Laser Consolidation Process for the Manufacturing of Structural Components for Advanced Robotic Mechatronic System
– A State of Art Review

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Abstract
Laser consolidation is an emerging computer-aided manufacturing (CAM) process that can produce net-shape functional components layer by layer directly from CAD models. Compared to conventional machining process, this novel process could build a complete part or features on an existing part by adding instead of removing material. This paper presents the laser consolidation process and its application for the manufacturing of structural components for Advanced Robotic Mechatronics System (ARMS) project.

1. Introduction
The Integrated Manufacturing Technologies Institute of the National Research Council Canada (IMTI-NRC) is developing a novel process called “Free-Form Laser Consolidation” to build functional net-shape components directly from metallic powder in one step [1-3]. The parts built by the laser consolidation process are metallurgically sound, free of porosity or cracks.

Laser consolidation is a one-step computer-aided manufacturing process that does not require any moulds or dies, and therefore provides the flexibility of quickly changing the design of the components. Thus, the lead-time to produce parts could be reduced significantly. In 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 instead of removing material. Due to the rapid solidification inherent to the process, excellent material properties are exhibited by various laser-consolidated materials, such as Ni-base superalloys, Co-alloys, Ti-alloys, stainless steels and tool steels [1-6].

Advanced Robotic Mechatronics System (ARMS) is a project initiated by MD Robotics to investigate the use of enabling and emerging technologies for the design and manufacture of the next generation space robotic arms with the goal of achieving low mass, reduced cost, improved structural performance and faster manufacturing time. Laser consolidation is being investigated as a rapid functional prototyping method for making structural components for the ARMS project.

In this paper, laser consolidation process will be introduced, the functional properties of the laser-consolidated materials will be described, and the application of the process for manufacturing structural components for ARMS project will be presented.

2. Process Description
Laser consolidation 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 bead 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 moulds or dies.

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 four typical laser-consolidated materials, Ni-base IN-625 and IN-738 alloys, Co-base Stellite 6 alloy and Fe-base CPM-9V tool steel, are discussed in this paper. A cheap, annealed A36 mild steel plate (0.29% C, 1.0% Mn, 0.2% Cu and Fe) with a thickness of 12.7 mm was used as the base material for the laser consolidation. The steel base plates were machined into coupons and ground to a consistent surface finish for the laser consolidation of different alloys.

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. Functional Properties of LC Materials

3.1 IN-625 Superalloy

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 dimensional accuracy.

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 0.050 mm. The average squareness between walls is 90.00° with a deviation of 0.02°, while the average perpendicularity of square walls against the base plate is 89.92°. 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 cylinder 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° compared to the required 10°. 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].

Table 1 Tensile properties of LC IN-625 alloy.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>σ0.2 (MPa)</th>
<th>σUTS (MPa)</th>
<th>δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC IN-625</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>518±9</td>
<td>797±8</td>
<td>31±2</td>
</tr>
<tr>
<td>Vertical</td>
<td>477±10</td>
<td>744±20</td>
<td>48±1</td>
</tr>
<tr>
<td>Cast IN-625 [8]</td>
<td>350</td>
<td>710</td>
<td>48</td>
</tr>
<tr>
<td>Wrought IN-625 [9]</td>
<td>490</td>
<td>855</td>
<td>50</td>
</tr>
</tbody>
</table>

The LC IN-625 material exhibits very good mechanical properties (Table 1). Along the horizontal direction (perpendicular to the build direction), the yield strength (σ0.2) and tensile strength (σUTS) 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 behavior 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.

Figure 4 shows a complex LC IN-625 part and its cross section at the middle. It is evident that this novel process can produce high quality, fairly complex shapes directly from a CAD model with acceptable surface finishes in as-consolidated condition without any further processing.

3.2 IN-738 Superalloy

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 5a). Compared to the cast IN-738 (Figure...
5b), the heat-treated LC IN-738 shows the similar but finer bimodal \( \gamma' \) distribution: coarse particles in near cuboidal shape plus fine particles.

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 (\( 1120^\circ C \times 2 \text{ hrs/air-cooling} + 845^\circ C \times 24 \text{ hrs/air-cooling} \)), the tensile strength of the LC IN-738 slightly increases to about 1269 MPa, while its yield strength and elongation remain the same.

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Condition</th>
<th>( \sigma_{UTS} ) (MPa)</th>
<th>( \sigma_{0.2} ) (MPa)</th>
<th>( \delta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC IN-738</td>
<td>Vertical direction</td>
<td>1202 ±23</td>
<td>869 ±5</td>
<td>18 ±2</td>
</tr>
<tr>
<td></td>
<td>As-consolidated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical direction</td>
<td>1269 ±35</td>
<td>869 ±19</td>
<td>17 ±2</td>
</tr>
<tr>
<td></td>
<td>Heat-treated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal direction</td>
<td>1084 ±23</td>
<td>880 ±14</td>
<td>6.7 ±1.7</td>
</tr>
<tr>
<td></td>
<td>As-consolidated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cast IN-738</td>
<td>Heat-treated</td>
<td>1100</td>
<td>915</td>
<td>5</td>
</tr>
<tr>
<td>[11]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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).

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>LC IN-738</th>
<th>LC IN-738/ Cast IN-738</th>
<th>Cast IN-738 Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>515 hrs.</td>
<td>123 hrs.</td>
<td>206 hrs.</td>
</tr>
<tr>
<td>#2</td>
<td>236 hrs.</td>
<td>175 hrs.</td>
<td>116 hrs.</td>
</tr>
<tr>
<td>#3</td>
<td>485 hrs.</td>
<td>128 hrs.</td>
<td>187 hrs.</td>
</tr>
<tr>
<td>#4</td>
<td>455 hrs.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>423 hrs.</td>
<td>142 hrs.</td>
<td>170 hrs.</td>
</tr>
</tbody>
</table>

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 \( \gamma' \) 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 for the LC IN-738/cast IN-738 specimens was unsatisfactory, which could lead to the relatively low value. Further analysis is being conducted on these samples to identify the causes of low readings.

Figure 6 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 \( \mu \)m under as-consolidated condition.

### 3.3 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 [12].

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 4).

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). Stellite 6 is a wear resistant alloy and its hardness represents the essential functionality. Laser consolidation increases the hardness of Stellite 6 material by a factor of 25-55%, 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%).

Table 4 Mechanical properties of the LC Stellite 6 alloy

<table>
<thead>
<tr>
<th>Processing Method</th>
<th>Condition</th>
<th>σUTS (MPa)</th>
<th>σ0.2 (MPa)</th>
<th>δ (%)</th>
<th>HRc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As-consolidated</td>
<td>1245</td>
<td>751</td>
<td>3.1</td>
<td>58</td>
</tr>
<tr>
<td>LC Stellite 6</td>
<td>(Vertical)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>As-consolidated</td>
<td>1362</td>
<td>1023</td>
<td>3.2</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>(Horizontal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment Casting [13]</td>
<td>As-cast</td>
<td>793</td>
<td>662</td>
<td>3</td>
<td>37</td>
</tr>
</tbody>
</table>

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 [14]. Generally speaking, an increase in the solidification rate reduces DAS and a mechanical property improvement usually accompanies this reduction [14]. 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 $10^7$ – $10^8$ K/sec [15]. 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.

Figure 7 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.

3.4 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 [16].

The LC CPM-9V has a very fine microstructure, which is very hard to identify under optical microscope. A high resolution SEM photo (Fig.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 (Fig.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 $(V, Cr)_2C_7$ type carbides, while the dark is $\alpha$ phase.

LC CPM-9V material shows very good tensile properties (Table 5). Along the vertical direction, the as-consolidated CPM-9V has average yield strength of 821 MPa and tensile strength of 1315 MPa. The Elastic
The 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 5 Tensile properties of LC CPM-9V tool steel

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

LC CPM-9V also shows excellent wear resistance (Fig.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 mm³, which was only about the 1/3 of the volume loss of D2 specimens (0.0595 mm³) and about one order of magnitude lower compared to the 4340 specimens (0.2185 mm³).

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 [16]. The excellent wear resistance of the LC CPM-9V may be attributed to the precipitation of (V,Cr)$_7$C$_3$ carbides due to the high vanadium contents in the alloy.

Fig.10 Laser consolidated CPM-9V rotary cutting die after final sharpening.

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 mm³, while the ball volume loss against the D2 and 4340 steel was increased double and triple (0.0417 mm³ and 0.0538 mm³), respectively.

The ARMS project will address the optimal design of the booms with the objective of integrating the boom and joint housing. The structure and performance of the booms will be optimized for mass, strength and stiffness as well as fastening of wiring and miniaturized electrical modules.

4. LC Components for ARMS Project

MD Robotics initiated an Advanced Robotic Mechatronics System (ARMS) project to investigate the emerging technologies for the design and manufacture of the next generation space robotic arms. One goal of the ARMS project is to develop a concept of “intelligent” and multifunction structure capable of:

- providing high structural stiffness,
- enclosing the electronic driver/control cards,
- providing the support for the data, power bus, and
- dissipating the heat generated by the electronic drivers.

The ARMS project will address the optimal design of the booms with the objective of integrating the boom and joint housing. The structure and performance of the booms will be optimized for mass, strength and stiffness as well as fastening of wiring and miniaturized electrical modules.
As being displayed in the last section, laser consolidated metallic materials show excellent mechanical properties at room temperature. Although the mechanical properties in the harsh space environment are to be determined, it is expected that the laser consolidated materials should have similar properties as wrought materials that are currently being used in space applications. It is expected that laser consolidated metallic materials will meet the functionality requirements for the structural components such as booms and joint housing for space applications.

Laser consolidation provides one step process to manufacture fully functional net shapes directly from CAD models. As displayed in Figures 4 and 7, this process can produce very complex thin-wall structures that are difficult to manufacture by other methods. By using laser consolidation process, more unique features can be added to the booms and joint housings to provide additional functionality, such as internal features inside the boom to hold electronic boards and cables (Figure 11).

![Fig.11 Concept of laser consolidated features inside of boom to hold electronic board.](image)

Laser consolidation is a material addition process that can directly build functional features on the existing components without the need of welding or brazing. The bond between the laser consolidated part and the substrate 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). Laser consolidation process provides the potential to build boom directly on the joint housing to form an integrated structure.

In addition, laser consolidation does not require any moulds or dies, and it provides the flexibility to change the design quickly. Therefore, the lead-time to produce space structural components could be reduced significantly.

Currently, various unique designs of booms are being considered to take advantages of the laser consolidation process. These booms will be built with laser consolidation process with a Ni-based IN-625 alloy to prove the design concept as well as for demonstration purpose. Integrated boom/housing structure will also be manufactured by laser consolidation process. These components will be tested structurally and the test results will be compared with modeling prediction. Final functional prototyping structural components for the ARMS project will be manufactured by laser consolidation of lightweight and high stiffness materials. The project is ongoing and the results will be reported in the near future.

MD Robotics, a well know developer of advanced robotics systems for space, has initiated the ARMS program with the intent of using LC to achieve a number of significant benefits in designing and manufacturing structural components for future Small Robotic manipulators. It is expected that parts manufactured by LC will have lower weight than similar parts produced using conventional technologies as the structural performance of final parts will have improved characteristics and therefore will be designed with reduced wall thickness. Another important advantage will be faster manufacturing time for components, as the LC manufacturing process is simpler and more flexible. Cost advantage is another important criterion as no tooling or fixtures are required. Increased design flexibility provides the opportunity of manufacturing complex parts. The ultimate objective is to develop small lightweight parts with increased structural stiffness and functional performance that can be manufactured in a short period of time.

Conclusions:

1. Laser consolidation builds metallurgically sound components with Ni-base IN-625 and IN-738 superalloys, Co-base Stellite 6 wear resistant alloy, and CPM-9V tool steel. The LC samples are fully dense, free of cracks or porosity.
2. The LC samples show good dimensional accuracy, excellent mechanical properties and other functionality.
3. Laser consolidation provides many unique advantages for manufacturing structural components for ARMS project and it will provide a means for developing small lightweight parts with increased structural stiffness and functional performance that can be manufactured in a short period of time.
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