acceptable range of the cast IN-738 baseline specimens (from 116 to 206 hours with an average life of 170 hours). It should be pointed out that the machining quality of the LC IN-738/cast IN-738 specimens was unsatisfactory, which could have contributed to the relatively low value. Further analysis is being conducted on these samples to identify the causes of low readings.

Figure 5 shows an IN-738 alloy airfoil built directly on a cast IN-738 substrate. The laser consolidated airfoil shows a good surface finish with an average roughness (Ra) of about 3 - 4 μm under as-consolidated condition.

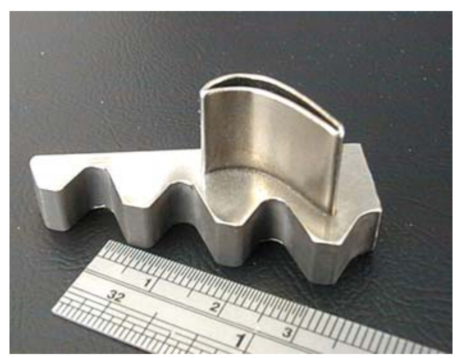
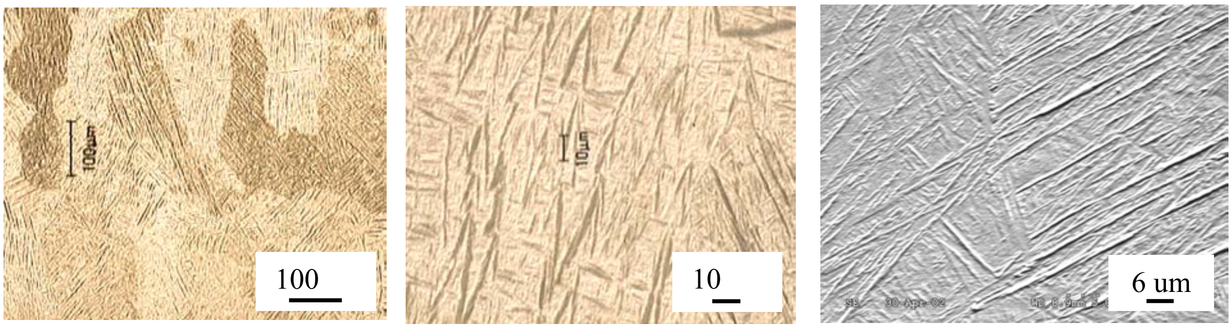


Figure 5: LC IN-738 airfoil built on cast IN-738 substrate.

3.3 Ti-6Al-4V Alloy

Ti-6Al-4V is an (α+β) alloy that contains α stabilizer element Al and β stabilizer element V. The typical as-cast Ti-6Al-4V microstructure consists of transformed β containing acicular α as well as α at prior-β grain boundaries, while the annealed wrought Ti-6Al-4V bar typically consists of equiaxed α grain plus intergranular β [12].



(a) Optical micrograph, ×100 **(b) Optical micrograph, ×1000** **(c) SEM micrograph, ×1500**

Figure 6: Microstructure of LC Ti-6Al-4V.

The microstructure of the LC Ti-6Al-4V along the vertical cross-section is shown in Figure 6. The LC Ti-6Al-4V shows somewhat equiaxed grains (Figure 6a) with acicular phase inside (Figure 6b). A high-resolution SEM photo reveals that grain boundary is hard to distinguish and no secondary phase can be observed along it (Figure 6c).

Table 4: Tensile properties of Ti-6Al-4V alloy

Materials	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	E (GPa)	δ (%)
LC Ti-6Al-4V (thick-wall specimens)	899	979	121	11.4
LC Ti-6Al-4V (thin-wall specimens)	1062	1157	116	6.2
Cast Ti-6Al-4V (As-cast or annealed) [13]	890	1035	-	10
Wrought Ti-6Al-4V (annealed bar) [14]	825	895	110	10
Wrought Ti-6Al-4V (solution treated and aged bar) [14]	965	1035	110	8
Wrought Ti-6Al-4V (solution heat treated + aged) [15]	1103	1172	-	10

The tensile properties of the LC Ti-6Al-4V materials are listed in Table 4. The thin-wall LC Ti-6Al-4V material has a yield strength of 1062 MPa and a tensile strength of 1157 MPa. The elongation in 25 mm gauge length is 6.2%. The tensile and yield strengths of the thin-wall LC Ti-6Al-4V are substantially higher than the as-cast/annealed cast Ti-6Al-4V and annealed wrought Ti-6Al-4V, and comparable to the wrought Ti-6Al-4V in solution treated plus aged condition. The elastic modulus of the thin-wall LC Ti-6Al-4V (116 GPa) is comparable to the wrought material (110 GPa). However, the elongation of the LC material is lower than the cast or wrought Ti-6Al-4V (8-10%).

The thick-wall LC Ti-6Al-4V material is found to have a slightly lower tensile and yield strengths but a higher ductility than the thin-wall material. The average yield and tensile strengths of this material in the as-consolidated condition are 899 MPa and 979 MPa respectively. The average elongation is around 11.4% and the elastic modulus is slightly higher at around 121 GPa. The tensile properties of thick-wall LC Ti-6Al-4V are still comparable to the as cast or annealed cast Ti-6Al-4V material and higher than the annealed wrought Ti-6Al-4V material.

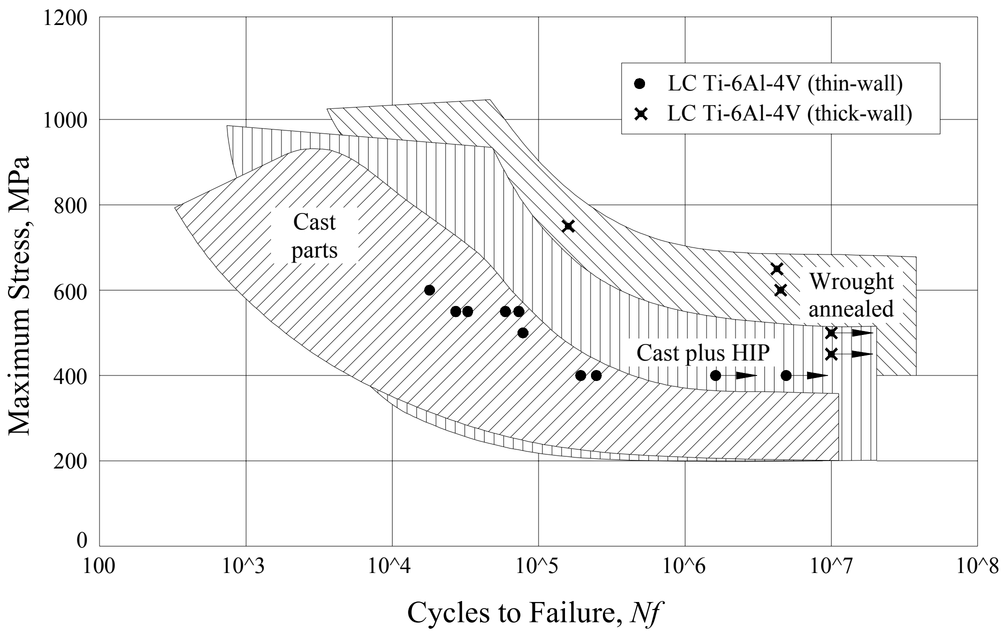


Figure 7: Fatigue data of laser consolidated Ti-6Al-4V compared with cast and wrought/anneal Ti-6Al-4V (R=+0.1) [16].

The results of the high-cycle fatigue tests are displayed in Figure 7. Both thin-wall and thick-wall LC Ti-6Al-4V specimens were tested in the as-consolidated condition at room temperature. As a preliminary study, only five thick-wall LC Ti-6Al-4V specimens were tested to determine how the fatigue properties of LC Ti-6Al-4V are affected by the LC process parameters. The plot also shows reference data [16] for cast, cast plus HIP and annealed wrought Ti-6Al-4V for comparison purposes. The endurance limit shown by the thin-wall LC Ti-6Al-4V specimens is around 400 MPa, which is at the high end of the cast material scatter band. The preliminary tests conducted on thick-wall LC Ti-6Al-4V specimens have demonstrated a significant improvement in fatigue resistance over the thin-wall specimens. The results show that the endurance limit of the thick-wall LC Ti-6Al-4V material is in excess of 500 MPa, which is well within the scatter band of annealed wrought material. These preliminary results are very promising and demonstrate that the adjustment of LC processing parameters can significantly improve the fatigue properties of LC Ti-6Al-4V.

The wall thickness of fatigue specimens can also affect the fatigue resistance results. For axial fatigue testing, a larger wall thickness results in a greater volume of material that is exposed to the maximum stress on each cycle. This typically leads to a greater likelihood of earlier crack initiation and therefore more conservative results of fatigue life. Consequently, the increased fatigue resistance of the thick-wall specimens should not be attributed to specimen geometry alone.

3.4 Stellite 6 Alloy

Stellite 6 is a Co-base wear resistant alloy containing 1% C, 27% Cr, 4.7% W and 0.9% Si. The Co-Cr-W system alloy retains its hardness at elevated temperatures and is especially effective for wear applications at high temperatures or in a corrosive environment, and are widely used as wear-, corrosion- and heat-resistant materials [17].

Compared to the conventional casting or powder metallurgy method, the laser consolidation produces Stellite 6 material with significantly better mechanical properties: harder, stronger, and even more ductile (Table 5).

Table 5: Mechanical properties of the LC Stellite 6 alloy

Processing Method	Condition	σ_{UTS} (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)	HRc
LC Stellite 6	As-consolidated (Vertical)	1245±55	751±16	3.1±0.1	58
	As-consolidated (Horizontal)	1362±30	1023±15	3.2±0.4	59
Sand Casting [18]	Stress-relieved	834	541	1 - 2	46
Investment Casting [18]	As-cast	793	662	3	37
Powder Metallurgy [18]	-	896	-	<1	40

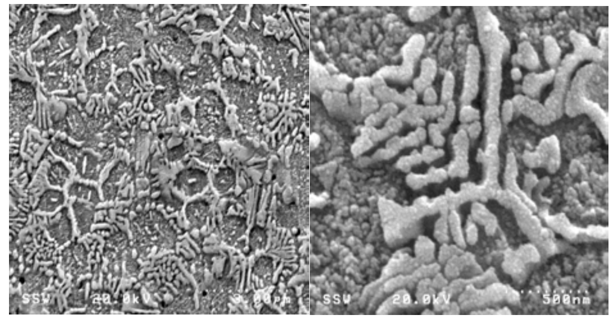
The tensile strength of LC Stellite 6 is about 1245 MPa in the vertical direction and 1362 MPa in the horizontal direction, which are about 50% higher than the values in the cast or powder metallurgy Stellite 6 (only about 793 to 896 MPa). The Laser consolidated Stellite 6 material is 25-55% harder, which is a significant increase. The average hardness of the LC Stellite 6 along vertical and horizontal directions is about Hv 663 and Hv 681 respectively, which is equivalent to about Rc 58 to 59, while only about Rc 37 ~ 46 is exhibited by the same material produced by the casting or powder metallurgy method. The yield strength of conventional cast and powder metallurgy Stellite 6 is about 541 to 662 MPa, while laser consolidation increases the yield strength to 751 MPa (vertical direction) and 1023 MPa (horizontal direction), representing an increase of 15-90%. The elongation of LC Stellite 6 material is about 3.1-3.2%, which is similar to that obtained by investment casting (3%), but much better than that produced by sand casting (1-2%) or the powder metallurgy method (<1%).

The excellent mechanical properties of the LC Stellite 6 material is attributed to its refined microstructure produced by the rapid solidification inherent to the process. It is well recognized that dendrite arm spacing (DAS) significantly affects the mechanical properties of cast alloys [19]. Generally speaking, an increase in the solidification rate reduces the DAS with increased mechanical properties. [19]. The cooling rate during the conventional casting process is in the range of 10^{-3} – 1 k/sec, which results in a characteristic DAS of 50 to 500 µm. The characteristic DAS in the LC Stellite 6 material is only about 1.2 – 3.3 µm, which represents a cooling rate of 10^3 – 10^6 K/sec [20]. The fine DAS in the LC Stellite 6 directly contributes to its exceptional mechanical properties compared to the conventional casting or powder metallurgy Stellite 6 material with a much coarser dendritic microstructure.

3.5 CPM-9V Tool Steel

CPM-9V is a vanadium-carbide type of tool steel developed by Crucible Research for powder metallurgy applications. The CPM-9V powder contains 1.8% C, 9.26% V, 5.35% Cr, 1.24% Mo and 0.91% Si. Compared to conventional tool steels, CPM-9V exhibits excellent wear resistance [21].

The LC CPM-9V has a very fine microstructure, which is very hard to identify under optical microscope. A high resolution SEM photo (Figure 8a) shows that as-consolidated CPM-9V has two-phase microstructure: a light, very fine and snowflake-like phase precipitated on the dark matrix. The thickness of the light snowflake-like phase is only about 100 nm (Figure 8b). EDS analysis indicates that the light phase contains higher percentage of Vanadium (about 12 – 14 %) and Chromium (about 6 – 6.6%) compared to the dark matrix (about 9% V and 5.7% Cr). The XRD analysis reveals that the light phase is $(V,Cr)_8C_7$ type carbides, while the dark is α phase.



(a) (b)

Figure 8: Microstructure of LC CPM-9V by high resolution SEM, (a) × 6,500, and (b) × 40,000.

LC CPM-9V material shows very good tensile properties (Table 6). Along the vertical direction, the as-consolidated CPM-9V has average yield strength of 821 MPa and tensile strength of 1315 MPa. The Elastic modulus of the consolidated CPM-9V is about 234 GPa. Unfortunately, all specimens failed outside of the gauge length and therefore, the accurate elongation data were not available. But based on the measured data within the gauge length, the average elongation of the as-consolidated CPM-9V will be 2.6% or higher. It should be noted that all tensile test data are very consistent and the scatter ranges are small, which again indicates that the laser consolidation process has excellent reproducibility.

Table 6: Tensile properties of LC CPM-9V tool steel

Sample No.	Vertical Direction (As Consolidated)			
	σ_{UTS} (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)	E (GPa)
#1	1358.9	883.8	2.3*	229.6
#2	1295.0	787.0	2.8*	230.6
#3	1303.8	835.9	2.2*	244.5
#4	1303.8	778.1	3.1*	232.7
Average	**1315±29**	**821±49**	**2.6***	**234±7**

LC CPM-9V also shows excellent wear resistance (Figure 9). Pin-on-disk test reveals that, under the given test conditions (samples tested against ¼" dia. WC ball under 500 g load at a linear speed of 0.28 m/s for a total distance of 8000 m), LC CPM-9V specimens (Rc.50-55) showed significantly better wear resistance compared to hardened D2 (Rc. 64-65) and normalised 4340 (Rc.35-36) materials. The average volume loss of the LC CPM-9V specimens was about 0.0211 mm^3, which was only about the 1/3 of the volume loss of D2 specimens (0.0595 mm^3) and about one order of magnitude lower compared to the 4340 specimens (0.2185 mm^3).

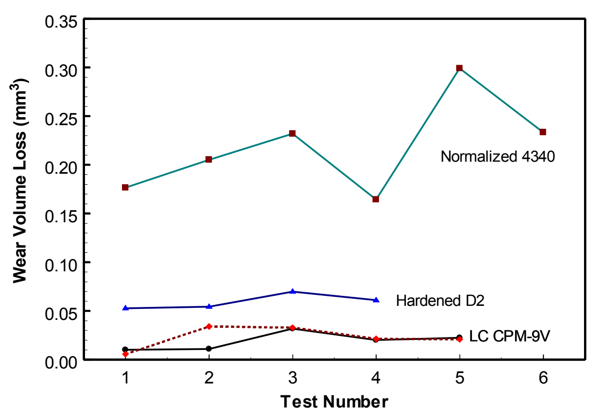


Figure 9: Pin-on-disk wear test results (disk volume loss).

In addition, the wear loss of WC balls against the LC CPM-9V material was also significantly lower than that of the same balls against the D2 and 4340 steel. The average wear volume loss of the WC balls against the LC CPM-9V was only about 0.01855 mm^3, while the ball volume loss against the D2 and 4340 steel was increased double and triple (0.0417 mm^3 and 0.0538 mm^3), respectively.

It is interesting to notice that although the hardness of the LC CPM-9V material is only around Rc.50-55, but its wear resistance is clearly superior to the hardened D2 steel with a hardness of around Rc. 64-65, which is consistent with the observation on powder metallurgy (P/M) CPM-9V material [21]. The excellent wear resistance of the LC CPM-9V may be attributed to the precipitation of $(V,Cr)_8C_7$ carbides due to the high vanadium contents in the alloy.

4.0 POTENTIAL APPLICATIONS

As evident in the preceding sections, the laser consolidation process provides a unique capability to manufacture fully functional net-shape components directly from CAD models in one-step. Especially, this process provides the potential to produce very complex thin-wall structures that are difficult or even impossible to manufacture by other methods.

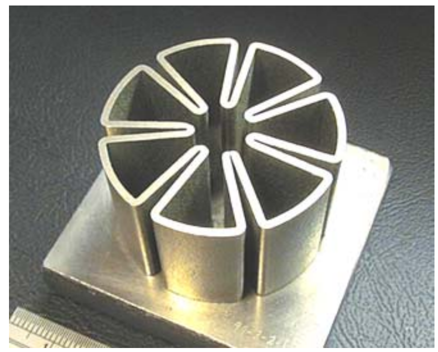


Figure 10: LC Stellite 6 sample.

Figure 10 shows a complex Stellite 6 shape built on an A36 steel substrate. The laser consolidated sample has smooth surface finish and its cross section reveals very uniform wall thickness.

Figure 11 shows a complex LC IN-625 shell and its cross section in the middle. It is evident that this novel process produces high quality, fairly complex shapes directly from a CAD model with acceptable surface finishes in as-consolidated condition without any further processing.

Figure 11: A complex LC IN-625 shell.

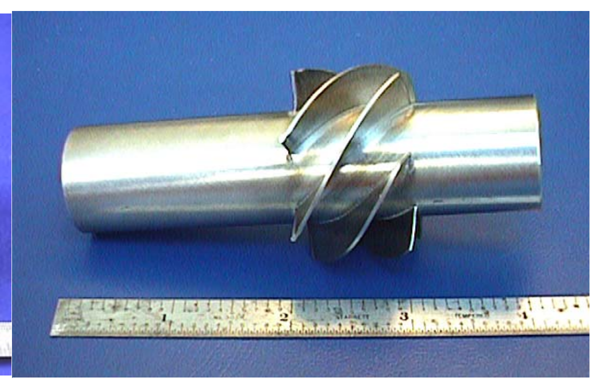


Figure 12: As-consolidated IN-625 alloy fins on a stainless steel

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. Figure 12 shows that several IN-625 alloy fins were built on a stainless steel shaft using the laser consolidation process. The bond between the laser consolidated features and the existing component is metallurgically sound, without crack and porosity. Compared to conventional welding process, the heat input from laser consolidation process to the substrate is minimal, resulting in a very small heat affected zone (several tens micrometers). By using the laser consolidation process, more unique features can be added to the components to provide additional functionality, reduce manufacturing time and cost.

In addition, since laser consolidation does not require any moulds or dies, it provides the flexibility to change the design quickly to make functional components to meet various industrial demands. The lead-time to produce customized components could be reduced significantly. Figure 13 shows a LC CPM-9V rotary cutting die after final sharpening. The die was manufactured by laser consolidation of CPM-9V to build customized cutting blades on pre-machined substrate. Several rotary cutting dies passed production testing and the LC CPM-9V die successfully cut more than 180,000 meters of labels without the need of re-sharpening. Custom's response to the laser-consolidated dies is very promising.

Figure 13: Laser consolidated CPM-9V rotary cutting die after final sharpening.

5.0 CONCLUSIONS

- Laser consolidation builds metallurgically sound samples with IN-625, IN-738, Ti-6Al-4V, Stellite 6 alloys and CPM-9V tool steel. The LC samples are fully dense, free of cracks or porosity.
- The LC samples show good surface finish, dimensional accuracy, excellent mechanical properties and other functionality.
- Laser consolidation provides many unique opportunities for manufacturing functional net-shape components for various industries, such as complex thin-wall structures that are difficult or even impossible to manufacture by other methods, add delicate features onto existing components, manufacture customized components, with short turn around time and reduced cost.

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MEETING DISCUSSION – PAPER NO: 15

Author: L. Xue

Discusser: P. Carroll

Question: 1. Powder size and usage? 2. Criticality of set-up?

Response: 1. All powders are reusable. Test shows that the re-used powders have the same mechanical properties. 2. Set up is critical. Technical know-how is essential to ensure the process stability.