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INVESTIGATION OF LASER CONSOLIDATION FOR MANUFACTURING FUNCTIONAL NET-SHAPE COMPONENTS FOR POTENTIAL ROCKET ENGINE APPLICATIONS

Paper #402

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Abstract

Laser consolidation is an emerging novel computer-aided manufacturing process that 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 material.

In this paper, laser consolidation of IN-625 and Ti-6Al-4V alloys has been investigated to build several generic shapes representing parts that may have potential rocket engine applications. Laser consolidation produces components with good surface finish, dimensional accuracy and mechanical properties, and demonstrates the potential for direct manufacturing of functional net-shape components and tooling. In addition, some preliminary results demonstrate that the laser consolidation, in combination with solid-state, net-shape powder metallurgy processing, may provide a unique manufacturing capability to make very complex components for the rocket engines.

Introduction

The Integrated Manufacturing Technologies Institute of National Research Council of Canada (NRC-IMTI) has been developing the advanced laser consolidation process for rapid manufacturing of net-shape functional components based on a CAD design directly from metallic powder [1]. Various industrial materials, including Ni-alloys, Ti-alloys, Co-alloys, Al-alloys, tool steels and stainless steels have been investigated [1-4].

The laser consolidation (LC) is a one-step computer-aided rapid 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 addition, this computer-aided manufacturing process provides an excellent opportunity for manufacturing complex parts that are difficult to produce by conventional manufacturing processes [5-7]. 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 obtained.

Pratt and Whitney Rocketdyne (P&WR) specializes in the design and manufacturing of rocket engines, which requires the manufacturing of various small quantity but complex shaped components. Laser consolidation process provides unique capability to manufacture these small quantity functional components to shorten the manufacturing cycle and to reduce (or even eliminate) tooling cost.

In addition, P&WR is also investigating nest-shape Hot Isostatic Pressing (HIP) of powder materials for producing complex components with high-level properties requirements. Laser consolidation process also provides the potential to make tooling for manufacturing these complex components.

Experimental Details

A 500W Lasag Nd:YAG laser coupled to a fiber-optic processing head was used for all the laser consolidation experiments. The laser was operated in a pulse mode with an average power ranging from 20 to 300 W. A Sulzer Metco 9MP powder feeder was used to deliver metallic powder into the melt pool through a nozzle with the powder feed rate ranging from 1 to 30 g/min. During the laser consolidation, the laser beam and the powder delivery nozzle were kept stationary, while the sample was moved using a multi-axis computer numerical controlled (CNC) motion system. All laser consolidation work was conducted at room temperature in a glove box, in which the oxygen content was maintained below 50 ppm during the process.

Chemical compositions of the two alloy powders investigated in this paper, Ni-base IN-625 and Ti-base Ti-6Al-4V are listed in Table 1. Annealed A36 and 1020 mild steel substrates were used as the base material for laser consolidation of IN-625, while wrought Ti-6Al-4V substrate and Ti-3Al-2.5V tubing were used for laser consolidation of Ti-6Al-4V. The substrate plates were machined and ground to a consistent surface finish for the laser consolidation of different alloy powders.

Table 1: Chemical composition of powder materials (wt. %)

Element	IN-625	Ti-6Al-4V
C	0.03	0.07
Ni	Bal.	0.02
Ti	-	Bal.
Al	-	6.18
Cr	22.0	0.02
Mo	9.0	-
Ta+Nb	3.7	-
V	-	3.94

The microstructures of the LC samples were examined using an Olympus optical microscope as well as a Hitachi S-3500 scanning electron microscope (SEM). A Philips X'Pert X-ray diffraction system with Mo tube 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.

Net-shape Functional Demonstration Parts

LC IN-625 Demonstration Pieces

A net-shape IN-625 part was initially designed to demonstrate the capability of the laser consolidation process (Figure 1). It consists of 5 portions: (a) cylinder #1 (3 mm thick), (b) cylinder #2 (2 mm thick), (3) a conical top on a short cylinder (0.81 mm thick), (4) a circular fin (2 mm thick), and (5) substrate disk (50 mm in diameter and 9.4 mm thick).

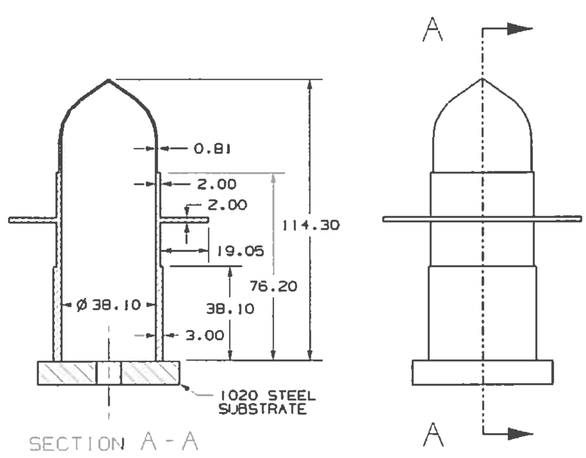
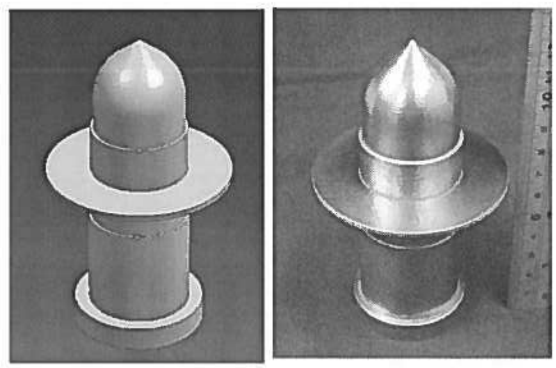


Figure 1: Design of the IN-625 demonstration piece.

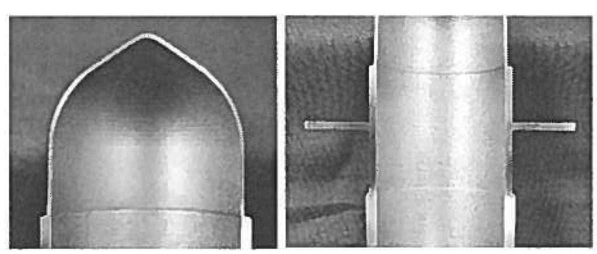
Laser consolidation of IN-625 was performed with a 5-axis motion system to build the demonstration piece on a 1020 steel substrate in the following sequence: cylinder #1, cylinder #2, conical top on a short cylinder and finally the circular fin. A hole with a diameter of 8 mm was pre-drilled in the middle of the substrate to allow the release of the loose powder inside the part after laser consolidation. The steel substrate forms the part of the final demonstration piece. Figure 2 shows the CAD drawing and the as-consolidated LC IN-625 demonstration piece after removing the loose powder. It is evident that the as-consolidated part shows very good surface finish.



(a) (b)

Figure 2: LC IN-625 demonstration piece with conical top, (a) CAD drawing and (b) LC part.

The cross-sectional view of the part (Figure 3a) reveals that, as per the CAD design requirement, the laser consolidation process managed to build the LC IN-625 conical top with very uniform wall thickness and the tip was sealed very well. Figure 3b shows that all four sections of the LC IN-625 piece demonstrate uniform



(a) (b)

Figure 3: Cross-section of LC IN-625 demonstration piece, (a) conical top and (b) middle section.

wall thickness. Detailed examination of the cross-section further revealed that all four portions of the LC IN-625 demonstration piece are metallurgically sound, without cracking or porosity. The bonding between sections and to substrate plate is excellent.

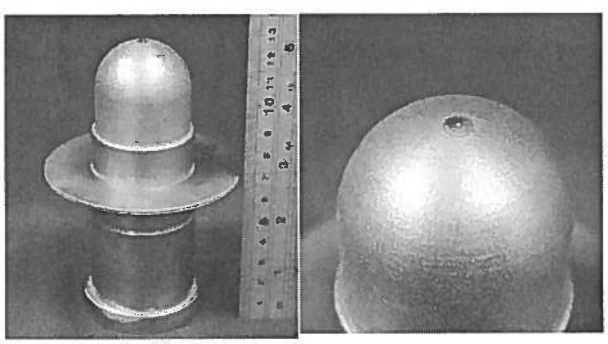
Dimensional Measurement

Dimensions measurement reveals that the internal diameter of the LC IN-625 part is 38.15 mm, which is only 0.05 mm larger than the design. The thickness of the conical top is 0.81 mm, exactly the same as per the design. The thickness of the cylinder is about 0.15 mm thicker than the design, which may be attributed to the deviation in arranging existing multi-pass to fit the required thickness and can be improved in the future.

Change of Design

The laser consolidation is a computer-aided manufacturing process that produces net-shape functional components without any moulds or dies, and therefore provides the flexibility to quickly change the design of the components to reduce the lead-time. One example we demonstrated is to change the conical top with a dome (spherical) top for the design of the demonstration piece.

After the design change, laser path was generated based on the CAD model and laser consolidation of IN-625 was performed to build the modified piece. Figure 4a shows an overall view of the as-consolidated LC IN-625 piece, while Figure 4b gives a more closed look of the dome top. It is evident that laser consolidation process readily accommodated the design change to produce the functional net-shape piece.



(a) (b)

Figure 4: LC IN-625 demonstration piece with dome top, (a) overall view and (b) close view.

Mechanical Properties of LC IN-625 Alloy

The LC IN-625 alloy shows very good tensile properties (Table 2). 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 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.

Table 2: 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

The anisotropic behaviour of the LC IN-625 may be attributed to its directionally solidified microstructure. The vertical cross-sectional view of LC IN-625 shows that the columnar grains have grown almost parallel to the build direction, while the horizontal cross section shows fine cells of around 2-3 μm in diameter [1]. The X-ray diffraction results reveal that the directional solidification follows the <100> direction, which is the dendritic growth direction of face-centered cubic structure materials [10].

LC Ti-6Al-4V Spherical Hollow Ball

The second demonstration piece is a spherical hollow ball made of Ti-6Al-4V. The ball requires an outside diameter of 51.501 mm with a deviation of +/- 0.254 mm and a wall thickness of about 0.7 mm. The ball requires fully sealed without leaking.

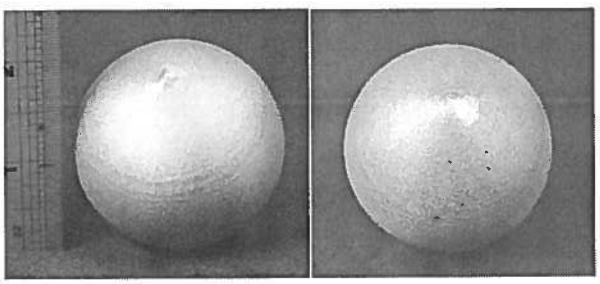
The Ti-6Al-4V hollow ball is usually manufactured by forming two halves of the ball separately through machining, forming or other appropriated methods and then welding them together, which involves many manufacturing steps. For high end users, the thickness uniformity of the ball, especially at the weld area is always a big concern.

As a rapid manufacturing process, laser consolidation process provides the possibility to build the spherical hollow ball directly. However, there is no reference available regarding other similar processes to build spherical hollow ball directly from Ti-6Al-4V powder.

Laser consolidation was investigated to build the entire functional net-shape spherical hollow ball from Ti-

6Al-4V powder in one step to demonstrate its processing capability. A 5-axis motion system was used for this work. A special laser consolidation procedure was developed to build the ball from a Ti-6Al-4V substrate and to close it at the top. After laser consolidation, the ball was machined off from the substrate.

Figure 5a shows a top view of the as-consolidated ball after removing loose powder. It is evident that the as-consolidated Ti-6Al-4V ball shows reasonably good surface finish. Especially, it reveals that laser consolidation process successfully closed the hollow ball without any defects. Figure 5b shows a bottom view of the ball, which reveals that a small portion of the substrate forms the part of the final ball after cutting off from the substrate.



(a) (b)
Figure 5: LC Ti-6Al-4V hollow ball, (a) top view, and (b) bottom view.

Dimensional Measurement of the LC Ti-6Al-4V Ball

The outside diameters of the LC Ti-6Al-4V ball were measured using a Mitutoyo Precision Height Gauge, 45° apart along both polar and equatorial orbits, and data were listed in Table 3. The measurements were compared with the nominal diameter from the CAD model of the ball and the deviation was calculated for each measurement.

Based on the CAD data, the outside diameter of the ball should be 51.501 mm. The measurement of the LC Ti-6Al-4V ball along polar orbit shows the maximum deviation of +0.074 mm and the minimum deviation of -0.104 mm. It should be noted that the minimum deviation was measured at the location where the ball was cut of from the substrate (Figure 5b), which will contribute to the relatively large value of the deviation. Along equatorial orbit, all the measurements are the same (51.575 mm in diameter), which demonstrated excellent uniformity of the ball.

It is obvious that the LC Ti-6al-4V ball shows excellent dimensional accuracy. The deviation of outsider diameter of the LC Ti-6Al-5V ball is in the range of +0.074 mm and -0.104 mm, which is significantly less than the required deviation of +/-0.254 mm. If disregard the (*) data that was affected by the cut-off process, the deviation will be even smaller (+0.074 mm and -0.028 mm).

Table 3: Outsider diameters of LC Ti-6Al-4V ball (mm)

Angle	Measurement	CAD	Deviation
Measured in polar orbit			
0°	51.575	51.501	+0.074
+45°	51.486	51.501	-0.015
+90°	51.397*	51.501	-0.104*
-45°	51.473	51.501	-0.028
Measured in equatorial orbit			
0°	51.575	51.501	0.074
+45°	51.575	51.501	0.074
+90°	51.575	51.501	0.074
-45°	51.575	51.501	0.074

Tensile Properties of LC Ti-6Al-4V Alloy

The LC Ti-6Al-4V alloy also shows excellent tensile properties (Table 4).

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

Materials	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	E (GPa)	δ (%)
LC Ti-6Al-4V	1062 ±6	1157 ±11	116 ±8	6.2 ±0.9
Cast Ti-6Al-4V (annealed) [11]	890	1035	-	10
Wrought Ti-6Al-4V (annealed) [12]	825	895	110	10
Wrought Ti-6Al-4V (heat-treated) [12]	965	1035	110	8
Wrought Ti-6Al-4V (heat treated) [13]	1103	1172	-	10

The average yield and ultimate tensile strengths of the as-consolidated Ti-6Al-4V are about 1062 MPa and 1157 MPa respectively, while the elongation is about 6.2 % and the elastic modulus is about 116 GPa.

Compared to the conventional cast or wrought material, the laser consolidated Ti-6Al-4V shows excellent tensile properties. From the references [11-12], the ultimate tensile and yield strengths of the annealed wrought Ti-6Al-4V are about 825 MPa and 895 MPa respectively, while the ultimate tensile and yield strengths of the cast Ti-6Al-4V in as-cast or annealed condition are about 890 MPa and 1035 MPa. The tensile and yield strengths of the as-consolidated 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 [12-13]. The elastic modulus of the as-consolidated Ti-6Al-4V (116 GPa) is about the same as the wrought material (110 GPa). However, the elongation of as-consolidated Ti-6Al-4V material is about 6%, which is lower than the value of cast or wrought Ti-6Al-4V (8-10%). An appropriate aging treatment may improve the elongation value.

LC Ti-6Al-4V demonstrated very good bonding strength to wrought Ti-6Al-4V substrate. Under tensile testing, the as-consolidated Ti-6Al-4V shows bond strength of about 1045 MPa in average with a standard deviation of 21 MPa. It is interesting to note that all bond test specimens failed in the LC Ti-6Al-4V due to the stress concentration effect instead of at the bond area, which indicates that the actual ultimate tensile strength at the bond area is high.

<u>Preliminary Fatigue Results of LC Ti-6Al-4V Alloy</u>

The preliminary fatigue test results are also very encouraging: the data of as-consolidated Ti-6Al-4V is at the high end of as-cast Ti-6Al-4V data. The endurance limit of the LC Ti-6Al-4V specimens is around 400 MPa, which is significantly higher than 200 MPa achieved by the as-cast Ti-6Al-4V [14]. Recent experimental results have demonstrated that significant improvement in fatigue resistance of LC Ti-6Al-4V alloy can be achieved through optimizing the processing parameters [15]. Preliminary results show that the endurance limit of the LC Ti-6Al-4V material is in excess of 500 MPa, which is well within the upper scatter band of annealed wrought material.

Tooling for Net-shape HIP

<u>Net-shape HIP</u>

Hot Isostatic Pressing (HIP) of powder materials is widely used in industry for production of critical components with high-level properties requirements. Net-shape HIP is a new technology that utilizes sacrificial tooling made from cheap low grade steels, filled with powder, and HIP'd to produce functional components. The low grade steel tooling will then be etched away to leave the "selectively" net shape part. This technology provides unique advantages, such as low cost, short development cycle, and reduced design limitations of traditional manufacturing techniques. The capability to fabricate complex, monolithic shapes without welding provides enhanced service life for critical components in addition to the fabrication and inspection cost savings [16-17]. However, the removal of the sacrificial tooling after the HIP possesses many technical challenges.

Laser consolidation process has the potential to produce net-shape tooling with the same material used for net-shape HIP. After HIP, the LC tooling will become the integrated part of the component and therefore will eliminate the need for removing tooling. The benefits of this concept would take advantage of the uniformly laser-consolidated thin-walled structures to provide a simplification of the deformation modeling (rheology) currently employed to predict component shapes after HIP. This could eliminate both the difficult structural modeling and the requirement for bulk tooling to prevent part distortion during HIP consolidation.

In this section, we are going to report our preliminary work on laser consolidation to build Ti-6Al-4V tooling for net-shape HIP for potential rocket engine components.

Cylindrical Capsule for Net-shape HIP

A cylindrical capsule was designed and manufactured to evaluate the feasibility of laser consolidation process to make tooling for the net-shape HIP.

<u>LC Ti-6Al-4V Cylindrical Capsule</u>

Ti-3Al-2.5V tubing with an O.D. of 26.67 mm (1.050") and an I.D. of 18.84 mm (0.742") was purchased. The tubing was machine to 20.27 mm (0.798") in I.D. with a wall thickness of 1.59 mm (0.0625") and a height of 44.45 mm (1.75") as a substrate. Laser consolidation was performed to build a Ti-6Al-4V tube with a wall thickness of 1.59 mm (0.0625") on the end of the pre-machined Ti-3Al-2.5V tubing substrate that was mounted on a rotary table of the CNC motion system.

A conical top was further built on the laser consolidated cylinder to seal the tube (Figure 6). The total length of the LC Ti-6Al-4V portion is about 101.6 mm (4") long. It is evident that the outside of the LC Ti-6Al-4V cylinder matches very well with the Ti-3Al-2.5V substrate.

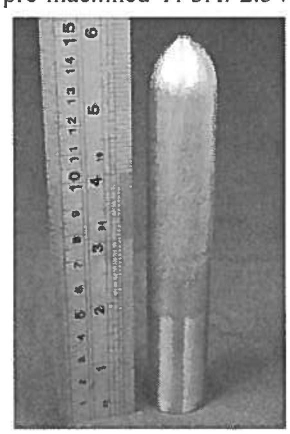


Figure 6: LC Ti-6Al-4V cylindrical capsule.

Cross-sectional view (Figure 7a) shows that the LC Ti-6Al-4V cylinder has very uniform wall thickness and the conical top seals the tube completely. The wall of the LC Ti-6Al-4V cylinder matches well with the Ti-3Al-2.5V tubing substrate both internally and externally (Figure 7b).

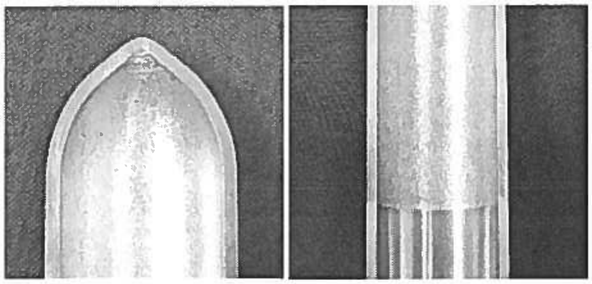


Figure 7: Cross-section of LC Ti-6Al-4V capsule, (a) conical top, and (b) bonding to substrate.

Metallurgical examination reveals that the bonding between the LC Ti-6Al-4V and the Ti-3Al-2.5V substrate is sound and laser consolidated Ti-6Al-4V portions don't have any porosity or cracks.

<u>HIP Testing</u>

HIP testing of the LC Ti-6Al-4V cylindrical capsule was performed by P&WR. The open end of the LC cylindrical capsule was seal welded to wrought titanium sheet stock and an evacuation tube was attached to support leak check and hot vacuum degas of the titanium powder. HIP temperature, pressure and time parameters were industry standards for the Ti-6Al-4V alloy and are generally conducted at a conservative margin below the beta transus temperature.

Figure 8 shows the LC Ti-6Al-4V cylindrical capsule after HIP. Thermally induced porosity (TIP) testing, metallography and density measurements were among the techniques used to verify complete consolidation of the powder. These manufacturing technologies also verified the integrity of the LC structure with the HIP-consolidated powder and its ability to uniformly deform at high temperature and pressure.

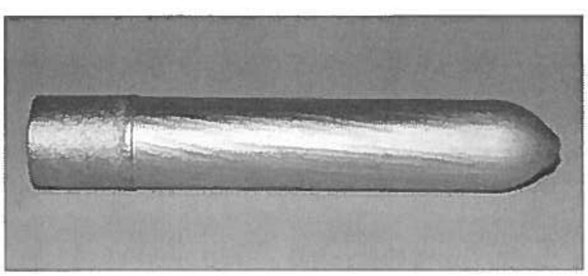


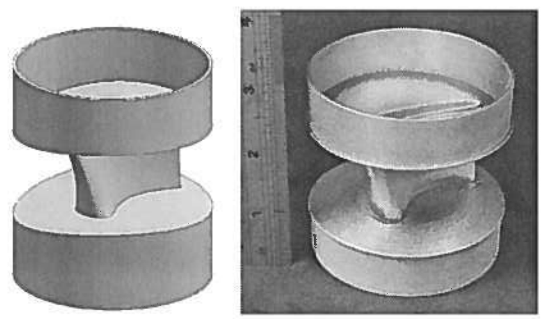
Figure 8: LC Ti-6Al-4V capsule after HIP.

Airfoil Capsule for Net-shape HIP

<u>LC Ti-6Al-4V Airfoil Capsule</u>

An airfoil capsule was designed to prove the concept for laser consolidation to build tooling for net-shape HIP. The airfoil capsule contains a twisted airfoil in the middle with each end connected to a saddle surface that caps on a cylinder (Figure 9a). This shape creates significant challenges for the existing laser consolidation process because of large overhangs.

In order to develop laser consolidation procedures with reduced technical challenges, the airfoil capsule was simplified by replacing the saddle surface with a flat surface. Laser path planning was performed as per the simplified design. Laser consolidation of Ti-6Al-4V alloy was successfully performed to build the airfoil capsule in the following sequence: starting from the middle airfoil, then the flat flanges on the two ends of the airfoil and finally two cylinders on the flanges. The initial trial demonstrated that the laser consolidation procedures are feasible and the as-consolidated simplified LC Ti-6Al-4V airfoil capsule looks good (Figure 9b).

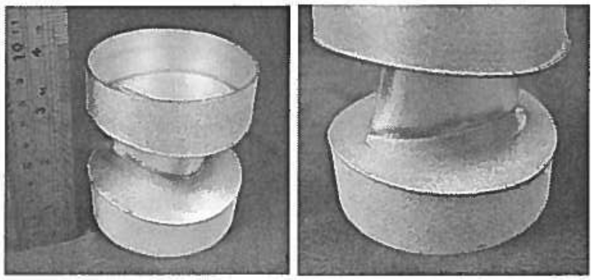


(a) (b)

Figure 9: LC Ti-6Al-4V airfoil capsule, (a) CAD drawing, and (b) as-consolidated simplified part.

Based on the results from the initial trial, the demonstration airfoil capsule with two saddle flanges was further investigated. Laser path was re-designed based on the demonstration airfoil capsule shape. Laser consolidation of Ti-6Al-4V alloy was successfully performed to build up the middle airfoil, saddle flanges on the two ends of the airfoil and two cylinders on the flanges.

Figure 10a shows an overall view of the LC Ti-6Al-4V demonstration airfoil capsule, while Figure 10b shows the intersection between the airfoil and the saddle flange. The consolidated part is about 86 mm (3.38") high and 38 mm (1.5") in diameter. The wall thickness is about 1.27 mm. It is obvious that the laser-



(a) (b)

Figure 10: LC Ti-6Al-4V airfoil capsule, (a) overall view, and (b) connection between airfoil and saddle flange.

consolidated airfoil capsule shows very good surface finish.

HIP Testing

HIP testing of the LC Ti-4Al-4V airfoil capsule was performed by P&WR. Two ends of the LC airfoil capsule were seal welded to wrought titanium sheet stock and an evacuation tube was attached to support leak check and hot vacuum degas of the titanium powder (Figure 11). HIP temperature, pressure and time parameters were industry standards for the Ti-6Al-4V alloy and are generally conducted at a conservative margin below the beta transus temperature.

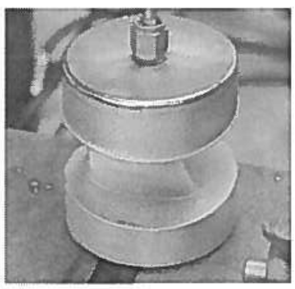


Figure 11: Sealed LC airfoil capsule ready for HIP consolidation.

The geometry of the airfoil, including a sharp interface with the saddle surface and the outer diameter of the capsule, makes this part difficult to consolidate. Several changes to the capsule interfaces to remove these stress concentrations were required to promote high pressure HIP consolidation.

LC Ti-6Al-4V for Building Impeller Segments

Laser consolidation of Ti-6Al-4V alloy to build tooling for net-shape HIP was investigated to manufacture segments of an impeller for demonstration.

Figure 12 shows a CAD drawing of vane passages of an impeller. Because of the complex geometry of the component, as per P&W Rocketdyne's suggestion, one 1/6 section (highlighted in red) of the impeller was selected as sub-scale feature to be built using laser consolidation of Ti-6Al-4V alloy.

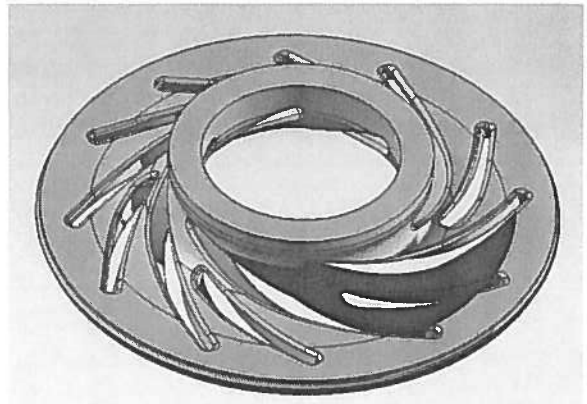


Figure 12: CAD drawing of vane passage of an impeller.

Based on the capability of the laser consolidation process, a CAD drawing of the vane passage segment was created (Figure 13a). The green "leg" portions are supporting structures for the required vane passage (red portion) and will be removed by CNC machining after laser consolidation. From the view of laser consolidation process, the vane passage segment is quite complex and presents many technical challenges to build it. For example, it requests horizontal start to build the part from the substrate and finishes the building almost vertically.

Laser consolidation strategy was developed to build the vane passage segment using a 5-axis motion system. It will start from horizontal orientation to build two hollow "legs" from a Ti-6Al-4V disk in parallel. Two hollow legs will then be merged into one integrated cavity. With the help of the 5-axis motion system, the cavity will be further built up gradually towards vertical direction. Figure 13b shows the as-consolidated Ti-6Al-4V vane passage segment. The part is about 127 mm (5") high and 60 mm (2.35") wide with a thickness of about 1.35 mm. It is evident that the LC Ti-6Al-4V part shows good quality.

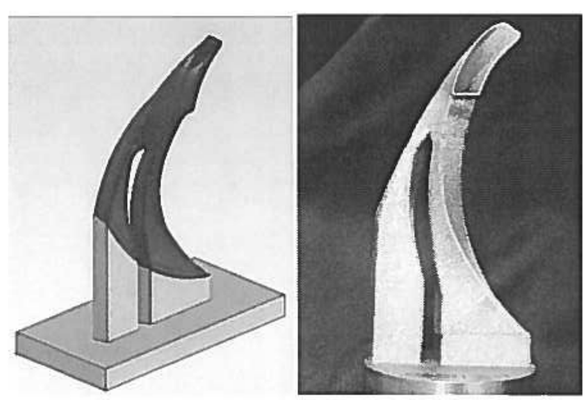


Figure 13: Vane passage segment of an impeller, (a) CAD drawing, and (b) LC Ti-6Al-4V part.

The preliminary results of this feasibility study have successfully proved that the laser consolidation process provides the potential to make tooling for net-shape HIP to produce complex components.

Conclusions

Laser consolidation of IN-625 and Ti-6Al-4V has been investigated to build several generic shapes representing parts that may have potential rocket engine applications. Laser consolidation produced components with good surface finish, excellent dimensional accuracy and mechanical properties, which demonstrated the potential for direct manufacturing of functional net-shape components for rocket engines.

Preliminary results demonstrated that the laser consolidation process successfully built Ti-6Al-4V cylindrical and airfoil capsules, as well as vane passage segments for an impeller. Experimental results demonstrated that the LC Ti-6Al-4V cylindrical capsule successfully resisted the extreme pressure and elevated temperature during the HIP process. In combination with solid-state, net-shape HIP, laser consolidation process may provide a unique manufacturing capability to make very complex components for the rocket engines.

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