

# Defect and Fatigue Damage in Additive Manufacturing Repair

Ibim Green

Federal Polytechnic of Oil and Gas, Bonny, Rivers State,+234, Nigeria.

Email: [abba.green@yahoo.com](mailto:abba.green@yahoo.com)

**Abstracts:** This research involves the use of additive laser deposition and machining processes to repair Aerospace titanium parts (alloy Ti-6Al-4V (Ti64)) and Ship marine crankshaft surfaces, thus extending the service life of these Aerospace and Shipping parts respectively. The study broadly included preparing the defects, laser deposition, machining, sample preparation and mechanical tests. With the aid of the Universal Testing Machine, comparative study of mechanical properties (Ultimate Tensile Strength, Yield Strength and percentage elongation) of the repaired samples to the ideal conditions was taken. The analysis used a virgin substrate whose Ultimate Tensile Strength, Yield Strength and percentage elongation are 850MPa, 780MPa and 13% respectively. The research result indicates that the average value of the UTS and YS from the samples with the cutter pull out defect is 893MPa and 826MPa respectively, which is on a higher side of the ideal values. This shows an enhancement of mechanical properties in the samples. The average value of the %elongation from the samples of the cutter pull out defect is 14.39%, which is close to the ideal value. The average value of the UTS and YS from the samples containing a deformation defect is 883MPa and 816MPa respectively, which is close to the ideal value. The average value of the % elongation from the samples of the deformation defect is 15.48%, which is on the higher side. Again, this shows an increase in the ductility of the samples. The average value of the UTS and YS from the samples containing an undercut defect is 854MPa and 786MPa respectively, which is very close to the ideal value. The average value of the % elongation from the samples containing the undercut defect is 17.34%, which is on the higher side. This shows an increase in the ductility of the samples. From the test results we can clearly see that the average value of data gathered conforms closely to the ideal properties of the substrate. Nevertheless, some samples yielded better results than the properties of the ideal substrate which shows enhancement of properties of the repaired parts.

**Index Terms:** Additive laser deposition, machining processes, titanium parts, marine crankshaft surfaces, defects.

## 1 INTRODUCTION

Everyone appreciates the benefits of recycling and reusing resources, tools and gadgets, as long as there is no loss of quality in the end products. Engineers today have to create attractive new products that exploit all means of recycling and at the same time, have to be able to effectively reuse and repair already existing appliances. From past experience and with the ongoing economic difficulties in Europe and other industrially developed parts of the world, we know that we no longer have the luxury of being able to throw away everything which is slightly damaged. Fortunately, Researchers particularly in the manufacturing industry understands that we have to reduce costs by repairing, regenerating and renovating. The Industry now desire Additive Manufacturing repairs to expand the life span of their machines and maximise profit. Even, if the resources are available, nobody is now prepared to throw their money to the winds. Thanks to these social changes, new attitudes and economic pressure, the repair and refurbishment sector of mechanical and manufacturing engineering is currently booming. The size and potential of Additive Manufacturing repair market is enormous (B.W. Bach, 2006).

Laser cladding technology is applied in the repair and reconditioning of all kinds of mechanical components. When dealing with high-value tools or components, there is often a need to alter design at some point in their lifetime, or to repair damage that impairs their function. Laser deposition can rescue your component from a

premature visit to the scrapheap, allowing you to execute small design alterations directly on the component and repair damage quickly and virtually without trace (T.M. Torims, 2013).

Conventional welding processes (i.e. tungsten inert gas or gas metal arc) create heat affected zones in the substrates close to the weld. This often causes distortion or change in properties, which makes the repair process even more difficult. Moreover, the metallurgical properties of the heat affected zone can be different from the base material far away from the weld. Laser deposition has a small and limited heat affected zone which makes the weld less vulnerable to degradation of properties (B.A. Bruckner, 2012).

Laser cladding technology has comparative advantages over other build-up technologies such as better overall quality of coating, reduced production time, minimal dilution and distortion, customised surface parameters and production of smart structures. The properties of the surface material obtained from Laser cladding technology have similar or even better characteristics than the original. The flexibility of laser cladding is being recognised by industry and research funders. The potential of this technology is massive, with research groups around the world continuing to contribute to its growth through research programmes, industrial applications and training students in laser cladding techniques (T. Toyserkani, 2010).

However, it is important to analyse the fatigue performance of Additive Manufacturing repair to address its durability with emphasis on the metallurgical bond between the

damaged surface area of a part and the added repair material. The mechanical properties (Ultimate Tensile Strength, Yield Strength and percentage elongation) of the repair part should be estimated to ascertain its capacity of withstanding fatigue load (ASTM, 2008).

In this research work, empirical comparative of mechanical properties of virgin substrate to that of repaired samples arising from deformation defect, undercut defect and cutter pull out defects was done. These tests were carried out in order to give us a better understanding of the damages and to come up with a reliable repair process.

## 2.0 APPLICATION OF LASER METAL DEPOSITION FOR REPAIR OF TITANIUM AND MARINE PARTS

Laser metal deposition was carried out using a diode laser, which produces a single wavelength laser at power level upto 1000 watts. The system is 808 nm with armoured 1mm fibre mounted on a Precitec YC50 laser cladding head. A NI real time controller was used to control the laser. The powder feeder was used to deliver powder at a rate as low as 0.1 g/min. The whole system was mounted on a Fadal 5 axis CNC machine was used as the motion driver. A multi-axis planning system (MAPS) was used to generate a laser deposition tool path by slicing the solid model. Before the actual laser metal deposition, a pre heat pass was generated at 1000 watts to bring the substrate to a higher temperature in order for the powder to get a better bonding during the actual deposition. The metal deposition was carried out at 800 watts of laser power at powder feed rate of 8g/min.

The machining operation was carried out on a 5 axis CNC machining center. The milling operations was operated using 0.25" and 0.5" face milling tools at a feed rate of 24in/min and a spindle speed of 6000rpm. The z axis depth varied at not more than 0.005" per cut. The profile cutting of the specimen was done using 0.1mm diameter tool at a feed rate of 2 in/min at a spindle speed of 24,000 rpm. The z axis depth was not more than 2mm. The samples was taken out of a transitional zone between the deposited layer and the substrate.

### 2.1 Powder for laser cladding of Titanium and Marine parts repair

The powder that was used for the laser cladding had a particle size of between 20 and 200  $\mu\text{m}$ . To achieve the best feeding properties, a spherical form of the particles, typical for atomised powders was used. Very little of the substrate was melted, thus creating a clad with nominal alloy composition. Surface properties such as wear, erosion, oxidation or corrosion were the basis for selecting the alloy application. The choice of laser used was based on the surface area to be covered, the thickness of clad required, and the complexity of the component. The overall aim was to produce a clad with appropriate service properties, a strong bond to the substrate, maximum coverage rate with the minimal addition of alloy and minimal distortion.

### 2.2 Procedure involving metal additive and subtractive processes

A procedure involving metal additive and subtractive processes was investigated. Experiments to validate the procedure for the samples were carried out. The work consisted of four tasks:

Task 1: Sample preparation process study: A procedure for preparation of repair samples to clean the damaged surface and to determine or make access for tools to reach the damaged area which involved minimum machining in the following order:

- (1) Finding optimum places for creating the damages: care was taken that the laser nozzle path is cleared of any obstruction during laser metal deposition.
- (2) Creating the damage (four types of damages) at the designated places – the block was cut down into four for better application of the Laser deposition and CNC machine.
- (3) Checking for foreign particles left in the damaged area: a blasting process was applied for removal of all unwanted particles.
- (4) Tool Path Planning: Tool path was calculated for machining the damaged surface, so that Laser Metal Deposition could be performed for the repair.

Task 2: Sample repair via additive technology: the deposition path was generated base on measured data. The optimal deposition parameters and setup were estimated. Timing of deposition and preheat pass were calculated.

Task 3: Sample machining/finishing: Samples were machined to original shape. It was done in the following order:

- (A) Creating Samples: Next was to cut out samples from the repaired portion of the part. Specimens were chosen in such a way that the test area was the most vulnerable spot of the test part. The aim was to cut out the maximum number of test specimens as possible, in order to reduce the variations in the results.
- (B) CNC machining: the repaired part from the major block was cut out. The cut-out part was optimised to get the maximum number of test samples. The surface from both sides was milled to get the samples.
- (C) The samples were created at the zone between the bonding of the laser deposition to the substrate.

Task 4. Sample microstructure: Repair samples were tested for microstructure analysis such as Ultimate Tensile Strength (UTS), Yield Tensile Strength (YTS) and % Elongation. The values were calculated for the mechanical properties (UTS, YS, and % Elongation).

### 2.3 Fatigue Performance Tests

The tensile tests was carried out using a Mechanical Testing and Simulation (MTS) universal testing machine. The load was applied through a wide range reaching upto a maximum of 1600 lb over a time period of 20min. The following mechanical properties were evaluated.

Ultimate Tensile Strength (UTS): is the maximum stress that a material can withstand while being stretched or

pulled before failing or breaking. The UTS gave us a fair idea of the strength of the repaired material as it is the resistance offered by the repaired material to a force tending to tear it apart. The UTS was found by performing a tensile test and recording the stress versus strain. The highest point of the stress strain curve is the UTS. Stress is the ratio of the applied load to the cross-sectional area of an element in the tension and is expressed in pounds per square inch (psi).

$$\text{Stress } (\sigma) = \frac{\text{Load (L)}}{\text{Area (A)}} \quad (1)$$

Strain is a measure of the deformation of the material.

$$\text{Strain } (\epsilon) = \frac{\text{Change in length } (\Delta L)}{\text{Original length (L)}} \quad (2)$$

Yield Strength (YS): is the indication of maximum stress that can be developed in a material without causing plastic deformation. It is the stress at which the repaired material exhibits a specified permanent deformation that is a practical approximation of elastic limit. Offset yield strength was determined from a stress-strain diagram. It is the stress corresponding to the intersection of the stress-strain curve, and a line parallel to its straight line portion offset by a specified strain.

The percentage elongation: is the maximum elongation of the gage length divided by the original gage length.

$$\text{Percentage elongation}(\%) = \frac{\text{final gage length} - \text{initial gage length}}{\text{initial gage length}} \quad (3)$$

The above parameters were used to make a comparative study between the properties of the original substrate and that of the repaired samples, in order for us to determine the reliability of the repair process.

### 3 RESULT

The tensile strength tests were carried out using the MTS tensile strength testing machine. Tables 1, 2 and 3 shows the UTS, YS and % elongation for the cutter pull out, deformation and undercut defect respectively.

**TABLE 1: UTS, YS, AND % ELONGATION OF CUTTER PULL OUT DEFECT**

Samples	UTS (MPa)	YS (MPa)	% elongation
Substrate	850	780	13
Sample 1	830	765	14.56
Sample 2	895	840	15.67
Sample 3	930	855	13.35
Sample 4	860	795	13.89
Sample 5	965	898	14.72
Sample 6	876	805	14.14

**TABLE 2: UTS, YS, AND % ELONGATION OF DEFORMATION DEFECT**

Samples	UTS (MPa)	YS (MPa)	% elongation
Substrate	850	780	13
Sample 1	820	755	15.67
Sample 2	885	830	16.78
Sample 3	920	845	14.46
Sample 4	850	785	14.91

Sample 5	955	887	15.83
Sample 6	866	795	15.25

**TABLE 3: UTS, YS, AND % ELONGATION OF UNDERCUT DEFECT**

Samples	UTS (MPa)	YS (MPa)	% elongation
Substrate	850	780	13
Sample 1	790	725	17.89
Sample 2	855	800	18.90
Sample 3	890	815	16.68
Sample 4	820	755	16.13
Sample 5	935	857	17.15
Sample 6	836	765	17.27

The test result indicates that average values of UTS for the deformed defect and undercut defect were very close to that of the substrate. On the other hand the average value of the cutter pull out defect was slightly higher than that of the substrate.

The result also shows that average values of YS of the deformed defect and undercut defect were very close to that of the substrate. On the other hand the average value of the cutter pull out defect was slightly higher than that of the substrate which is very much similar to the result of the UTS comparative study.

In addition, an average value of % elongation for the cutter pull out defect was very close to that of the substrate. On the other hand the average value of the deformed defect and undercut defect were slightly higher than that of the substrate. The variation in the data was slightly more than that of the other comparative study.

Hence, the result shows an increase in the ductility and enhancement of mechanical properties in the repaired samples.

### REFERENCES

- [1] A.T. Allegri, "A new semi-empirical model for stress ratio effect on mode II fatigue delamination growth". Composites Part A 42:733-40, 2011.
- [2] American Society for testing of materials, "ASTM D 3528 Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading", Publisher reapproved, 2008.
- [3] B.W. Bach,. Modern Surface Technology, Weinheim (Germany), Verlag Gmbh & Co., WILEY-VCH collection, ISBN 3-527- 31532-2, 2006.
- [4] B. Benjamin, "Laser metal deposition as repair technology for stainless steel and titanium alloys", Physics Procedia, Vol 39, Pg 376-381, 2012.
- [5] Birger, E.M., Moskvitin, G.V., Polyakov, A.N., Arkhipov, V.E. (2011). Industrial laser cladding: current state and future. In: Welding International, Vol. 25 No. 3, 234-243.
- [6] B.A. Bruckner, Innovations in laser cladding and direct metal deposition, SPIE Proceedings - The International Society for Optical Engineering, 8239, art. No. 823904, 2012.

- [7] I.S. Ion, Laser Processing of Engineering Materials, Elsevier Butterworth- Heinemann, Oxford (UK), 2005, ISBN 008097189 X, 2005.
- [8] K.M.S. Klimpel, "Laser repair hard facing of Titanium alloy", Journal of achievement in material and manufacturing engineering, Issue 49, 2011.
- [9] N.E. Nowotny, "Current use of laser technology for build-up welding applications", in Surface Engineering, 27 (4), pp. 231-233, 2011.
- [10] S.T. Steen, Laser Material Processing, Springer, London (UK), ISBN 978-1-8499-6061-8, 2010.
- [11] T.M. Torims, "Laser cladding device for in-situ repairs of marine crankshafts", in Advanced Materials Research, Vols. 712-715, pp. 709-714, 2013.
- [12] T. Toyserkani, Laser Cladding, Taylor & Francis, Abingdon (UK), ISBN 1420039172, 2010.
- [13] W. Woodyard, Pounder's Marine Diesel Engines and Gas Turbines, 9th Edition, Butterworth Heinemann, Oxford, p. 896, ISBN 0750689846, 2009.

IJSER