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Laser Consolidation - A Novel Additive Manufacturing Process for Making Net-Shape Functional Metallic Components for Various Applications

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Abstract Summary

Laser consolidation (LC) is a novel additive manufacturing process being developed by the National Research Council Canada (NRC) at its London facility. LC offers unique capabilities in the production of net-shape functional metallic parts requiring no further post-processing. NRC's LC technology has achieved dimensional accuracy of up to +/-0.05 mm with a surface finish up to 1 μm Ra (depending on the materials used in the manufacturing process). The LC process differs from other additive manufacturing technologies by its high precision deposition system that can build functional parts or build features using various alloys and high performance materials on top of an existing part. In this presentation, laser consolidation of various high performance materials (such as Ni-alloys, Co-alloys, Ti-alloys and Al-alloys) will be discussed in respect to their unique microstructure and mechanical properties (including fatigue/fracture properties). The examples will be given on building complex functional components and repairing parts otherwise unrepairable for aerospace, defense and other applications.

Laser Consolidation - A Novel Additive Manufacturing Process for Making Net-Shape Functional Metallic Components for Various Applications

INTRODUCTION:

The National Research Council Canada (NRC) at its London facility has been developing a novel process called "Laser Consolidation (LC)" to build net-shape functional components directly from metallic powder in one step [1-2]. Compared to other laser cladding based additive manufacturing processes, NRC's LC process enables to build net-shape functional metallic components with a surface finish up to 1 µm Ra, a dimensional accuracy of up to +/-0.05 mm [2] and with challenging geometries [3]. As opposed to the conventional machining process, this additive manufacturing technology builds complete parts or features on existing components by adding instead of removing material. Due to the rapid solidification inherent to the process, excellent material properties are exhibited by various laser-consolidated metallic materials [2-7]. This presentation will summarize some of the NRC's work on the LC of metallic materials for building functional components and repairing damaged components.

EXPERIMENTAL DETAILS

Laser consolidation experiments were carried out by using a 500 W Nd:YAG laser of 1.064 µm wavelength along with a processing head with a focal length of 115 mm, which was connected through a 600 µm diameter optical fiber. 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 molten pool through a nozzle with the powder feed rate ranging from 1 to 30 g/min. Argon was used as a carrying and shielding gas. During the LC process, the laser beam and the powder delivery nozzle were kept stationary, while the sample was moved using a 3- to 5-axis computer numerical control (CNC) motion system. All LC work was conducted in a glove box and at room temperature, in which the oxygen content was typically maintained below 50 ppm during the process.

Commercial Ni-base IN-625, IN-738 alloys, and Ti-base Ti-6Al-4V alloy powders were used and all of them were spherical in shape with the size less than 45 µm. All the test specimens were built using virgin powders. Cast IN-738, wrought IN-625 and wrought Ti-6Al-4V alloy substrates with the thickness of around 9.5 mm were used for LC of IN-738, IN-625 and Ti-6Al-4V alloys, respectively. The substrate plates were machined and ground to a consistent surface finish (~ 0.2 µm Ra) for the laser consolidation of different alloy powders. The microstructures of the LC samples were examined using an Olympus Optical Microscope (OM) as well as a Hitachi S-3500 Scanning Electron Microscope (SEM).

Flat tensile specimens were prepared for LC IN-718, LC Ti-6Al-4V and LC IN-738 alloys and flat fatigue specimens were prepared for LC Ti-6Al-4V alloy. The geometries of flat tensile and fatigue specimens are shown in Fig.1. The thickness (t) of the flat tensile and fatigue specimens is about 0.8 mm. The specimen surfaces in the gauge length area were manually polished down to 600 grit. The tensile and fatigue tests for flat specimens were performed at room temperature with a 100 kN Instron servo-hydraulic Mechanical Testing System. The axial high cycle fatigue testing was conducted in a sine wave form with an R ratio of +0.1 and a frequency of 60 Hz.

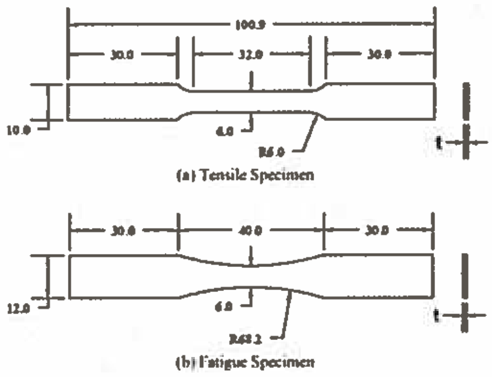


Fig.1: Flat specimen geometry for (a) tensile and (b) fatigue testing (dimensions in mm).

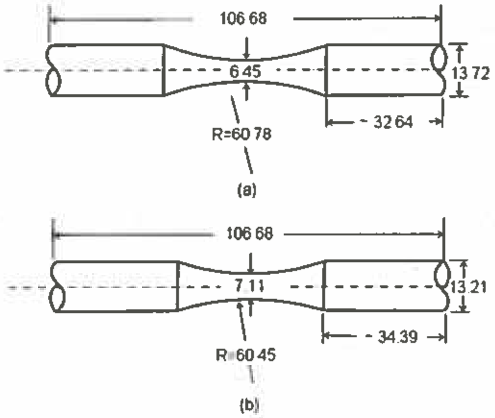
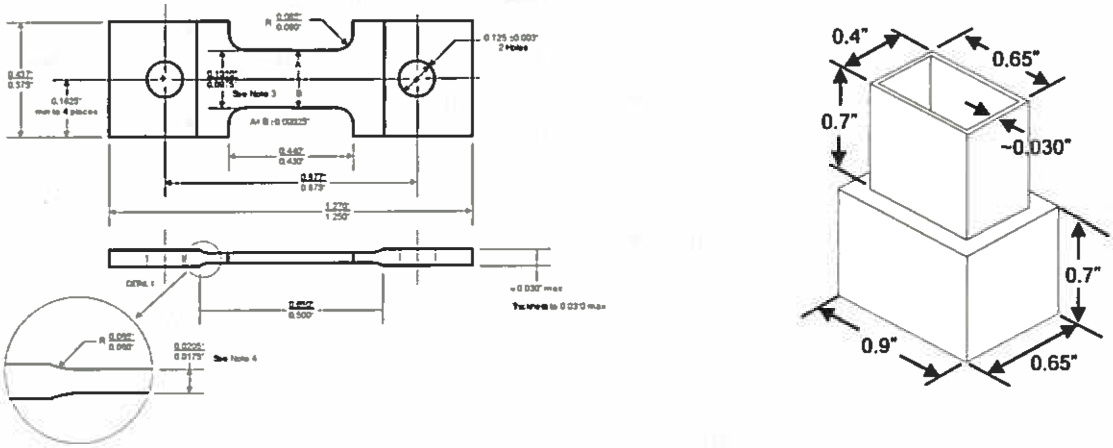


Fig.2: Dimension of laser-clad IN-625 round fatigue specimens.

For round laser-clad IN-625 fatigue specimens, heat-treated IN-625 bars were machined to undersized cylindrical cores for laser cladding (Fig.2a). The final dimension of fatigue specimens is illustrated in Fig.2b. After laser cladding and/or machining, the surface of the fatigue specimen was initially polished with 400 grit and finally with 600 grit sand paper. All fatigue tests for round IN-625 specimens were performed on a 100 kN Instron servo-hydraulic mechanical testing system operated under stress control with sinusoidal waveform and a min/max stress ratio of R=0.1 and a frequency of 40 Hz.

The stress rupture testing was conducted at the bond area between the laser-consolidated IN-738 and cast IN-738 substrate. Fig.3a shows the geometry of stress rupture sample, which is machined from the laser-consolidated coupon as shown in Fig.3b.



(a) Stress rupture test specimen (dimension in inches).

(b) Laser-consolidated coupon for making stress rupture test specimens (dimension in inches).

Fig.3: Specimen geometry for stress rupture testing.

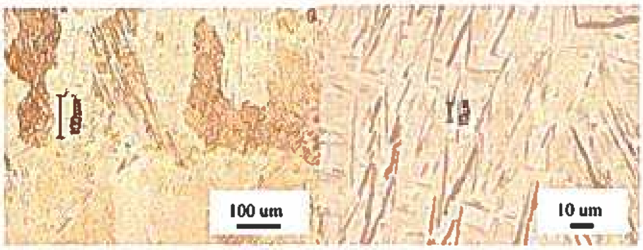
For comparison, fully LC IN-738 and cast IN-738 stress rupture specimens were also prepared according to Fig.3a. All laser-consolidated and cast IN-738 coupons were heat-treated in a vacuum furnace prior to any machining. The stress rupture testing was conducted at 1010°C (1850°F) and 55 MPa (8 ksi).

RESULTS/DISCUSSION

1. LC Ti-6Al-4V Alloy

The laser consolidated thin-wall Ti-6Al-4V is metallurgically sound, showing somewhat equiaxed grains (Fig.4a) with acicular phase inside (Fig.4b). A high-resolution SEM photo reveals that grain boundary is hard to distinguish and no secondary phase can be observed along it [5].

The LC Ti-6Al-4V alloy shows excellent tensile properties. Four LC thin-wall Ti-6Al-4V tensile specimens were tested. 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. It should be noted that the tensile properties of the LC Ti-6Al-4V material also have very small scatter. The standard deviations of yield strength and ultimate tensile strength are only 6 MPa and 11 MPa respectively, while the standard deviations of the elastic modulus and elongation are 8 GPa and 0.9 % respectively, which indicates again that the LC Ti-6Al-4V material has good consistency.



(a) (b)

Fig.4: Microstructure of as-consolidated Ti-6Al-4V.

Compared to the conventional cast or wrought material, the LC Ti-6Al-4V shows excellent tensile properties. From the references, 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 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 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 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 post heat treatment may improve the elongation value.

Ti-6Al-4V material is widely used in aerospace and medical device industries. Its fatigue life is one of the most important functional properties. Fig.5 is a classic S-N curve showing the high cycle fatigue testing results of as-consolidated Ti-6Al-4V material. The fatigue data of as-cast Ti-6Al-4V from the reference [8] is also plotted for comparison. The preliminary fatigue test results are very encouraging: the data of as-consolidated Ti-6Al-4V without any heat treatment is at the high end of as-cast Ti-6Al-4V

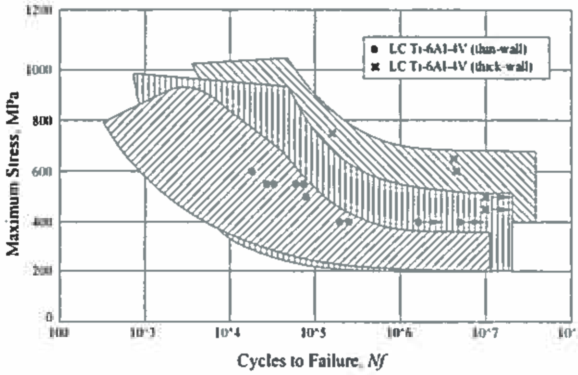


Fig.5. Fatigue data of LC Ti-6Al-4V compared with cast and wrought/anneal Ti-6Al-4V (R=+0.1)

data, which indicates that as-consolidated Ti-6Al-4V material has longer fatigue life as compared to the as-cast Ti-6Al-4V material. The endurance limit of the thin-wall LC Ti-6Al-4V specimens is around 400 MPa, which is significantly higher than 200 MPa achieved by the as-cast Ti-6Al-4V (data from the reference [8]). It also demonstrated that significant improvement in fatigue resistance of LC Ti-6Al-4V alloy can be achieved through optimizing the processing parameters. Preliminary 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 upper scatter band of annealed wrought material.

Fig.6a shows a typical fracture surface of a thin-wall LC Ti-6Al-4V specimen with the crack initiation site. The maximum cyclic stress for this particular specimen was 400 MPa with a corresponding fatigue life of 247,726 cycles. Fig.6b illustrates the existence of a relatively large porous region (~135 μm wide) consisting of partially fused powder particles. Even though the high stress concentration sites caused by the presence of these partially fused powder particles significantly reduce the fatigue resistance of this material, the results for the thin-wall LC Ti-6Al-4V material are still at the high end of the cast reference material.

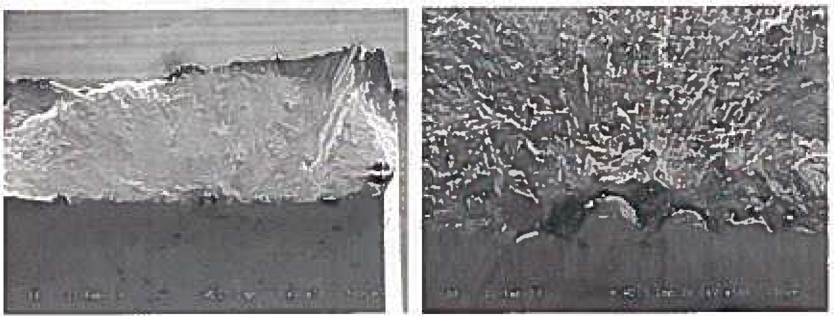

(a) (b)

Fig.6. SEM observation of a typical fatigue crack initiation site on a thin-wall LC Ti-6Al-4V specimen; (a) overall fracture surface, and (b) magnified crack initiation site.

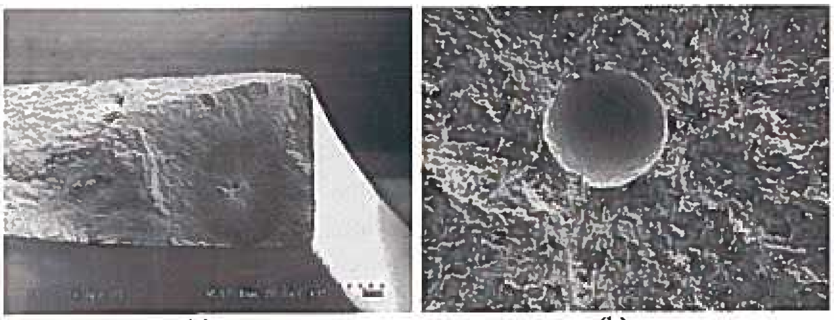

(a) (b)

Fig.7. SEM observation of a typical fatigue crack initiation site on a thick-wall LC Ti-6Al-4V specimen; (a) overall fracture surface, and (b) magnified crack initiation site.

The SEM examination of a typical fracture surface of a thick-wall LC Ti-6Al-4V specimen is shown in Fig.7a. This specimen was tested at a maximum stress of 600 MPa and had a fatigue life of 4,508,428 cycles. In this case, the fatigue crack initiation site was identified as a relatively large spherical pore (Fig.7b). The spherical pore appears to be approximately 75 μm in diameter. The exact cause of this porosity is currently being investigated. Based on the rounded and relatively smooth inside surface of these pores, it appears to be associated with gas entrapment.

2. LC IN-738 Alloy

IN-738 alloy is usually very difficult to deposit using conventional welding process or even laser deposition process without inducing cracking. We successfully developed LC processing parameters to produce metallurgically sound IN-738 samples on cast IN-738 substrate without preheating [4].

The LC IN-738 shows directionally solidified microstructure: very fine columnar γ dendrites growing almost parallel to the building direction. XRD analysis reveals that the preferred orientation is also along the (100). Precipitation of γ' particles is the primary strengthening mechanism for the IN-738 alloy. 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 (Fig.8a). Compared to the cast IN-738 (Fig.8b), the heat-treated LC IN-738 shows the similar but finer bimodal γ' distribution: coarse particles in near cuboidal shape plus fine particles.

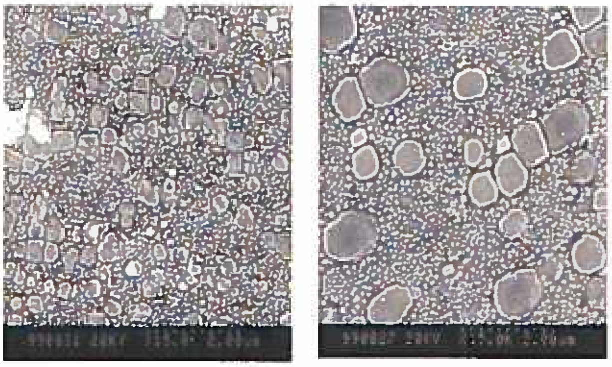

(a) LC IN-738 (x 15,000)
(b) Airfoil IN-738 (x 15,000)

Fig.8: High-resolution SEM observation of γ'-precipitates.

The LC IN-738 material shows very good tensile properties. Along the vertical direction, the ultimate tensile and the yield strength of the as-consolidated IN-738 are 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 ultimate tensile strength of the LC IN-738 slightly increases to about 1269 MPa, while its yield strength and elongation remain the same. Compared to the vertical direction, the as-consolidated IN-738 along the horizontal direction shows slightly higher yield strength (880 MPa), but relatively lower ultimate tensile strength (1084 MPa) and smaller elongation (6.7%). It should be noted that the tensile test data are very consistent within each testing group, which indicates that the LC process has very good reproducibility. Compared to the tensile properties of cast IN-738 after heat treatment, the heat-treated LC IN-738 along the vertical direction shows 15% higher ultimate tensile strength and 240% higher elongation, although its yield strength is slightly reduced by about 5%.

IN-738 is widely used for making hot-section of gas turbine components and stress rupture life is essential for its functionality. A miniature specimen with the gauge length of 11 mm was used to evaluate the stress rupture life of the bond area between the LC IN-738 and cast airfoil IN-738 substrate. For comparison, the stress rupture lives of the fully LC IN-738 and cast IN-738 baseline specimens with the same configuration were examined as well (Table 1). 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.

Table 1: Stress rupture life of LC IN-738 alloy (1010°C and 55 MPa).

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 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.

3. LC IN-625 Alloy

Laser cladding procedure was developed to clad IN-625 on pre-machined IN-625 substrates. Laser-clad IN-625 layer is metallurgically sound and bonded well with the IN-625 substrate, without any cracks or pores observed in the clad layer, substrate and bonding area. OM and SEM observations reveal that the laser-clad IN-625 layer shows very fine cellular dendritic microstructure with a secondary dendritic arm spacing (SDAS) of about 1 to 2 μm. A layer of fine equiaxial grains was formed at the interface between IN-625 clad and wrought IN-625 substrate [7].

Room temperature fatigue testing results are displayed in Fig.9. It is interesting to note that heat treatment method has played a significant role on the fatigue life of wrought IN-625 baseline specimens. The wrought IN-625 specimens heat-treated in air (Air HT) show significantly longer fatigue life than the same specimens heat-treated in vacuum (Vac HT). For example, tested at the maximum stress of 620 MPa, the wrought IN-625 specimens heat-treated in vacuum (Vac HT) has a fatigue life between 405,160 and 490,500 cycles, while the same material heat-treated in air (Air HT) demonstrated a fatigue life of 3,050,018 cycles.

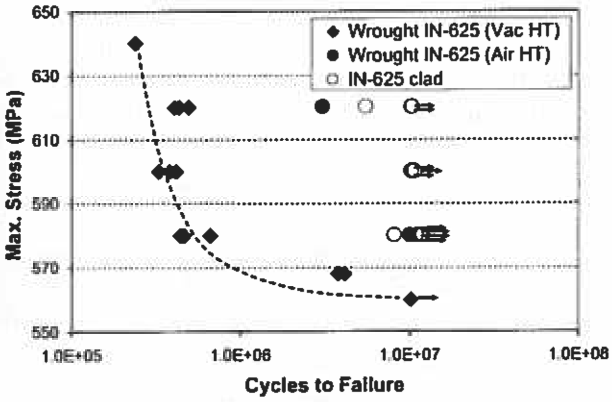


Fig.9: Room temperature fatigue testing results

Laser-clad specimens without any post heat treatment demonstrated substantially improved room temperature fatigue life than the IN-625 baseline specimens heat-treated in vacuum and comparable (or even longer) fatigue life than the IN-625 baseline specimens heat-treated in air. Under all three testing conditions (the maximum stress level of 580 MPa, 600 MPa and 620 MPa, respectively), majority of the laser-clad specimens show a fatigue life longer than

10,000,000 cycles. For example, for testing at the maximum stress level of 620 MPa, two laser-clad specimens lasted 10,000,000 cycles without failure and one failed at 5,502,538 cycles.

All wrought IN-625 baseline specimens used for high temperature fatigue testing were heat-treated in air (air HT). Laser-clad IN-625 specimens without any post heat treatment demonstrated comparable or even substantially improved fatigue life as compared to the baseline specimens during the fatigue testing performed at 649°C (1200°F) (Fig.10). When testing at the maximum stress level of 480 MPa, the fatigue life of baseline specimens was in the range from 3,294,399 cycles to above 10,000,000 cycles. Laser-clad specimens demonstrate comparable fatigue life (from 5,864,632 cycles to above 10,000,000 cycles). At higher maximum stress level (500 MPa), the baseline specimens show a fatigue life in the range of 156,316 cycles to 186,311 cycles. Two laser-clad specimens demonstrate substantially improved fatigue life (lasted 5,600,000 cycles and 10,000,000 cycles, respectively, without failure), while one clad specimen showed similar fatigue life (failed at 162,982 cycles) as compared to the baseline specimens.

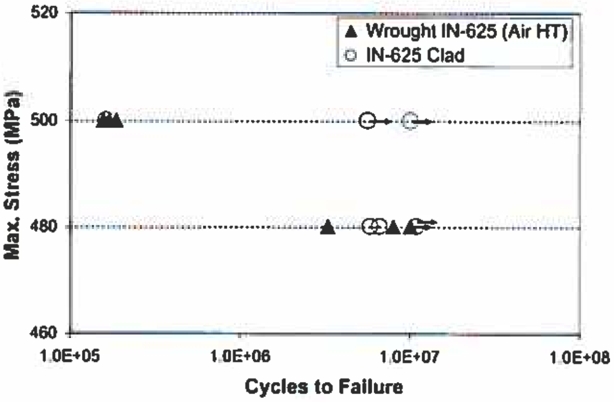
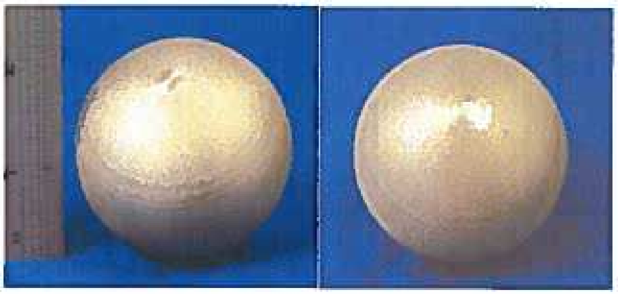


Fig.10: High temperature fatigue testing results performed at 649°C (1200°F).

4. LC Ti-6Al-4V Spherical Hollow Ball

A functional net-shape spherical hollow ball was built from Ti-6Al-4V powder in one step as a demonstration piece to show the capability and dimensional accuracy of LC process [9]. Fig.11a 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 good surface finish. Especially, it reveals that laser consolidation process successfully closed the hollow ball without any defects [20]. Fig.11b 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)

Fig.11: LC Ti-6Al-4V hollow ball, (a) top view, and (b) bottom view.

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 orbit. 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 off from the substrate (Fig.11b), 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-4V 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).

5. LC Repair of Gas Turbine Fuel Nozzle

Many nickel based alloys such as IN-625 are used in the manufacture of various engine parts. These parts must withstand very harsh engine conditions for long periods of time. Frequently, fretting of adjacent metallic surfaces due to vibratory loads, can lead to sufficient material deterioration so as to limit the life of the part in spite of the fact that its primary function remains intact. Fig.12 shows a gas turbine fuel nozzle with excessive external fretting, which could be challenging to restore.

A 5-axis CNC motion system was used for the laser cladding repair [7]. The fixture holding the nozzle assembly was mounted on the rotary table tilted to horizontal direction. Laser cladding of IN-625 alloy was successfully conducted to repair damaged nozzles using a Nd:YAG laser. Cross-sectional examination reveals that the laser-clad IN-625 is metallurgically sound and bonded well to the nozzle surface.

Fig.12: Damaged fuel nozzle swirler.

Fig.13: Laser clad repaired fuel nozzle swirler after final machining.

Fig.13 shows the laser clad repaired fuel nozzle swirler after final machining. Compared to Fig.12, it is obvious that laser cladding process successfully restored damaged areas (including the missing edges of holes). Fluorescent Penetration Inspection (FPI) of the repaired fuel nozzles was performed as per specification. FPI results reveal that all laser cladding repaired fuel nozzles met the inspection requirements.

CONCLUSIONS

The laser consolidated alloys present excellent mechanical properties, which allows the LC process to directly build functional components or to repair damaged components for aerospace applications. Compared to similar laser powder deposition processes, LC produces metallurgically sound samples with much better surface finish [2-3].

The LC process provides the unique capability to build net-shape functional metallic components or features on existing components that are difficult or even impossible to manufacture using conventional manufacturing processes. Compared to similar laser powder deposition process, LC process has much smaller heat input and, therefore, much better control. It is especially suitable to perform "precision repair" of aerospace and defense components.

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