Near Net Shape Rapid Manufacture & Repair by LENS®

Dr. Martin Hedges
Neotech Services MTP
Petzolt Str. 3
D-90443, Nuremberg
GERMANY

info@neotechservices.com

Dr. Neil Calder
North West Aerospace Alliance –
Aerospace Innovation Centre
Pendle Business Centre, Commercial Road
Nelson, Lancashire, BB9 9BT
UK

neil@aerospace.co.uk

ABSTRACT

Components and systems manufactured from advanced materials such as titanium alloys, superalloys or special steels are critical to the performance of the armed forces. However, utilising performance materials presents several challenges. By their very nature, they are difficult, costly and time consuming to process. The main manufacturing routes of casting, forging and machining typically exhibit long lead times, extreme Buy-to-Use ratios and, being tool based, inherently inflexible. This seriously impacts on systems affordability and development times.

Defence manufacturing is low volume with production runs being typically limited to a maximum of several thousand parts. In some cases, a series of prototype parts, constantly evolving in design need to be manufactured. Production runs of many components may be less than ten or twenty units before they are updated. 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 cost.

During operation components produced from advanced materials operate in severe environments and suffer from rapid wear and damage. Quite often, existing repair procedures cannot cope with these difficult to work materials. The only alternative replacement at high cost, driving up total life cycle costs and draining military budgets and natural resources. As an example of the scale of this problem, the US Military's maintenance operations support more than 500 ships, 16,000 aircraft, 50,000 ground vehicles, and other military assets at a cost of greater than $40 billion annually. The high cost of maintenance puts a severe drain on military budgets. With defence departments now looking to extend systems lifetimes beyond the original designed lifetime, the need for effective repair techniques is becoming increasingly important.

Over the last 10 years, CAD driven, additive manufacturing technologies have been developed. The leading technology for defence applications is Laser Engineered Net Shaping (LENS®).Since its conception at Sandia National Laboratory and during it's commercial development by Optomec Inc., it has been focussed on Near Net Shape (NNS) rapid manufacture, modification and repair of components in advanced materials. The process creates/repairs fully functional parts, in a wide array of alloys including titanium, nickel, cobalt, steel and novel materials such as Metal Matrix Composites and Functionally Gradient Materials.

This paper will review the State of the Art for the technology and present application case studies where LENS® is being applied to vehicle technology in the defence industry. In addition, case studies from other industries will be shown, from which benefits could be applied to the defence field. Particular focus of the

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paper will be on material quality and the time, cost and quality benefits obtained in current and future applications. The paper will also discuss the future direction of technology developments to further establish this technology as a fully approved manufacturing and repair technique.

1.0 LENS® PROCESS AND MATERIALS PROPERTIES.

Figure 1 shows the stages involved in the LENS® process. First the engineer designs the part using CAD. The resulting STL file is then processed using the proprietary PartPrep® software which turns the CAD data into a digital tool path. This tool path drives the laser, at the heart of the process. The Work Station Control software controls the manufacturing process with the ability to adjust processing parameters in real time.

A schematic representation of the process is depicted in Figure 2. The process, uses a high power laser (Nd:YAG or Fibre laser) focused onto a metal substrate to create a molten melt pool. Powder is then injected into the melt pool to increase the material volume. The deposition head is then scanned relative to the component to write lines of the metal with a finite width and thickness. Rastering of the head back and forth creates a pattern and fill to complete the layer of material to be deposited. Finally, this procedure is repeated many times until the entire object represented in the three-dimensional CAD model is produced. In this fashion, a part is essentially built up from powders to form a solid object. The finished part is Near Net Shape and requires only final surface finishing. The build process is conducted in an inert Ar atmosphere which maintains combined Oxygen and moisture levels to under 10ppm.

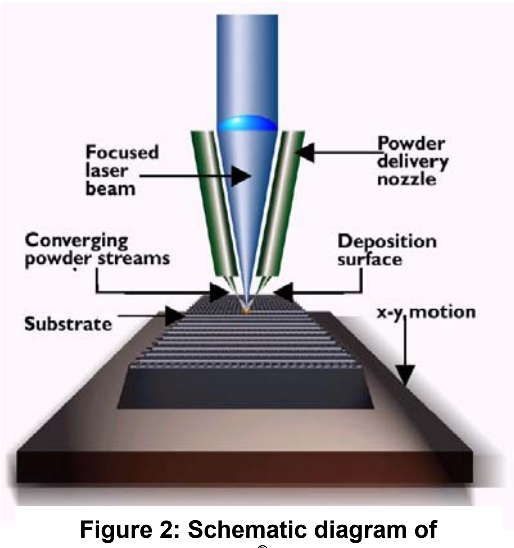
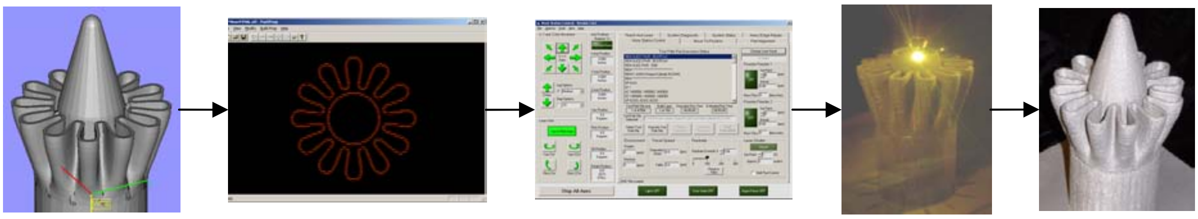


Figure 2: Schematic diagram of the LENS® process

One area where this process differs for other additive techniques are in the ability to produce a wide range of materials to exacting specifications required by the defence industry, Table 1. The properties obtained by the process in different alloys are comparable [1 & 2] to forged materials, and in some cases exceed them.



Engineering CAD Drawing | PartPrep® Software | LENS® Work Station Control Software | Deposition | Fabricated Part

Figure 1: Process Steps in LENS® Rapid Manufacture.

Table 1. Range of Materials Processed.

LENS® Preferred Alloys			
Alloy Class	**Alloy**	**Alloy Class**	**Alloy**
Titanium	Ti	Steels	H13
	Ti 6-4		S7
	Ti 6-2-4-2		17-4PH
	Ti 6-2-4-6		PH 13-8 Mo
Nickel Based	625, 713, 718		304, 316, 420
	Hastelloy X	Aluminium	4047
Cobalt Base	CoCr (Stellite)	Copper	Cu-Ni
LENS® Developmental Alloys			
Alloy Class	**Alloy**	**Alloy Class**	**Alloy**
Titanium	Ti 48-2-2	Steels	A2
	Ti 22Al-23Nb		15-5PH
Nickel Based	600 & 690		309, 410, 416
	Haynes 188 & 230		MM 10
	MarM 247		CPM 10V
	CMSX-3		Aermet 100
	Waspalloy	Copper	GRCop-84
	Rene 142 & N5		Cu-10% Sn
Miscellaneous: Commercially Pure W, V, Mo, Ta, Re, Nb, Mo-Si_B, Nb-Si, C103, Norem, NanoSteel.			

Table 2 shows a comparison between the tensile properties of LENS® manufactured and forged Titanium, 6% Aluminium, 4% Vanadium (Ti 6-4). The technology offers equivalent tensile properties to forged material which indicates that the parts will meet performance criteria in the target industries. A recent study of fatigue properties [3] shows that LENS® manufactured Ti-6-4 is equivalent to the highest quality forged material: >162 million cycles at 587MPa. Figures 3 & 4 respectively show the Ti 6-4 macro- and micro-structures. During manufacture the majority of the laser heat is dissipated by conduction down the deposit structure. In Ti 6-4 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 and alloy cleanliness can also be noted. The mechanical property and structure data confirm the suitability for use in critical component manufacture.

Table 2. Comparison of Tensile Properties for LENS Ti 6-4 vs. Forged Ti 6-4.

Material Type	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
LENS® Ti 6-4	932	1004	13
Ti 6-4 Forged & Annealed Bar	883	952	14

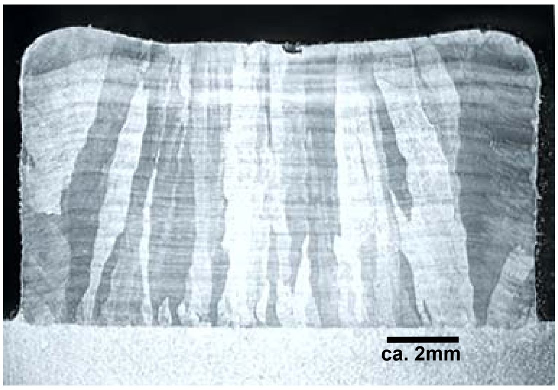


Figure 3: LENS® Ti 6-4 Macro-structure.

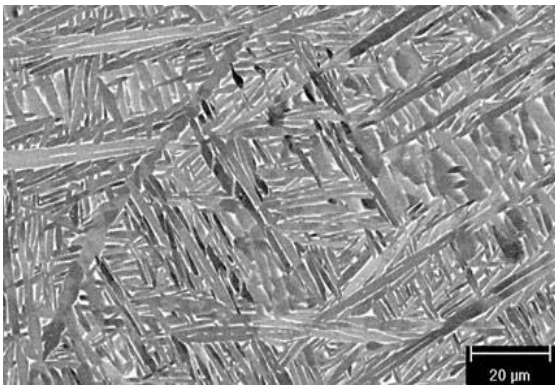


Figure 4: LENS® Ti 6-4 Micro-structure.

Other materials systems deposited exhibit similar characteristics: dense, fine feature micro-structures resulting in excellent materials properties.

On the basis of such outstanding mechanical properties LENS® can be considered as a candidate route for manufacturing and repairing critical components. The CAD driven, additive nature of the process has many technical and commercial benefits allowing cost-effective rapid manufacture and repair. The potential exists to leverage benefits in:

- Economic, Rapid Manufacture, Repair and Re-manufacture
- Agile Manufacture
- Improved design flexibility
- Cost effective part modification, repair & replacement

to support the needs of the armed forces by improving performance and reducing acquisition and life cycle costs.

2.0 COMPONENT DESIGN & MANUFACTURE

High performance components are time consuming and expensive to produce using subtractive methods. In extreme cases, the defence 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 because additive manufacturing provides for lower processing costs, faster turnaround, and significantly reduced material waste. 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.

2.1 Tool-less Rapid Manufacture.

Figure 5 shows an example of functional prototyping in the aerospace industry [4]. The component shown is a 1/6 scale gas thruster from a new design of military helicopter. For this new concept in rotary wing aircraft there is a need to eliminate the tail rotor to reduce radar profile, reduce noise levels and increase safety for ground crews. The thruster, manufactured from Ti 6-4, works using the engine exhaust gases and is designed to counteract tail movement. LENS® was chosen to manufacture this part as the component requires high material integrity and fast delivery. The time to design and produce a titanium casting was 9 weeks, including rapid tooling via Selective Layer Sintering. The LENS® part was delivered within 3 weeks (build time 8 hours) from date of order. The cost of the part vs. a cast part (including tooling cost) was approximately equal.

Figure 5: Gas Thruster in Ti 6-4. Courtesy: Bell Helicopter Inc.

2.2 Reduced Cost.

The design criteria for components in defence systems often calls for high strength and light weight. Weight reduction can be achieved by selecting the correct material system and designing the part so that any excess material that is not contributing structurally is removed. Using traditional subtractive manufacturing techniques this often results in the high Buy:Use ratios mentioned above. An analogous situation often arises in the F1 race industry [5]. An example is suspension mounting brackets, Figure 6. These parts suffer from high material losses of 87% during machining from solid Ti 6-4. Building up with LENS® results in a near-net shape part in a single step. The part is then finish machined in the traditional way with excess material being removed from each surface. In this way material losses are significantly reduced and the time to manufacture is cut by 50%, freeing up machining and operator capacity. On a low volume series basis, typically 10-20 parts in F1, it is calculated that a significant cost saving can be realised. By using increased laser power it is expected that this component can be built in ca. 20 minutes.

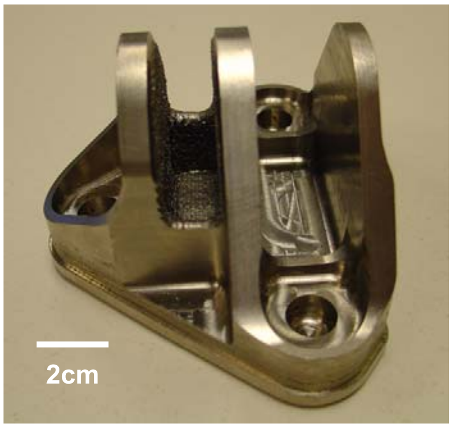


Figure 6. Ti 6-4 Suspension Mounting. Courtesy Red Bull.

Another F1 component studied further exhibits the need for reduced processing and waste. The standard production route for the "Gearbox Spider" is currently machining from solid bar which results in material losses of 98% and machine times of up to 10 hours. Figure 7 shows the as deposited spider which was manufactured within 2 hours for the first sample. It is estimated that with further refinement this can be reduced to under an hour allowing reduced cost, faster iterations in design and the reduction of waste.

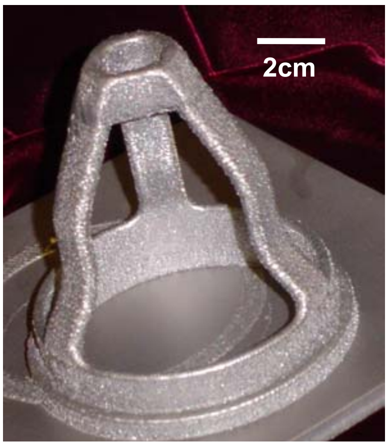


Figure 7. Ti 6-4 Gearbox Spider Courtesy Red Bull.

2.3 Agile Rapid Manufacture.

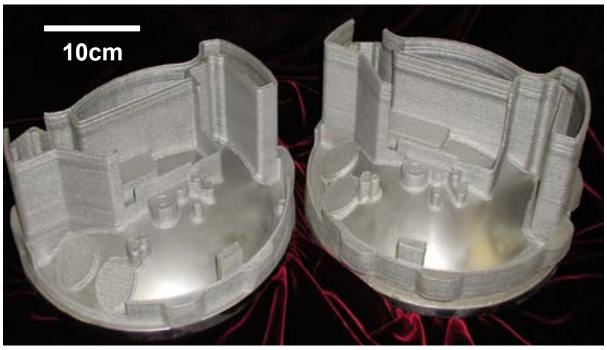


Figure 8. A LENS manufactured housing (Courtesy of Sandia National Laboratory)

LENS® produces the near net shape in a single step without tooling. Thus, a newly designed component can be produced, finished and in service in a matter of hours, offering significant time compression benefits. The process is both “agile” and “elastic” [6 & 7]: i.e. total flexibility in implementing design changes is offered and the financial risk associated with the continual development process is reduced. The fast design iterations required by the defence industry, can be accommodated by modifying CAD file manufacturing the new part, without the need for re-tooling. An example of the benefits of applying the process are shown in Figure 8. This is a defence application which required a housing to be built from 316 stainless steel. Due to the low volume (1-10 of each design) and rapid evolution of design the customer was having to wait in excess of 6 months for the components to be manufactured and faced high cost penalties. By using the LENS® process the parts were manufactured within 3 days and the cost of manufacture was reduced by over 65%. As the process is CAD driven, the customer was able to change the design during manufacture. This part is also a good example for hybrid manufacturing routes. This additive process can be integrated in to existing manufacturing routes creating unique hybrid solutions. In this part, the area consisting of a simple, bulky shape, the domed disc at the base of the part, was machined from plate material. LENS® was added in to create the thin, complex shaped walls. In this way the part was broken down into a series of features with each feature being manufactured using the most appropriate route.

2.4. Improved Design Flexibility.

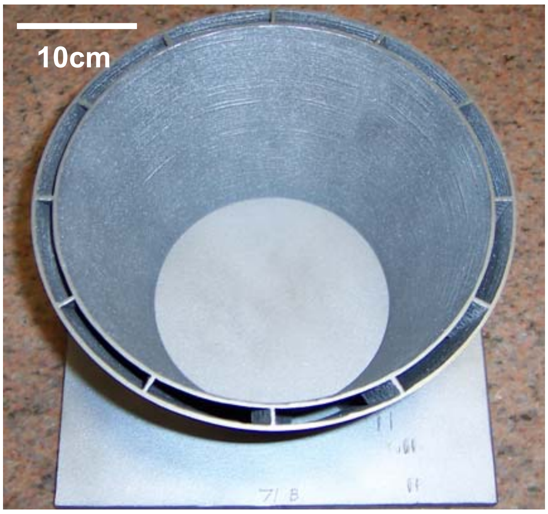


Figure 9. Dual Wall Exhaust Duct in Ti 6-4. Courtesy: RPM & Associates Inc.

CAD driven additive manufacturing allows the user to fabricate the part with features that cannot be readily produced by other methods, increasing design flexibility. An example of this is shown in Figure 9, a proof of concept demonstrator for a Dual Wall Exhaust Duct for a military turbine engine. This novel design manufactured with LENS® will save both cost and weight versus conventional duct fabrication methods. This project is ongoing following successful rig testing of full scale demonstrator engine.

Another example of design flexibility is in the Rapid Manufacture of Ti 6-4 satellite housings by Lockheed Martin Inc, Figure 10. LENS® was applied to rapidly manufacture the prototypes for the design iterations and also the final flight article via a hybrid route. This component, with its skeletal structural framework and many thin-wall appendages (1mm) was difficult (if not impossible) to fabricate through conventional methods. The manufacture of the design was carried out several separate steps using a hybrid approach, Figure 11. First the centre antennae section was machined from titanium plate. LENS® was then used to directly build on the frame rails. The final skeletal features are separately built which are then fixtured on to make the final complex assembly. Direct manufacture of the skeletal structures was not considered due to the presence of unsupported overhangs.

Hybrid manufacturing by LENS® was shown to add design flexibility by:

- creating shapes that would be extremely difficult to produce through other methods
- producing full-scale functional metal mock-ups
- implementing rapid design changes
- using higher strength materials than standard, with little or no weight penalty

This hybrid route combining machining, LENS® and fabrication steps proved to be both cost and time effective. An important point illustrated by this study is that the designer needs to learn how to use this process most effectively to create novel designs, either as a stand alone process or in a hybrid route combined with more traditional techniques. Components no longer need to be viewed as a single entity, rather as a series of features which can be made in the most cost and/or time effective way by hybrid manufacture.

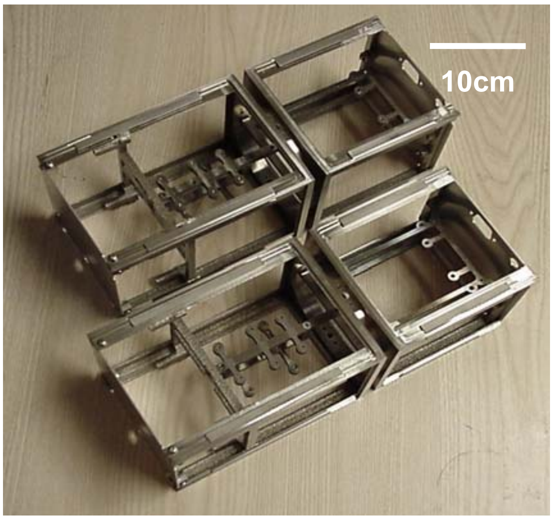


Figure 10. Ti 6-4 Satellite Housing (6). Courtesy: Lockheed Martin/ICE Prototyping.

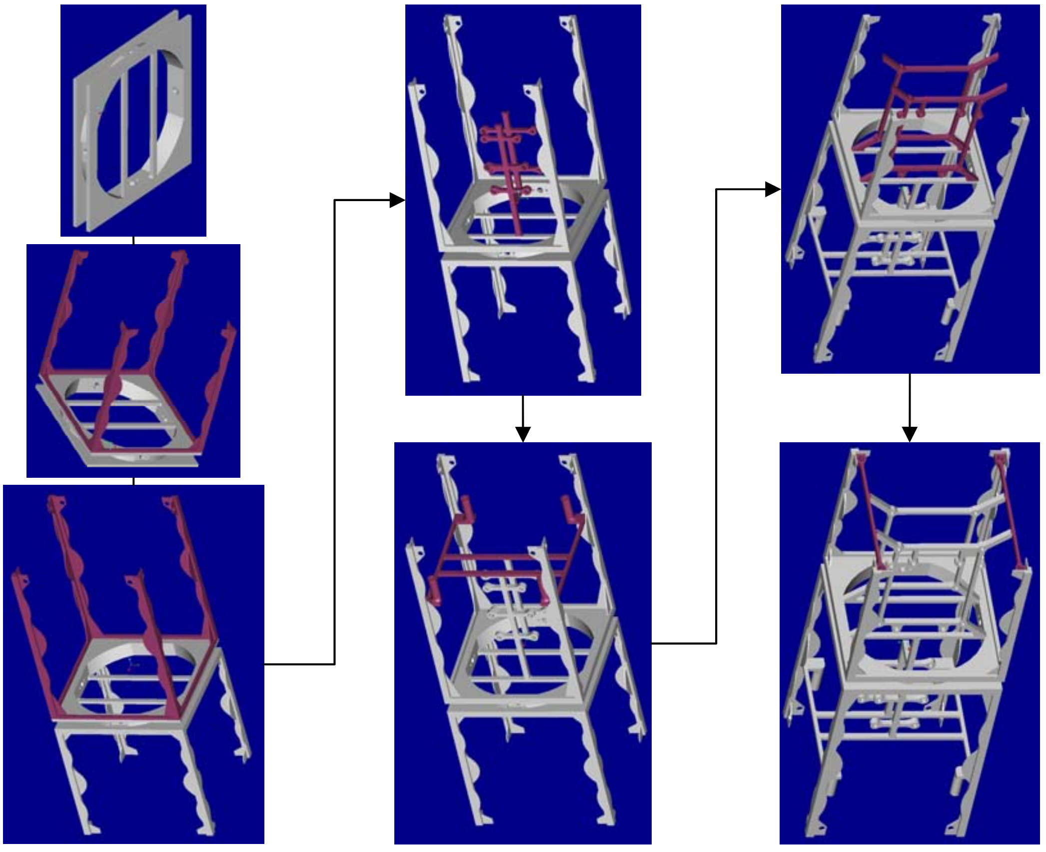


Figure 11. The manufacturing process flow for building the satellite housing.

3.0 COMPONENT REPAIR

Life-cycle costs are becoming an increasingly important factor when calculating military budgets. LENS® can be utilised to reduce lifecycle costs with its ability to repair and modify components as well as manufacture them. The system provides a production ready repair platform that delivers economic and functional benefits in terms of:

- Lower per-part repair costs
- Ability to repair heat sensitive components
- Reduced inventory requirements
- Longer service life
- Quick turnaround for rapid return to service

A key feature in repair is the highly targeted deposition that produces a very fine weld bead, exposing the component to far less heat than conventional methods. The resulting "heat affected zone" is smaller and more controlled so that the repair process does not damage the underlying part. And, since the deposit is much finer and more precise than conventional welding techniques, far less finishing work is required. With exceptional material and interface characteristics that are often superior to those of the native material, a LENS® repair can potentially reduce future maintenance requirements. The military repair applications for the technology cover aircraft, as well as land and sea based systems. Some examples of where it is being applied include:

3.1 Cost Effective Repairs.

Not only does the process offer significant functional advantages over traditional techniques, it also has a very low cost base. This cost advantage is based on a combination of speed, simplicity and increased quality of repairs. It allows users to make faster, higher quality repairs to a more complete range of parts than competing means. In one example, the US Army's Anniston Army Depot (ANAD) has been using this system to repair a number of Honeywell gas turbine engine components for the M1 Abrams Tank. The Tank-Automotive & Armament Command (TACOM) has approved the process, and ANAD estimates annual savings of up to $5 million for repairing just a handful of component types. With the success of this first system installation, ANAD has recently installed a second LENS® machine. This successful project led to the DoD Commercial Technologies for Maintenance Activities (CTMA) team, securing the "Defense Manufacturing Excellence Award" in 2002.

Figure 12. Submarine Cooling System Ti 6-4 Ball Valve repaired with LENS®.

3.2 Repairing "Un-repairable" Parts.

In many cases, components in the defence industry cannot be repaired using traditional techniques. Problems of welding type repairs include high heat input, part distortion, creation of sink/undercut and poor materials properties. An example of "un-repairable" parts is the Ti 6-4 ball valves from submarine cooling systems, Figure 12. In service small amounts of debris can scratch the surface and cause the system to leak. These components cannot be successfully repaired using welding techniques due to the creation of undercut surrounding the weld repair. Due to the targeted and controlled heat input within the protective environment LENS® was able to quickly and economically repair these "un-repairable" components. After finishing the repair area is returned to original tolerance.

Figure 13. Inconel 718 Compressor Seal. Courtesy: RPM & Associates.

Another example of parts waiting for a repair solution is T700 Gas Turbine Engine Compressor Seal, Figure 13. These seals, manufactured from Inconel 718 are used in AH-64 and UH-60 helicopters. Corpus Christi Army Depot (CCAD) had 500 of these worn seals in stock waiting for a suitable repair process to be developed. The existing practice was to replace the seals at a new cost of ca. $1,000 each. RPM & Associates Inc. developed a LENS® repair procedure for these parts. The repair cost of ca. $500 including finishing resulting in savings $250,000. These seals are only one component from the estimated $100M+ of used parts in the Storage, Analysis, Failure Evaluation, and Reclamation (SAFR) inventory at CCAD. Additional components are now being assessed for suitability of repair with LENS.

3.3 Repairing Delicate Structures.

This low heat input of LENS® repairs also reduces part distortion, an important factor when repairing thin section components. An example of where such a feature is required leading edges of blisk (Bladed Discs) blades. These single piece components are a relative new development in gas turbines and expensive to manufacture. The materials used are of the highest quality and it is necessary to develop advanced repair processes to successfully maintain them. The example shown in Figure 14 is a blisk form a T700 helicopter engine used by the US Army and Navy. The T700 Stage 1 and 2 Blisks are characterized by premature failure (leading edge abrasion) and are highly susceptible to foreign object damage: Ingested sand and grit has seriously reduced the operating lifetime of helicopter engines flying over in rugged environments.

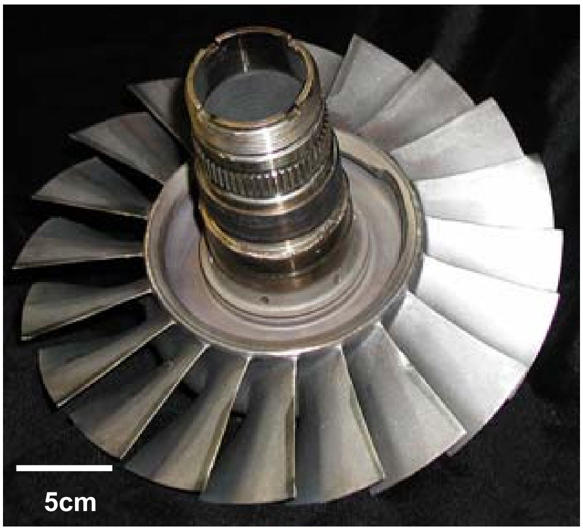


Figure 14. Blisk repair, post finishing, for T700 Engine.

The "standard" repair method is replacement, which carries significant cost and lead-time penalties. Removal of the engine and replacement of the blisk is a high cost exercise. 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 now becoming a major area for advanced repairs with the highest quality material without any defects being required straight from the machine.

3.4 Repairing Manufacturing Defects.

LENS® is not just being used to repair components which have worn or been damaged in service, it can also be used to repair manufacturing defects, for example in investment castings, or from mis-machining. In these applications the quality of the repair material is often superior to the substrate materials.

3.5 Large Repairs.

Not all components repaired using LENS® are limited to the current envelope of 1.5m x 1m x 1m. The largest component repaired to date is a 5m long coal mine swing shaft that weighs 10 metric tonnes. During operation the bearing surfaces of 4340 steel wear out. Conventional welding repairs cause failure problems due heat input. RPM developed a repair using 420 SS which not only repairs the part but also increases the wear resistance and hence service life. Repair cost is approximately 50% less than new, and extends shafts life compared to new due to material selection. It is feasible to carry out similar repairs for large components; for example in naval applications.

3.6 Mobile Repairs.

The US Army has been using LENS® as a key component in its Mobile Parts Hospital (MPH) [8]. The MPH aims to provide a real-time battlefield repair or replacement capability that reduces the need to deploy large spare parts inventories and helps minimize down time of mission critical assets. The MPH is a compact communications and manufacturing unit. It is designed for deployment to remote locations for emergency repair of non-operational equipment. A combination of advanced technologies enables the MPH to quickly and efficiently produce and repair parts on demand.

4.0 FUTURE DEVELOPMETS.

As can be seen form the above applications and case studies, LENS® is a rapidly maturing technology, in or nearing production readiness in diverse applications. To fully leverage the potential benefits offered by the process it needs to meet the manufacturing requirements demanded by the defence industry. These requirements can be spit into two distinct areas: technological maturity and economic maturity.

4.1 Technological Maturity.

Technological maturity requires a process that is certified in accordance with industry standards and directives. The need here is for the process to be consistent in its output such that the deposited material will have reproducible mechanical properties within tight bounds. For defence applications this would mainly be fatigue endurance, but would also require a consistent mass and stiffness in order to be used as part of a carefully designed structure. Design allowables and manuals need to be available within the supply chain in order to allow LENS® to be fully included in manufacturing process planning.

This issue is currently being addressed in several ways. Repair applications are typically easier to qualify than manufacturing applications. Numerous repairs for land based vehicles are already qualified and operate on a production basis. Plans call for the first several repairs for aircraft to be fully qualified and to enter service in 2006. The real need to reduce life cycle costs is driving these efforts. For manufacture, the approval process is generally more complex. LENS® produced components have already demonstrated a high level of mechanical integrity (tensile and fatigue properties). The next step is to generate a database of statistically significant mechanical properties which give designers confidence and allow design manuals to be developed.

4.2 Economic Maturity.

The economic needs for full maturity are for there to be sufficient manufacturing capacity to satisfy the requirements of orders generated by multiple prime contractors on multiple parts on multiple vehicle projects. The existence of capability for proof of concept production within Universities and research organisations does not constitute the critical mass of capacity for series production. The conditions for significant investment in capacity have to be met. Optomec is leading the drive to economic maturity for additive manufacturing and now has 25 LENS® systems in the field, several of which are running multiple shifts on production repairs applications. This installed base is set to rapidly increase not just in defence but also other less demanding markets. The key is to select applications with a strong business case and high ROI.

Compared to traditional techniques, the installation of manufacturing capacity with LENS® is simpler. LENS® capacity is essentially modular, requires no special infrastructure within the factory and is easily scalable with and investment cost between $500,000 and $1M per unit. Rather than the user investing multiple millions in complete casting or forging plant, systems can be added incrementally to build up capacity to match demand. Also, with the use of fibre lasers LENS® capacity within the machine becomes easily scalable. Systems can be initially installed with lower laser power, say 500W-1kW, then as demand rises additional diode boards can be added to increase power to speed up production.

To support the continued drive to technological and economic maturity Optomec has several major projects ongoing to:

- Developing process “toolboxes” for Ti, Ni and Fe alloys so that processes are fixed and documented. The focus for this development is on Defence and Aerospace applications, particularly safety-critical applications;
- Develop a mobile LENS® machine with high deposition rate, small footprint and low utility requirements;
- Increase the application range by development of application specific deposition heads; improved 5-7 axis hardware and software; improved tool-path generation software; use of a laser scanning arm for QA, tool-path generation and reverse engineering;
- Improve speed and robustness of the LENS® systems in production environments.

These programs will deliver improved economics, throughput, assured quality, and applications flexibility.

In short, despite being a medium-long term process, technological maturity is ongoing with economy of scale and production capacity is being built up. Taking the parallel of carbon fibre composites as a similar paradigm shift in aerospace production, the thin end of the wedge has taken many decades to thicken into its current position where civil airliner airframes are cited as 40-50% composites by mass. LENS additive manufacture and repair offers the potential to repeat this level of success and support defence departments in increasing both capability and systems affordability.

SUMMARY

Military systems are increasingly required to have a balance between high capability and minimum cost. Most of the structural components used in these high performance systems are manufactured from advanced materials such as titanium alloys, superalloys and special steels. The high performance of these materials also means that components are inherently expensive and difficult to manufacture. This drives up procurement cost and development lead times. During service in harsh environments these components wear or get damaged, often necessitating replacement at high cost.

The additive manufacturing technology, Laser Engineered Net Shaping (LENS®), offers the potential to rapidly manufacture and effectively repair a wide range of these components. The benefits to military customers include reduced procurement costs, improved performance, reduced development times and also lower life cycle costs. Currently, LENS® is being used extensively in product design/development and production repairs for military systems. In the coming years the process will reach technological maturity for both production level manufacture and repair. Furthermore, ongoing technology development programs will further establish LENS® as the leading additive manufacturing and repair process for defence applications.

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MEETING DISCUSSION – PAPER NO: 13

Author: M. Hedges

Discusser: C. Styles

Question: Are LENS system being used at service and repair depots (military)? i.e. not just Mobile Parts Hospital?

Response: Yes, two production units in USA.

Discusser: D. Dicus

Question: One chart showed a list of LENS preferred materials. On that list was an aluminum alloy. Given the challenges posed, why is aluminum a preferred material for LENS?

Response: The Al alloy is "preferred" in the sense that we have more experience with it than the other Al alloys shown. Al is not as well developed as Ti, Fe, Steel…

Discusser: B. Bodger

Question: 1. Have you had any problems sourcing your feed stock (powder)? 2. Are you involved in the powder's development?

Response: 1. No. 2. We invest effort in the complete supply chain. We use standard powders and have preferred sources. Development is more concerned with commercial maturity of powders.

Discusser: B. Bodger

Question: Have any aviation repairs been approved to date?

Response: Several are pending.

Discusser: C. Bampton

Question: 1. Any experience showing LENS repair works with non-weldable Ni-based super alloys? 2. Any experience with anisotropic elastic properties of LENS-deposited Ni-based super alloys?

Response: 1. Some limited, needs some work. 2. This can be a fundamental feature in some alloy systems.

Discusser: J. Allen

Question: What are the current research and development topics re: LENS at Sandia Labs?

Response: Not aware of major developments, Optomec took over commercialization in 1998.