Repair and Manufacture of High Performance Products for Medicine and Aviation with Laser Technology

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Abstract

High performance products used for special purposes in medicine and aviation are often manufactured from advanced materials such as titanium and nickel based alloys. As the most promising and effective technology for such production and repair the Laser Rapid Prototyping technologies are being used and implemented into the practice. Special focus has been orientated into the Laser Net Shape (LENS) technology. This paper will review the State of the Art of the LENS laser technology and present application case studies where LENS is being applied to manufacture of modern medical implants such as bone fixation plate and jet engine turbine inconel blades.

***Keywords**: LENS technology, Bone fixation plate, Turbine blade, Inconel 718, Titanium alloy*

1 Introduction

Components and systems manufactured from different advanced materials such as titanium and nickel based alloys (Inconel) play very important role in manufacturing process of different applications for medicine, aviation, space and military industry. Despite their favourable material and mechanical properties present such materials several challenges in different fields. They are expensive to buy, difficult to machine, with costly and time consuming production of final products.

Medicine, aviation and space industry have characteristics of low volume manufacturing process with production limited to a maximum of several thousand parts. In some cases a series of prototype parts which are constantly evolving in design need to be manufactured. In the case of re-manufacturing legacy parts, single components may be required. Consequently high set up and tooling costs are therefore only amortised over a small number of components, driving up procurement costs, [1].

High performance products are products which can withstand environmental loads between 1000-2500 N/mm$^{2.}$. Failure in their design and functionality principle could have fatal consequences on working environment. Typical examples of such products are compressor and turbine blades in the jet engine where the leading edge and the top of the blades are susceptible to the wear caused by foreign objects. Similar characterisation could be used for modern medical implants which could severely effect on the whole body with undesirable side effects if inappropriate material and functionality principles had been chosen.

2 Laser technology for high performance products

2.1 *Laser technologies*

Good alternative to conventional manufacturing technologies specially for manufacturing of high performance products made of titanium alloy and other metallic materials is Rapid Prototyping (RP) which is the name for a group of technologies where the 3D physical model is built directly from the CAD file without the intermediary action. The RP technologies are divided into two main groups which are technologies adding the material and technologies removing the material during the prototype manufacture, [2]. Laser technology represents major role among RP technologies. It can be used for precision cutting, selective hardening of product, welding and drilling. The manufacturing accuracy is within the range of 10 μm. The CO_2, Nd:YAG or diode lasers are available. The introduction of the 5 KW ray beam and linear drives in the laser cutting devices results in the increase of efficiency and accuracy of machining. As very interesting and effective laser technology for building products made of titanium and similar metallic materials Laser Engineered Net Shaping Technology (LENS) is used. This laser fabrication technique was developed at Sandia National Laboratories and subsequently commercialized by the Optomec Design Company of Albuquerque, New Mexico, USA.

2.2 *LENS technology*

LENS is layer manufacturing technology which produces a very fine weld bead, exposing the component to far less heat than conventional methods due to smaller and more controlled heat affected zone which does not damage the underlying part. Once a geometry and material or material combination has been identified LENS can rapidly produce a 3-dimensional prototype with good mechanical properties, [3]. It enables the designer full functional and structural analysis. The tool-less process is driven directly from CAD data so a prototype of a new design or design iteration can be produced in few hours providing significant time compression advantages. The process of manufacturing a prototype is based on 3D CAD model which is converted into the STL file. The metallic powder of selected material is delivered by nozzle to the spot where it is melted via Nd: YAG or Fiber Laser and built in certain shape, [4]. The process of building product with LENS technology has following characteristics. A high power laser is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head. The laser beam typically travels through the center of the head and is focused to a small spot by one or more lenses. The X-Y table is moved in raster fashion to fabricate each layer of the object. Typically the head is moved up vertically as each layer is completed. The laser beam may be delivered to the work by any convenient means. Metal powders are delivered and distributed around the circumference of the head either by gravity or by using an inert pressurized carrier gas (inert gas like argon, helium or nitrogen). Multiple powder compositions can be fed simultaneously or sequentially to produce alloying at the focal zone or provide choice of material relative to location within a desired part even in cases where it is not required for feeding an inert shroud gas is typically used to shield the melt pool from atmospheric oxygen for better control of properties and to promote layer to layer adhesion by providing better surface wetting. The building area is usually contained within a chamber both to isolate the process from the ambient surroundings and to shield the operators from possible exposure to fine powders and the laser beam. The laser power used varies greatly from a few hundred watts to 20 KW or more depending on the particular material feed-rate and other parameters. Objects fabricated are near net shape but generally will require finish machining. They are fully-dense with good grain structure and have properties similar to or even better than the intrinsic materials, [5].

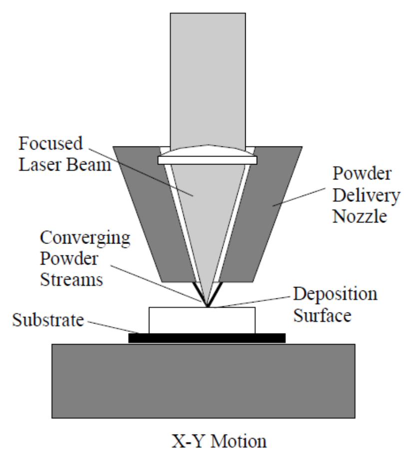
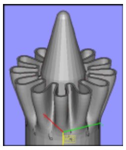
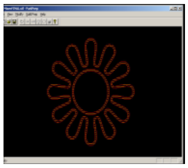
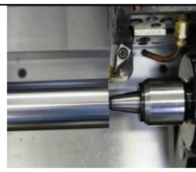


Figure 1: Schematic diagram of the LENS technology

Table 1: LENS Process steps

Engineering CAD Drawing	Part Preparation Software	LENS Work Station Control Software
		
Deposition	Fabricated Part	Final machining (if needed)
		

This process exhibits enormous potential to revolutionize the way in which metal parts, such as complex prototypes, tooling, and small-lot production parts, are produced. The result is a complex, fully dense, near-net-shape part. LENS has many potential applications, including rapid prototyping, rapid tooling, and dissimilar metal joining. Samples have been successfully manufactured from a variety of materials including steels, stainless steels (SS), nickel-based alloys, refractory metals, tool steel alloys, titanium and intermetallic compounds. Fabrications of bi-material joints as well as functionally graded materials through the use of LENS have also been successfully processed. Laser source has the benefit of concentrating much energy in the spot, but the drawback is its high cost, [6].

During manufacture the majority of the laser heat is dissipated by conduction down the deposit structure. In case of titanium alloy Ti6Al4V this results in epitaxial grain growth giving a macro-structure with fine columnar grains. The micro-structure consists of a very fine Widmanstätten structure, [11]. High level of density and alloy cleanliness can also be noted. The mechanical property and structure data confirm the suitability for use in critical component manufacture, [11].

LENS is a technology that is gaining in importance and is in early stages of commercialization. Its strength lies in the ability to fabricate fully-dense metal parts with good metallurgical properties at reasonable speeds. A lot of research is still being done in USA laboratories. There are only three installations of LENS machines in Europe: UK, France and Slovenia.

3 Manufacture of modern medical implants with LENS technology

Modern medical implants are products which have to satisfy strict requirements regarding materials, machining technologies and their functionality. They could be used in almost every organ of the human body. Ideally they should have biomechanical properties comparable to those of autogenous tissues without any adverse effects. The principal requirements of all medical implants are corrosion resistance, biocompatibility, bioadhesion, biofunctionality, machinability and availability. To fulfil these requirements most of the tests are directed into the study extracts from the material, offering screens for genotoxicity, carcinogenicity, reproductive toxicity, cytotoxicity, irritation, sensitivity and sterilization agent residues, [12].

Modern medical implants are regulated and classified in order to ensure safety and effectiveness to the patient. One of the most favourable biomaterial used for biomedical applications is titanium alloy Ti6Al4V due to its combination of the most desirable characteristics including immunity to corrosion, biocompatibility, shear strength, density and osteointegration. The excellent chemical and corrosion resistance of titanium is caused by the chemical stability of its solid oxide surface layer to a depth of 10 nm, [8]. Under *in-vivo* conditions the titanium oxide (TiO2) is the only stable reaction product whose surface acts as catalyst for a number of chemical reactions, [9].

The relatively high cost of titanium machining has hindered wider use. To minimize the inherent cost problem, successful applications must take advantage of the special features and characteristics of titanium. This requires a more complete understanding of titanium alloys as compared to other competing materials, including the interplay between cost, processing methods, and performance, [10].

Research and development of modern medical implants is complex multi-stage design and manufacturing process primarily based on *in-vitro* and *in-vivo* tests.

Medical implant as product has to be extremely flexible to fit in a specific patient. This is the reason why a lot of applications are "custom-made". It is also important that the weight/volume ration of these products is optimal offering to the patient comfortable life and functioning. This is the reason why thin–walled and hollow parts are more welcomed. Such structure of the product is extremely hard (if almost not impossible) to manufacture with conventional machining technologies.

LENS technology can be effectively used to cost-competitively manufacture standard or even custom implants with a range of functional enhancements that improve wear characteristics and ultimate quality of life for the patient. The dimensions of performance in medicine where LENS can offer significant benefits include:

- Possible novel designs of the implant which improves functionality principle,
- Reducing implant wear at key points.
- Fostering implant integration with native tissue.
- Avoiding toxicity, autoimmune response and bacterial formations.
- Avoiding structural failure and adverse mechanical properties.
- Maintaining long term fixation of the implant.
- Facilitating diagnosis of implant problems without surgery.

Implants manufactured by using LENS principle have same or even better mechanical and material properties. Beside novel product designs offers such manufacturing process also possibility to build smaller sized implants which would withstand the same or even greater loading of the environment as current products.

Major advantage of LENS technology comparing to other RP technologies such as Direct Laser Metal Sintering (DLMS) or Selective Laser Sintering (SLS) which could also enable improved implant design is in physical characteristics of the process.

During manufacture the majority of the laser heat is dissipated by conduction down the deposit structure. In case of Ti6Al4V this results in epitaxial grain growth giving a macro-structure with fine columnar grains. The micro-structure consists of a very fine Widmanstätten structure. High level of density, alloy cleanliness and almost no porosity can also be noted, [11]. Such micro-structure leads to better mechanical properties and structure data. LENS technology offers equivalent tensile properties to forged material which indicates that the parts will meet performance criteria in the target industries. A study of fatigue properties shows that LENS manufactured Ti6Al4V testing probes offer equivalent to the highest quality forged material; more than 162 million cycles at 587MPa, [11].

To confirm described advantages of the prototypes manufactured with LENS, some basic mechanical and material tests had been performed at Faculty of Mechanical Engineering, University of Ljubljana on specially manufactured Ti6Al4V testing probes.

The determination of the force–displacement relation and the ultimate force to failure and elongation to break (Static testing) was performed by a constant rate of specimen extension (CRE) standard on the universal testing machine type Zwick Z050. The accuracy of the testing machine was 0.5 N for force measurements and 0.04 mm for measurement of displacement. The maximum payload of the machine was 10 kN and the maximum displacement was 0.8 m. The chosen constant rate of displacement of the moving clamp was 1 mm/s. The specimen was loaded with uniaxial tension and extended until rupture. The values of the static testing is presented in the table 2.

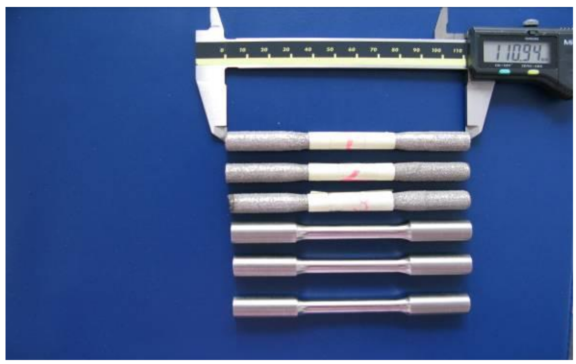


Figure 2: Testing probes made of wrought and LENS Ti6Al4V

Table 2: Comparison of mechanical properties between LENS and wrought Ti6Al4V testing probes

	LENS Ti6Al4V	Wrought and annealed Ti6Al4V
E Modulus, [N/mm^2]	118669.00	103696.00
Rp 0.1, [N/mm^2]	949.34	937.99
Rp 0.2, [N/mm^2]	964.20	954.00
Rp x 1%, [N/mm^2]	988.80	947.80
Rm, [N/mm^2]	1056.09	1017.82
ε-Fmax	3.68	3.68
RB, [N/mm^2]	1047.41	739.46
ε-at break, [%]	12.09	12.23

Macro-structure and micro-structure had been examined in the electronic microscope at UCEM Maribor, under 50x, 100x, 2000x and 4000x magnifications. Very fine Widmanstätten structure had been identified. On the specimen are visible some very small areas of less welded material (black spots) due to oxides on the original powder material, but in general almost no porosity is identified, (figure. 3,4).

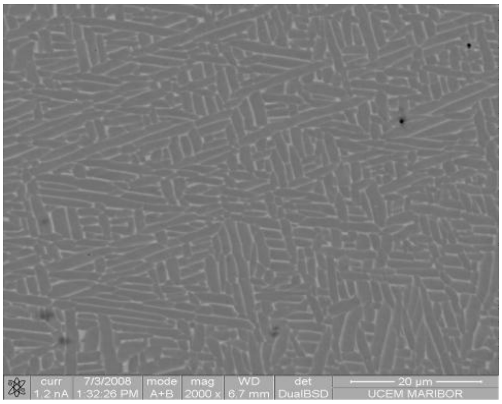


Figure 3: Micro-structure of LENS specimen under 2000x magnification

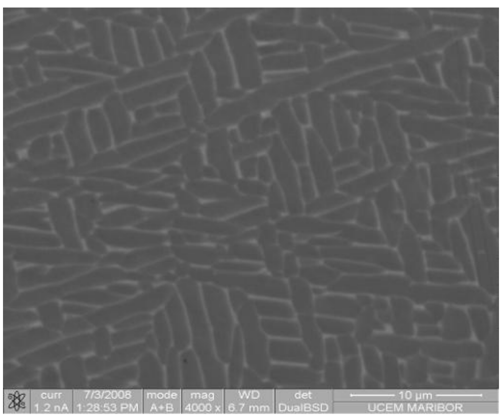


Figure 4: Micro-structure of LENS specimen under 4000x magnification

As an example of modern medical implant manufactured with LENS technology the hollow and thin walled bone fixation plate had been chosen. Such plate design could offer possibility to integrate some internal systems which would enable changing the bone-plate stiffness joint during the healing process (app. 1-2 months after operation insertion). Such "Smart plate" could significantly contribute to better and more effective healing process of the fractured long bones in the human body (Tibia, Humerus bone). Proposed functionality principle of the plate prototype would enable imitation of the natural bone healing process which is consisted of 4 phases: inflammation; soft callus; hard callus and bone remodelation, [13,14]. Functionality design enables loosening of the bone-plate stiffness joint and stimulates formation of the soft callus. To fix the plate on the fractured bone the same principle as at Locking Compression Plates (LCP) is used, [15]. Choice between compression (Interfragmentary or dynamic-axial compression) and angular stable locking screws (favorable hold also in osteoporotic bone, possibility of multiple fragment fractures, undamaged periosteum and retained circulation) will be possible. Main feature of such prototype is low contact profile which enables reduced impairment of periosteal blood supply due to limited plate-periosteum contact

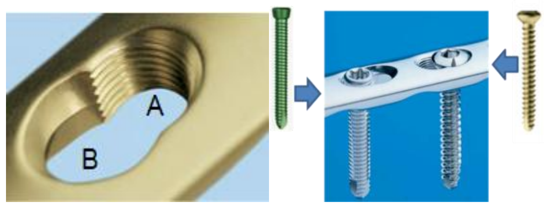


Figure 5: Screw hole for angular stable locking screws (A) and compression screws (B)

Despite thin walls (1 mm thick) and hollow structure should plate prototype withstand loads which appear in the human body during its implantation. Special focus is into bending existence of the prototype (achieved with special prototype shapes) and good implant tensile properties (main load acting on the implant).

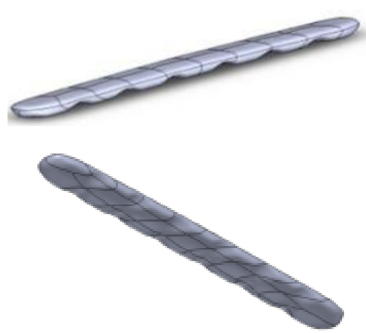


Figure 6: CAD model of the LENS fixation plate prototype

The prototype of the plate has been developed and prototyped as joint project of Laboratory of Cutting (LABOD), Faculty of Mechanical Engineering, University of Ljubljana, Department of Traumatology, University Medical Centre in Ljubljana and Artros Medical Centre for Orthopaedics and Sports Injuries.

More different prototypes had been manufactured on Optomec LENS 850R machine in company TIC LENS d.o.o. in Celje. Material used for manufacturing was biocertified titanium alloy Ti6Al4V (Titanium, 6% Aluminium, 4% Vanadium) in powder form (45 µm grain size).

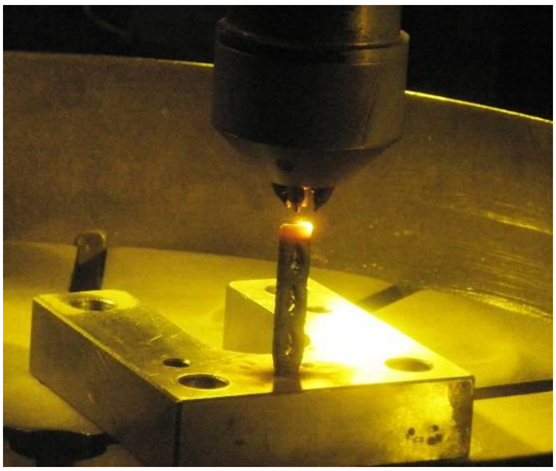


Figure 7: Manufacturing of the fixation plate prototype on Optomec LENS 850R machine

To investigate the possibility of precise screw holes machining for angular stable locking screws and compression screws, some machining tests had been performed. Intentionally developed cutting (milling) tool had been used and the accuracy of the screw holes profile measured.

Figure 8: Machined screw holes and intentionally developed cutting tool

Results of the machining tests had shown that good understanding of the tool wear appearance at milling of LENS Ti6Al4V plays very important role. In case of intentionally developed cutting tool is this very important because of just one cutting edge of the tool. Such cutting tool geometry is necessarily to machine appropriate cone screw hole.

Functionality principle of the fixation plate prototype is being tested on special testing machines for biomechanical studies. Prototype is inserted into cadaver part which is loaded cyclically under loads which are expected to act on the implant in the human body. After completion of biomechanical studies the clinical studies on 50 patients will follow.

4 Repair and Manufacture of high performance products for aviation purposes

High performance components are time consuming and expensive to produce using subtractive methods. In extreme cases, the aviation industry quotes “buy-to-use” ratios for machined parts that can be as high as 20:1, highlighting the inefficiency and waste that is inherent in traditional manufacturing methods. LENS is an ideal alternative for producing such highly shaped components due to its lower processing costs, faster turnaround, and significantly reduced material waste, [1]. Additionally, the technique integrates well with other processes to create unique hybrid manufacturing solutions by adding high-resolution features to forged or cast components, or by adding layers of wear-resistant materials as a protective surface.

Repair methods using LENS technology present special interest in aviation industry. In many cases, components cannot be repaired using traditional repairing techniques. Problems of welding type repairs include high heat input, part distortion, creation of sink/undercut and poor materials properties, [4]. Special problem appears when thin section components have to be repaired. These components could distort if they are exposed to high values of heat input. An example of such component is leading edge of the blisk (Bladed Discs) blades. These single piece components are a relative new development in jet gas turbines and expensive to manufacture. Blades in blisk are made of temperature resistant alloys such as Inconel (Nickel based alloys). Stage 1 and 2 of the blisks are characterized by premature failure (leading edge abrasion) and are highly susceptible to foreign object damage. Ingested sand and grit can seriously reduce the operating lifetime of engine flying over in rugged environments.

The "standard" repair method is replacement, which carries significant cost and lead-time penalties. The LENS re-manufacture cuts this "repair" cost and also provide longer component life by applying a wear resistant repair material to the damaged area. Blisk repair is becoming a major area for advanced repairs with the highest quality material without any defects being required straight from the machine.

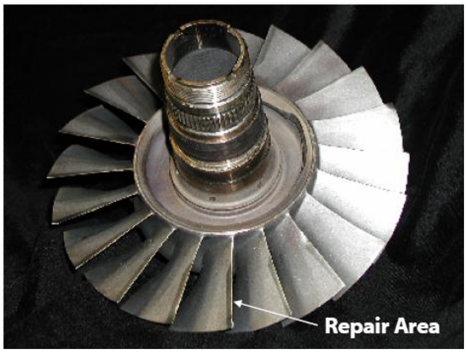


Figure 9: Example of repaired blisk for T700 jet engine, [4].

To examine possibility of manufacturing and repairing delicate, high performance parts for aviation industry the turbine blisk of CT7-9B turboprop engine had been manufactured using LENS technology principle. The General Electric CT7-9B engine is used on Saab 340 passenger aircraft, providing 305 kW (1,750 shp) of thrust. CT7-9B engine deliver maximum performance from short runways, added range, payload flexibility and economy of operation, [16].

Prototype of the blisk was manufactured in company TIC LENS d.o.o. in Celje and post-finished at Faculty of Mechanical Engineering, University of Ljubljana. Material used for manufacture was Inconel 718.

For mechanical and material tests few individual blades from the blisk had been manufactured. Micro and macro structure of the blades prototypes had been evaluated. The layers of the laser beam path are clearly visible (figure 10 a) and heat affected zone on the basic material, under the root of the blade is relatively small (figure 10b). During the manufacture process no special problems regarding blade geometry had been recognized.

Next predicted tests will be focused into static and dynamic testings to prove advantages of LENS technology for manufacturing and repairing of delicate aviation parts.

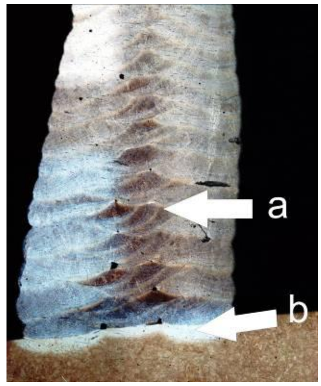


Figure 10: Microstructure of the blade; a) clearly visible laser beam paths, b) small heat affected zone under the blade

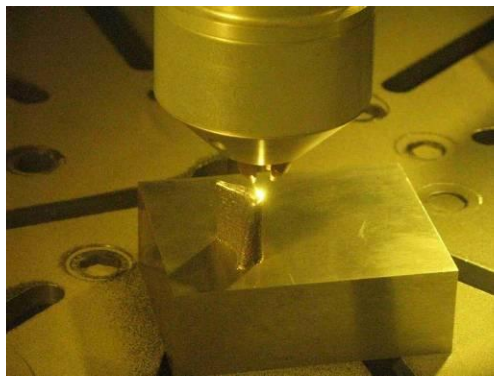


Figure 11: Building of the individual testing blade on the Optomec 850R machine

Figure 12: Final shape of the individual testing blisk blade

5 Conclusions

The additive manufacturing technology (LENS) due to its process advantages offers the potential for rapid manufacture of delicate high performance products in aviation industry and medicine. This has been proven by developing, manufacturing and testing prototypes of the bone fixation plate and possibility of manufacture and testing the turbine blisk of the GE CT7-9B engine. Test results for both types of prototypes have proven good micro and macro structure with almost no porosity in the material, small heat affected zone and good mechanical properties.

In case of individual blisk blades manufacture has LENS technology proven also its advantages for repair of delicate and thin parts for aviation purposes.

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