14 Aug 2013

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Nanda Kumar Dey

Frank W. Liou
Missouri University of Science and Technology, liou@mst.edu

C. Nedic

International SFF Symposium
University of Texas at Austin
August 12-14, 2013, Austin, Texas

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N.K.Dey*, F.W.Liou*, C. Nedic**

*Department of Mechanical & Aerospace Engineering
Missouri University of Science & Technology, Rolla

**GKN Aerospace, Hazelwood, St Louis, MO
Accepted August 16th 2013

ABSTRACT

Parts or products from high performance metal are very expensive, partly due to the processing complexities during manufacturing. The purpose of this project is to use additive laser deposition and machining processes to repair titanium parts, thus extending the service life of these parts. The study broadly included preparing the defects, laser deposition, machining, sample preparation and mechanical tests. Comparative study of mechanical properties (UTS, YS, percentage elongation) of the repaired samples to the ideal conditions was undertaken. The research throws up interesting facts where the data from the test sample shows enhancement of properties of the repaired part.

1. INTRODUCTION

In recent years, the significance of using laser metal powder deposition for repair has increased manifolds. This research paper focuses on development of a reliable repair process of damaged Ti-6Al-4V parts using hybrid manufacturing technology at in house Laser Aided Manufacturing Process (LAMP) Laboratory. The basic principle of the laser process is a laser beam creating a metallurgical bond between the damaged surface area of a part, known as the substrate, and the added repair material, which is a metal powder [1]. The focused laser beam melts the surface of the target material and generates a small molten pool of base material. Powder delivered into this same spot is absorbed into the melt pool, thus generating a deposit that may range from 0.005 to 0.040 in. thick and 0.040 to 0.160 in. wide. The resulting deposits may then be used to build or repair metal parts for a variety of different applications. The economic advantage of this process is the value addition to the component by layer by layer deposition of material that significantly increases the operating life of the component that needs to be run reliably over an extended period of time.

Aerospace parts are generally very complex and expensive. It is found to be more economical to repair the parts rather than procuring new parts, as the new parts are either exorbitantly expensive or require a large lead time for delivery. In some cases the original equipment manufacturer might be out of business. Under these circumstances repair is a more viable and economical option for getting the parts restored to their original form.

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. Further, using this process a better microstructure and a smaller dilution zone can be achieved. This allows for greater repeatability and reproducibility of layer by layer deposition of material. The powder filler material is fed by a nozzle in an inert gas atmosphere, as powder gives us more flexibility of chemical composition of filler material.

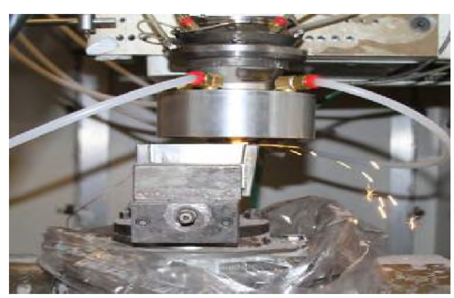

Fig. 1. Laser Deposition.

2. CONCEPT AND PROCESS

The research objective is to use laser deposition and machining processes to repair damaged titanium parts of alloy Ti-6Al-4V (Ti64). The ability to repair Ti64 parts with sound microstructure using metal additive processes is currently at nascent stage. This effort is a significant enabler to the metal repair technology by using hybrid laser deposition and machining technology that is currently rudimentary and limiting implementation of the technology.

Ti64 is essentially alpha-beta structured Titanium alloy which have an excellent combination of strength and ductility. They are stronger than the alpha or beta alloys. Welding alpha-beta alloy titanium can significantly change strength, ductility and toughness characteristics as a result of the thermal cycles to which they are exposed. The change in the ductility can be attributed to the phase transformation of the alloy. Ti64 has an excellent weldability, which can be attributed to two principle factors. First, the alpha-prime martensite that forms in the Ti64 is not as hard and brittle as that exhibited by more heavily beta-stabilized alloys. Secondly, Ti64 exhibits a relatively low hardenability on cooling from solution treatment temperatures. This behavior allows the formation of higher proportion of the more desirable Widmanstten alpha-plus-retained beta microstructure even at relatively high rates of weld cooling. Ti64 when welded with filler metal of matching composition of extra low interstitial grade, it improves the ductility and toughness. Due to its single phase mode of solidification (i.e. absence of low melting point eutectics), Ti64 is also highly resistant to solidification related and liquation related cracking [2].

From the current historical data available from the aerospace industry, there are different types of defects found in components. These defects may arise from numerous reason like fatigue to manufacturing. These were further classified into different categories. They broadly are deformation defect, undercut defect, cutter pull out defect and cutter mark defect. The classification were carried out in order to give us a better understanding of the damages and to come up with a reliable repair process. The classification follows a common pattern evolved during the gathering of data from abundant damaged samples provided by the industry participant. All such major defects were replicated in test parts provided by the industry participant.

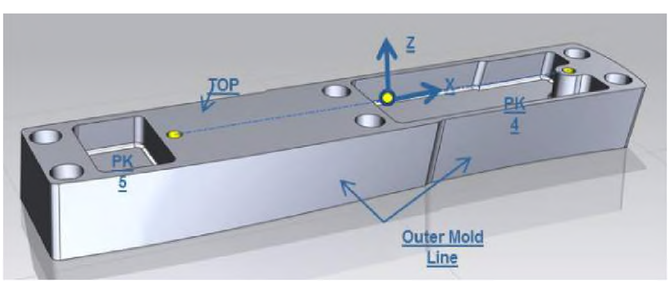

Fig. 2. Test part

A procedure involving metal additive and subtractive processes will be investigated. Experiments to validate the procedure for Ti64 samples will be carried out. The work will consist of four tasks:

Task 1: Sample preparation process study: a procedure for preparation of repair samples is necessary, such as to clean the damaged surface and to determine or make access for tools to reach the damaged area. This could also involve minimum machining.
Step 1. Finding optimum places for creating the damages – care should be taken that the laser nozzle path should be clear of any obstruction during laser metal deposition.
Step 2. Creating the damage (four types of damages) at the designated places – there was a need to cut down the block into four parts for better fixturing in the Laser deposition and CNC machine.
Step 3. Checking for foreign particles left in the damaged area. If necessary, a blasting process was applied for removal of all unwanted particles.
Step 4. Tool Path Planning – Tool path was calculated for machining the damaged surface, so that Laser Metal Deposition could be performed for the repair.

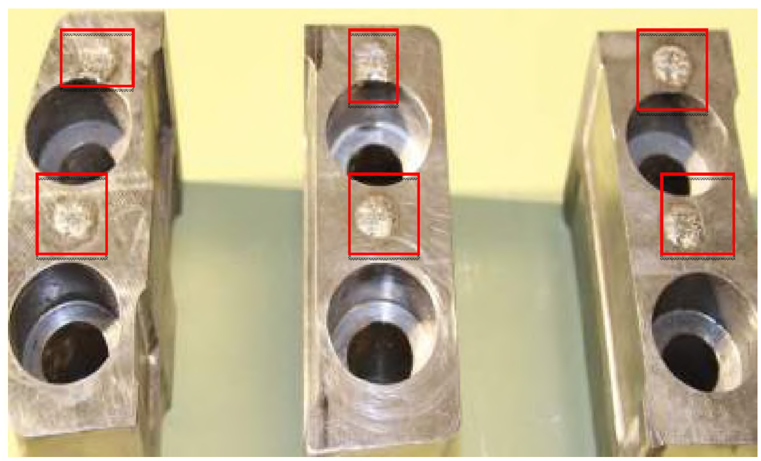

Fig. 3. Laser deposited parts

Task 2: Sample repair via additive technology: to generate the deposition path based on measured data will be investigated. The optimal deposition parameters and setup for Ti64 deposition will also be studied.
Step 1. Path planning for Laser Metal Deposition (LMD). This step required precise planning because the laser nozzle has a limited work envelope. Calculations were needed for the time of deposition and preheat pass.

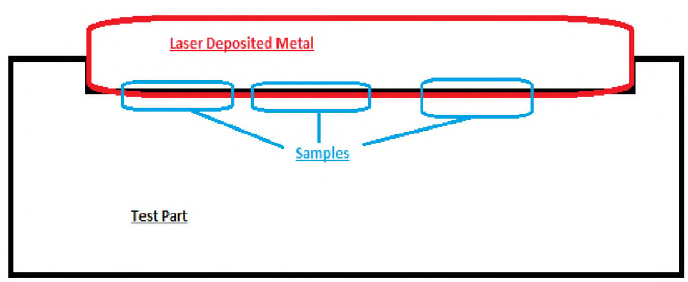

Fig. 4. Test specimen zone

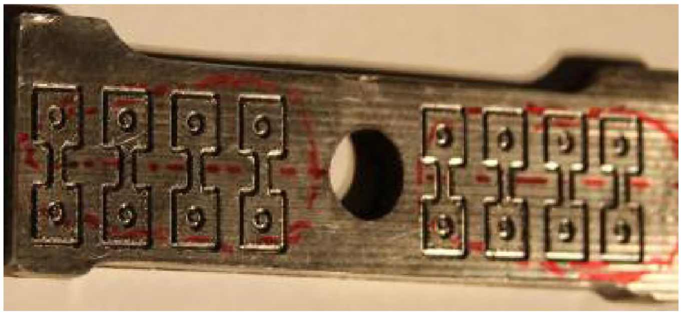

Fig. 5. Test specimen

Task 3: Sample machining/finishing: Samples were machined to original shape.

Step 1. 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 is 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.

Step 2. CNC machining – Cut out the repaired part from the major block. Optimized the cut-out part to get the maximum number of test samples. Milled the surface from both sides to get the samples.

Step 3. The samples were created at the zone between the bonding of the laser deposition to the substrate, and can be seen in fig 4.

Task 4. Sample microstructure: Repair samples will be tested for microstructure analysis, UTS, YTS and % Elongation.

Step 1. Tensile Test – From the test specimens, tests were conducted for the UTS, YS, and % Elongation. The values were then calculated for the UTS, YS, and % Elongation.

3. EXPERIMENT

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 manufactured at 808 nm and is ideally suited for welding, cladding and surface modification. Its armored 1mm fiber is mounted on a Precitec YC50 laser cladding head. A NI real time controller is used to control the laser. The powder feeder can deliver powder at a rate as low as 0.1 g/min. The whole system is mounted on a Fadal 5 axis CNC machine which is used as the motion driver. The deposition nozzle is mounted on the side of the spindle, which forms a hybrid manufacturing system on a single workstation as shown in Fig 7. A multi-axis planning system (MAPS) was used to generate a laser deposition tool path by slicing the solid model.

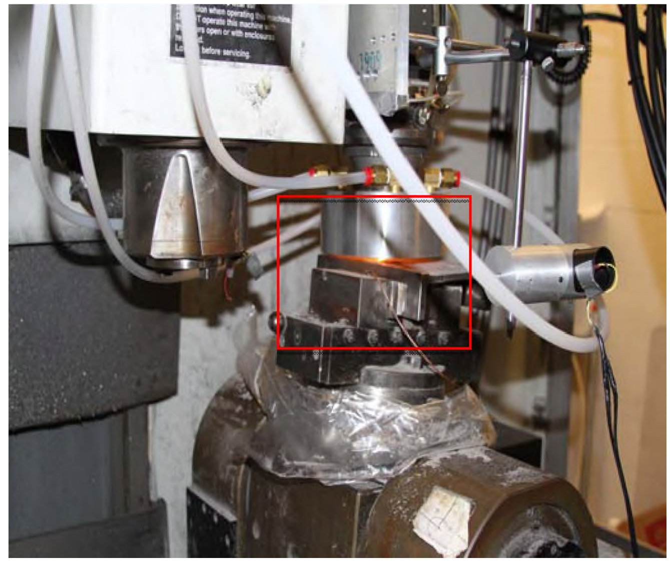

Fig. 7. Laser deposition process in progress

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.

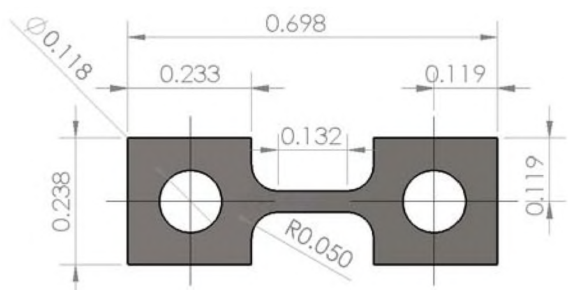

Fig. 8. Dimensions of test specimen (inches)

The machining operation was carried out on a 5 axis CNC machining center. The milling operations were performed 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 performed 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 were taken out of a transitional zone between the deposited layer and the substrate as shown in Fig. 4

Fig.9. Milling operation

The tensile tests were carried out using a MTS universal testing machine. The load varied through a wide range reaching upto a maximum 1600 lb over a time period of 20min. The resultant graph plotted for the UTS and YS is shown in Fig. 10

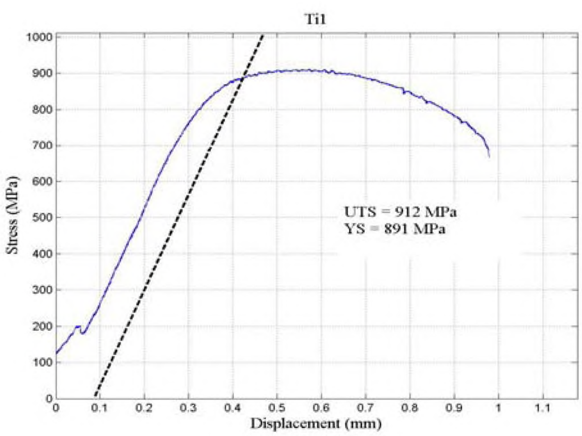

Fig. 10. UTS, YS graph

3. TESTS & RESULTS

Ultimate tensile strength (UTS), is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking. The UTS gives us a fair idea of the strength of the material as it is the resistance offered by the material to a force tending to tear it apart. The UTS is usually 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)

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

Strain is a measure of the deformation of the material.

$$\text{Strain}(\varepsilon) = \frac{\text{change in length}(\Delta L)}{\text{Original length (L)}}$$

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 a material exhibits a specified permanent deformation and is a practical approximation of elastic limit. Offset yield strength is 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. Offset for metals are usually specified as 0.2%, i.e., the intersection of the offset line and the 0-stress axis is at 0.2% strain. This can be viewed in Fig.10

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

$$\text{Percent elongation} = \frac{\text{final gage length} - \text{initial gage length}}{\text{initial gage length}}$$

The above parameters were chosen 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].

The tensile strength tests were carried out using the MTS tensile strength test machine. The result for the test for the undercut defect is shown in Table 1. The normal value of Ultimate Tensile Strength (UTS) for a virgin Ti64 substrate is 950 MPa. The value for Yield Strength (YS) of a Ti64 substrate is 880 MPa. The normal percentage elongation (% elongation) is 14%. The substrate data gives us a fair idea of our test result.

Ti – 6Al – 4V	UTS	YS	%elongation
Substrate	950	880	14
Samples	**UTS(MPa)**	**YS(MPa)**	**%elongation**
Sample 1	912	891	21.7
Sample 2	930	898	22.98
Sample 3	933	694	20.89
Sample 4	882	869	20.8
Sample 5	967	951	14.95
Sample 6	964	925	18.5
Sample 7	1026	922	17.6
Sample 8	954	903	17.31

Table 1. UTS, YS, and % elongation of undercut defect

Table 2 shows the result from the cutter pull out defect. We can see that the value for the UTS, YS, and % elongation is on the higher side than that of the virgin substrate. Table 3 shows the result for the deformation defect. Here the results are very close to the data for the virgin substrate.

Samples	UTS(MPa)	YS(MPa)	%elongation
Sample 1	907	879	17.9
Sample 2	925	920	16.72
Sample 3	1037	996	11.94
Sample 4	1043	1018	13.45
Sample 5	1052	1033	20.7
Sample 6	1006	997	11.94
Sample 7	1102	1060	14.02
Sample 8	969	952	20.3

Table 2. UTS, YS, and % elongation of cutter pull out defect

Ti – 6Al – 4V	UTS	YS	%elongation
Substrate	950	880	14

Samples	UTS(MPa)	YS(MPa)	%elongation
Sample 1	985	964	20.59
Sample 2	1025	984	18.5
Sample 3	920	898	22.98
Sample 4	994	957	18.8
Sample 5	911	687	14.35

Table 3. UTS, YS, and % elongation of deformation defect

Table 4 shows a comparative study of the UTS of the various samples, from all types of defects, to the value of the substrate. We can see that the average values of UTS for the deformed defect and undercut defect are very close to that of the substrate. On the other hand the average value of the cutter pull out defect is slightly higher than that of the substrate.

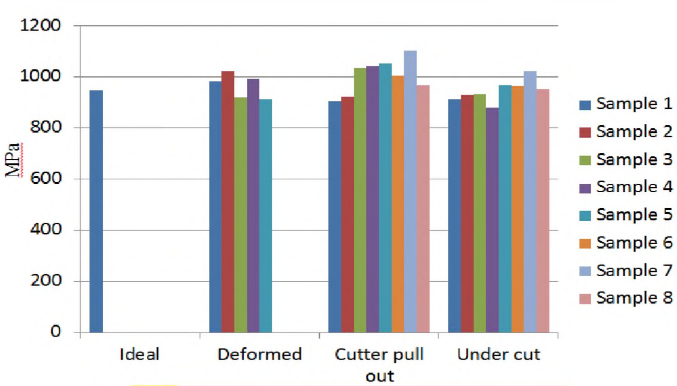

Table 4. Comparative study UTS result

Table 5 shows a comparative study of the YS of the various samples from all types of the defect to the value of the substrate. We can see that the average values of YS of deformed defect and undercut defect is very close to that of the substrate. On the other hand the average value of the cutter pull out defect is slightly higher than that of the substrate. This is very much similar to the result of the UTS comparative study.

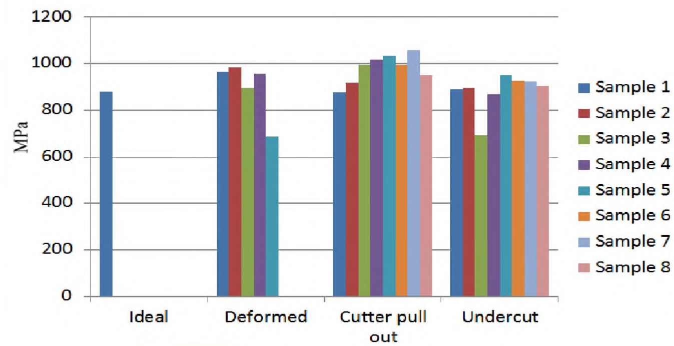

Table 5. Comparative study of YS result

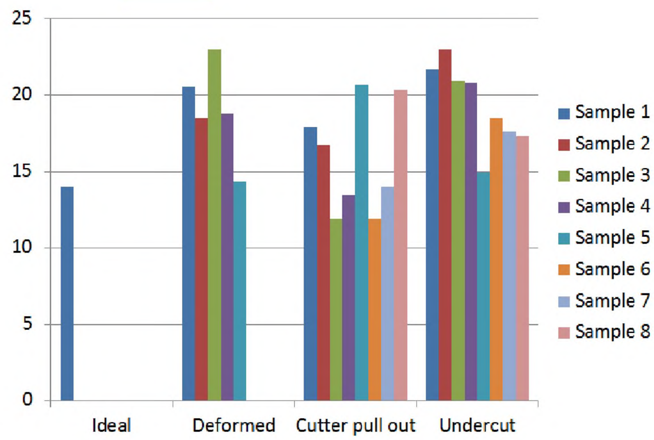

Table 6. Comparative study of % elongation result

Table 6 below shows a comparative study of the % elongation of the various samples from all types of defects, to the value of the substrate. We can see that the average value of % elongation for the cutter pull out defect is very close to that of the substrate. On the other hand the average value of the deformed defect and undercut defect are slightly higher than that of the substrate. We can also see that the variation in the data is slightly more than that of the other comparative study.

4.1 DISCUSSION OF RESULT

The ideal properties for Ti-6Al-4V substrate are as follows:

UTS – 950 MPa
YS - 880 MPa
% Elongation – 14 %

The average value of the UTS and YS from the samples containing an undercut defect is 946 MPa and 881.63 respectively [Table 1], which is very close to the ideal value. The average value of the % elongation [Table 1] from the samples containing the undercut defect is 19.34%, which is on the higher side. This shows an increase in the ductility of the samples. The average value of the UTS and YS from the samples with the cutter pull out defect is 1005.13 MPa and 981.88 [Table 2] 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 [Table 2] from the samples of the cutter pull out defect is 15.87%, which is very close to the ideal value. The average value of the UTS and YS from the samples containing a deformation defect is 967 MPa and 898 [Table 3] respectively, which is close to the ideal value. The average value of the % elongation [Table 3] from the samples of the deformation defect is 19.04%, which is on the higher side. Again, these shows and increase in the ductility of the samples.

From the above test results we can clearly see that the average value of data gathered conforms closely to ideal properties of Ti64, although there was slight deviation in the properties of few samples. Some samples yielded better results to the tune of 11% more than the properties of ideal substrate. This can be attributed to the fact that compressive stresses were induced in few damages. While creating the damage for the deformation defect a force of 3500 N was used to induce the damage to the substrate. The imposition of stress by an external agent usually creates some strain (deformation) in the material, even if it is too small to be detected. In a solid material, such strain will in turn generate an internal elastic stress, analogous to the reaction force of a stretched spring tending to restore the material to its original undeformed state. This occurs largely due to the transformation of the beta structure to alpha-beta structure which leads to increased strength. Few of the samples also resulted in values lower than that of the ideal samples. This can be concluded from the fact that, few samples had higher heat affected zone during the Laser deposition process. It has been seen that properties of Titanium alter in the areas of the heat affected zone immediately adjacent to the fission zone; specifically those regions which reach temperatures above 1800 F [4]. The percentage elongation changes directly indicate to the change in the ductility of the samples. The ductility of Titanium drastically changes with its microstructure and the grain size change [5]. From the results its evident that the most fluctuations occurred in the percentage elongation properties due to the change in the microstructure and the grain size of titanium. The results from the UTS, YS tests follow a close proximity to the ideal value of a virgin substrate, referring that the mechanical properties of the repaired samples has not been altered to a large extent.

Other factors which generally play a role in determining the properties of Ti64 are the presence of oxygen, nitrogen, hydrogen and carbon, which are interstitial elements, and tends to increase the strength and decrease the ductility. Aluminum is the most important substitutional solid solution strengthener. Its effect on the strength is linear. Other, less important sources of strengthening are interstitial solid solution strengthening, grain size effect, second phase (beta) effects, ordering the alpha, age hardening, and the effects of crystallographic texture [2].

5. CONCLUSION

The properties of the material were enhanced by the compressive stress induced during deformation. An enhancement of the properties can be seen from the test specimens tested from the cutter pull out defect. The properties of the specimens tested with an undercut defect conform to the properties of the ideal condition of substrate.

The study was performed on parts supplied by Missouri University of Science and Technology and GKN Aerospace. An extensive study on the properties of the repaired parts was performed. The study included preparing the defect for laser deposition, depositing the Ti-6Al-4V by laser, machining the deposition to complete the repair, and making samples out of the repaired part for property testing. The testing was performed to evaluate the yield strength, ultimate tensile strength, and % elongation of the sample created from the repaired part. The study revealed encouraging results, backing the current technique of repair as effective.

6. ACKNOWLEDGEMENT

This research was supported by GNK Aerospace and National Science Foundation Grant IIP-1046492, Intelligent Systems Center and Material Research Center at Missouri University of Science and Technology. Their support is greatly appreciated.

The author would like to thanks Todd Sparks from Dept of Mechanical & Aerospace Engineering, Missouri S&T for his continuous support to the research. The author would also like to thanks Laura Bartlett of Dept. of Material Science, Missouri S&T for helping us conduct the tensile strength test, Bob Hribar from machine shop and John Tyler from Rock Mechanics, Missouri S&T for their valuable contribution to the project. Also all people attached directly or indirectly to the project.

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