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Laser-based Refurbishment and Repair

Background document

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1. Introduction

The CSIR National Laser Centre has been developing a suite of laser-based manufacturing technologies over the past 15 years. Within this suite of laser-based manufacturing technologies, a key application area is laser-based refurbishment and repair that has been developed and has the ability to repair and improve the operational performance of high value components, plant and/or infrastructure. This offering is based on a process called laser cladding, which is a weld overlay processing using the laser as an energy source. Another technology available from the CSIR NLC that bolsters this service offering is laser hardening. In laser hardening the laser beam is used as an energy source to selective heat and selective harden irradiated areas on metal components.

This document provides some technical background information on these technologies, the potential application areas, as well as key markets in which the technology can be applied.

2. Background

Laser based manufacturing serves a critical role in today’s economy and is generally see as an enabler to innovation in the manufacturing industry. Recently laser-based refurbishment technologies have also been developed that offers significant potential for innovation in repair and refurbishment applications, as well as the potential for cost savings across a wide range of industry sectors. At the CSIR National Laser Centre R&D programs have been supported over the past 15 years to support technology and application development in the following laser-based manufacturing technologies:

- Laser Enabled Manufacturing
  - 3D Cutting
  - Laser welding
- Laser-based refurbishment and surface engineering
  - Laser cladding
  - Laser hardening
CSIR has been working to mature these technologies towards industrial readiness, and has focussed on developing a number of industry applications which have already been implemented on a service basis. Apart from this work the CSIR has also invested in developing a mobile laser-based processing cell that allow laser cladding and laser hardening processing to be done on the shop floor, or at the client's factory or plant.

3. Technical information

3.1. Laser cladding

The unique properties of a laser beam allows precision welding technology (laser cladding) to be developed which is characterized by low heat input and the possibility for closed loop control, resulting in the ability to accurately repair / resurface complex and high value components. Laser cladding is a process that differentiates itself from traditional weld overlay techniques due to significant benefits and unique features offered by the use of a high power laser beam as the heat source for welding. In laser cladding, the laser beam is used to produce a very shallow melt pool on the surface of the substrate. A metal powder is deposited by means of a powder nozzle into the weld pool. The inert carrier gas, which transports the powder, also provides shielding for the weld pool. When the weld pool is moved along the surface of the metal, the deposited consumable solidifies to form a metallurgically bonded weld bead. By successive overlapping of weld beads, a continuous surface layer is produced.

The laser beam offers a highly localized heat source that can be much more accurately controlled compared to conventional arc welding sources. The localized heat input enables laser cladding to provide a number of important advantages over conventional arc welding and other surface coating processes. These include:
• **Low dilution of the cladded layer onto the substrate material.** This means that few thin layers are required to achieve the desired surface chemistry compared to conventional processes where multiple thick layers are required because of the high dilution rates. This allows the cost effective utilization of more expensive materials for the refurbishment of components. Since this is in essence a welding process, a very good metallurgical bond exists between the base materials and the overlay material.

• **Low heat input.** This factor limits the extent of the heat affected zone as well as associated metallurgical problems. The low heat input also results in much reduced distortion and allows for the processing of smaller components. The high solidification rates resulting from the low heat input produce non-equilibrium microstructures with unique properties such as phase distribution, and enhanced hardness due to fine microstructures.

By virtue of the nature of the process it also offers the following advantages:

• **Flexibility.** Laser cladding is not limited to utilising available wire consumables but can also employ the extensive range of powder consumables that are available on the market. New alloy compositions can be prepared by merely blending available powders. It is even possible to continuously change the composition of the deposited layer by combining powder feeds from several programmable powder feeders. In this way functionally graded layers could be produced, graded for instance to overcome metallurgical incompatibility between the substrate and the overlay material.

• **Control.** Laser cladding is essentially an automated CNC welding process which uses a highly controllable heat source in the form of a laser. As such laser cladding offers a very high degree of control which yields high levels of reproducibility which are independent of operator skills.

• **Metallurgically bonded layers** with good resistance to impact and fatigue.

### 3.1.1. Laser cladding applications:

Components in manufacturing/production equipment are often subject to extreme operating conditions that may include oxidation, high temperature corrosion, thermal fatigue, high compressive stresses and abrasive wear. These conditions result in accelerated deterioration of the functional surfaces and consequentially a reduction in the service life of the component. It is therefore part of everyday life that when operating any type of
mechanical equipment with moving parts, worn metal components need to be repaired or rebuilt. Repairing the component at a fraction of the cost of a new component will save the user a substantial amount of money. In addition, repair of components to original specification will also reduce the need to keep spares, and can significantly reduce down time if repairs can be implemented rapidly, also in-situ. When a worn part is rebuilt, the potential also exists to repair that component in such a manner that its performance is enhanced resulting in a longer wear life than a new part.

![Image](image.png)

Figure 1: Wear and corrosion processes

Because of the unique capabilities of laser-based refurbishment this process will be suitable for the refurbishment of the vast majority of components and in some cases even the enhancement of these components. However, components that will benefit the most from the laser cladding refurbishment process are generally high value components where refurbishment and servicing occurs on a regular basis. Although refurbishment applications using lasers and donor materials for component repair, surface patterning and strengthening have been under development for decades, laser based refurbishment is just now gaining widespread industrial and commercial adoption. The reasons for increased adoption are similar to those for the growth in laser welding; the advent of higher-power laser systems with tailored beam profiles, improved parts quality and longevity, as well as the increased...
need for environmentally sustainable engineering practices that reduce energy consumption, toxic emissions, and material waste.

While all metallurgical surface coating technologies provide cost and performance advantages for demanding applications (extreme corrosion, abrasion, and impact forces), laser cladding provides more advantages compared to typical thermal spray methods in material properties, coating quality, and ease of use. This makes laser cladding a top choice in many repair and resurfacing applications as well as the enhancement of surfaces.

The use of this innovative process to treat high value components subjected to extreme operating conditions is possible due to the CSIR’s extensive experience and knowledge in the development of various laser based materials processing systems over the last several years for various applications.\textsuperscript{1} Several unique laser-based refurbishment solutions have been developed and is already implemented in industry as a service offering from the CSIR National Laser Centre.

Laser cladding is most advantageous for applications where replacing a worn part entirely is too expensive or not possible. For example, marine propeller shafts require a high wear resistance, high corrosion resistance, and require replacement after a short amount of time. Due to the sheer volume and size of the shaft, it is obviously uneconomical to replace the entire shaft when only the surface is the issue. Laser cladding the surface can bring the component back to the original specification. This is made possible due to the low heat input welding processes that limits distortion, but provides a full metallurgical bond that will not adversely affect the performance of the component. It is also possible to deposit alternative

\textsuperscript{1} C. van Rooyen, “Microstructural development during laser cladding of low-C Martensitic stainless steel,” Welding in the World 52, 2008

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Power station turbines}
\end{figure}
metal alloys that can provide properties that improve the original specification of the shaft (or any other component) in its original state, doubling or even tripling the life of the shaft.

3.1.1.1. Laser cladding applications developed by CSIR NLC

Applications of repair, refurbishment and the implementation new coatings to extend service life that have been developed by the NLC and have already been implemented as a service offering into industry on an ad hoc basis:

- Journals on steam turbine rotors, oxygen rotors and generator shafts
- Pump shaft journals
- Seal areas on rotors, seal areas on casings
- Seal areas on impellors and screw compressors
- Various tooling applications (injection mould tooling and trim tooling)
- Gears and pulleys
- Turbine blades (rebuilding of blade rivets (tenons) and leading edge erosion repair)
- Valve seats

3.1.1.2. Generic laser cladding applications

Because of the unique capabilities of laser cladding this process will be suitable for the refurbishment of the vast majority of components. However, components that will benefit the most from the laser cladding refurbishment process are generally high value components where refurbishment and servicing occurs on a regular basis. These conditions optimise the exploitation of the initial capital outlay associated with the laser cladding system. These include:

- Metals
  - Refurbishment of continuous casting rolls
  - Bearing journals
  - Mandrils, other plant infrastructure
- Automotive
  - Cylinders
  - Surfacing of automotive and diesel valves
  - Repair of moulds
  - Drive shafts
- Mining & Drilling
Hard facing of valves, valve seats
- Refurbishment of crushers
- Hard-bandung of drill rods,
- Shafts, pumps
- General mining equipment

**Aerospace**
- Repair of high value components, such as turbine housings

**Power generation**
- Steam turbine blades
- Gas turbine blades
- Hydraulic cylinders on oil rigs
- Turbine casings
- Plant and infrastructure

**Petro-chemical**
- Plant and infrastructure
- Wear plates
- Valves and pump shafts
- Turbine components

**Transport**
- Refurbishment of the running surfaces of axles, crankshafts
- Laser cladding of wheels to restore the wheel profiles
- Exhauster Cap Refurbishment
- High temperature corrosion protection of exhaust valves with laser cladding for low-speed two-stroke diesel engines used for ship propulsion
- Laser cladding of boiler tubes in ship engines
- Repair of high wear components on dock side cranes
- Refurbishment of worn propeller shafts

**Paper and Pulp**
- Rollers
- Crushers
- Pump shafts, impellors

Other applications include the repair of construction equipment, agricultural equipment, hot extrusion dies, oil rig components, aerospace components, and marine components where extreme abrasion and corrosion accelerate material degradation.
3.1.2. Competing technologies

The two main competing technologies for laser cladding are briefly described below:

![Figure 3: Competing technologies for laser cladding](image)

<table>
<thead>
<tr>
<th>Thermal Spraying</th>
<th>Laser Cladding</th>
<th>PTA welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Not metallurgical bond</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Thin layers 0.1-0.5mm (metal / ceramic)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Not suited for impact or thermal fatigue applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Good metallurgical bond</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Low dilution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Localised repair possible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Superior mechanical and corrosion properties compared to arc welding processes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• High heat input – distortion risk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Medium dilution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• High deposition rate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3.1.1. Thermal Spraying

Thermal spraying is a process where a molten stream of coating material, typically metal alloys, ceramics or carbides, is sprayed onto the surface of the substrate. Thermal spraying consists of various technologies that include high velocity oxy-fuel (HVOF), plasma spray, arc spray and flame spray processes. Thermal spray coatings are applied to refurbish components subjected to oxidation, abrasive wear and corrosion. Mechanically bonded thermal spraying is a complementary technology to metallurgically bonded welding processes for the refurbishment of components.

3.3.1.2. Conventional weld overlay processes:

Also competing in this market is conventional welding. While conventional welding is widespread in South Africa due to its low cost, robust nature and high productivity output, heat deposition is very high which results in distortions and requires deposition of many layers to achieve the desired chemistry. In high volume low cost applications this is not a
problem. However, as soon as you introduce high value components that cannot incur any distortions, traditional welding methods are no longer feasible.

### 3.3.1.3. Comparison of the processes:

The advantages and disadvantages of laser cladding are therefore described at the hand of these processes.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Conventional Welding</th>
<th>Thermal Spraying</th>
<th>Laser Cladding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Consumables</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Process Control</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Quality</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Heat Input</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Heat Affected Zone</td>
<td>Big</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Deposition Rate</td>
<td>High</td>
<td>Very low</td>
<td>Low</td>
</tr>
<tr>
<td>Coating thickness</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Porosity</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Bonding</td>
<td>Metallurgical</td>
<td>Mechanical</td>
<td>Metallurgical</td>
</tr>
<tr>
<td>Impact Resistance</td>
<td>High</td>
<td>Poor</td>
<td>High</td>
</tr>
<tr>
<td>Fatigue Resistance</td>
<td>High</td>
<td>Poor</td>
<td>High</td>
</tr>
<tr>
<td>Distortion</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Dilution</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Materials</td>
<td>Limited</td>
<td>Wide</td>
<td>Wide</td>
</tr>
</tbody>
</table>

Table 1: Comparing various surface repair technologies with laser cladding

It is worthwhile noting that although laser cladding has lower deposition rates than welding and thicker layers compared to thermal spraying these do not influence the overall advantage laser cladding has over the other processes due to the low dilution and heat input which makes it a much more efficient process. Our laser cladding system will present prospective clients with the following advantage over their offerings:

- Significant cost saving due to extended service life and reduced maintenance of their parts or equipment
- Complex alloy structures that will improve a components chemical and or mechanical properties
Customisation and versatility to refurbish a broad variety of components (small (mm) to large (m))

3.1.3. Laser-based refurbishment – Environmental drivers

We find that there are four fundamental environmental drivers to the technology.

- Reducing energy during the manufacturing chain - Refurbishment can replace processes where significant amounts of energy are wasted to build and machine replacement components
- Reducing material wastage – Refurbishment can significantly reduce the amount of waste due to the scrapping of damaged or worn out components
- Reducing transportation, logistics and packaging – Refurbishment can reduce many stages of the traditional supply chain by decreasing the need to maintain large quantities of spare parts and the shipment of replacement parts that increases fuel and energy costs and serves to drive up the cost of goods manufactured away from the consumer base
- Life cycle carbon footprint - One of the most important manufacturing considerations today is life-cycle engineering, where the designer must consider both the implications of the part through its service life and the end of life disposal of the part. This means that we must now consider the life-cycle implication of a component in terms of its carbon footprint and the long-term impact of the part on the environment. With refurbishment, by optimising the design of a product and manufacturing it with absolute minimum material, it is possible to significantly decrease the weight of parts. However, if that part happens to be an aircraft or automotive components, then the life cycle carbon foot print of the vehicle will be significantly reduced, as the component part made using LAM will weigh less generating a lower fuel burden.

3.2. Laser Hardening

Laser hardening is a surface hardening process used exclusively on ferrous materials like certain steels and cast irons. The process requires relatively low power densities and can be used to rapidly treat very large areas. The laser beam is used to heat the surface of the target material to just under the melting temperature as the laser beam moves across the
surface. This heating causes the iron atoms to change their position within the metal lattice. As the laser beam moves away the previously heated area undergoes rapid cooling by the surrounding material, a process known as self-quenching. As a result the metal lattice cannot return to its original structure. This transformation yields a surface with much greater hardness. This provides improved properties such as greater wear resistance, increased strength and due to introduced compressive residual stresses, improved fatigue properties.

The hardening depth is typically 0.1 to 1.5 millimetres deep although greater depths can be achieved in certain materials. The latter requires larger volumes of surrounding substrate to ensure that the heat dissipates quickly and the hardening zone cools rapidly enough. Laser hardening is a complementary process to conventional flame and induction hardening processes but offers certain advantages:

- Can treat small areas on sensitive, high-value components
- Selected areas can be hardened without affecting the surrounding material
- Minimal heat input results in limited distortion and reduces the need for additional machining
- Accurate control of the process which allow reproducibility and accurate treatment
- Superior hardness compared to conventional processes
- No external quenching is required
- Fast turnaround times
- The process can be automated and integrated with other inline production processes;

### 3.2.1. Laser hardening applications:

Typical applications of laser hardening include:

- **Aerospace**
  - Turbine blades
  - Helicopter blades
- **Automotive**
  - Drive shafts and stub axles
  - Car door torsion springs
  - Synchronous gears and gear selectors
  - Steering system
  - Pumps
  - Piston rings
Piston ring grooves in heavy duty engines
- Forming Tools and Moulds:
  - Transport
    - Train wheels
    - Wheel axles
    - Bearing races

Laser transformation hardening is an essential technology to the South African industry, enabling users to compete worldwide in the production of cost-effective, high-quality products.

4. Competitors

4.1. Local Competitors

A comprehensive survey of possible competitors was done during the investigation into laser cladding. No local companies were found that are active in this field and have parameter wise, comparable laser cladding systems in the market. However, there are several companies active in the thermal spraying coating market.

- AfriWeld
- AllWeld Marine
- Coatec Mechanical Solutions
- Dormac
- Fe Powder Supplies
- General Thermal Spray
- Ithuba Valves & Industrial Supplies
- MacKay's
- Power Transmission Technology
- Ratamang
- ThermaSpray
- United Thermal Technologies

Also competing in this market is conventional welding. While conventional welding is widespread in South Africa due to its low cost, robust nature and high productivity output, heat deposition is very high which results in distortions and requires deposition of many
layers to achieve the desired chemistry. In high volume low cost applications this is not a problem. However, as soon as you introduce high value components that cannot incur any distortions, traditional welding methods are no longer feasible.

It is worthwhile noting that although laser cladding has lower deposition rates than welding and thicker layers compared to thermal spraying these do not influence the overall advantage laser cladding has over the other processes due to the low dilution and heat input which makes it a much more efficient process. Our laser cladding system will present prospective clients with the following advantage over their offerings:

- Significant cost saving due to extended service life and reduced maintenance of their parts or equipment
- Complex alloy structures that will improve a components chemical and or mechanical properties
- Customisation and versatility to refurbish a broad variety of components (small (mm) to large (m))

4.2. International service providers

There are a number of potential international competitors in the laser cladding market to name but a few:

- Maren Corporation - Lean manufacturing. Laser cladding services. Capabilities include repair, precision machining, rebuilding, shot blasting, testing, inspection, turning, milling, remanufacturing, welding & boring.
- Joining Technologies - Certified high speed & accuracy laser welding services. High & low voltage electron beam welding services. Surface treatment and cladding services for metal surfaces with laser energy and metallic powder. Welding for aerospace turbine components, plastic mould and die repair.
- Hayden Corporation - Certified laser cladding services for valves, seats & down-hole tools. Leverage our extensive history in the coating and welding industry with the highest-quality laser processing hardware available to provide expert laser cladding service in delivering the best engineered laser cladding solution.
- IPG Photonics Corp. - Certified custom manufacturer of laser systems including lasers for OEM, medical, aerospace & laboratories. Types of lasers include
continuous wave, YAG, Nd:YAG, Q-switched, pulsed, semiconductor, carbon dioxide, single frequency diode-pumped & fiber lasers. Lasers are suitable for marking, trimming, micromachining, precision drilling, welding and cutting applications.

- **Industrial Laser Systems, LLC** - Laser cladding services using high power direct diode laser systems (HPDDL). Industries served include electronic, semiconductor, medical, automotive and sheet metal.

- **Laser Applications Incorporated** - Certified 5-axis laser cladding services performed with Nd:YAG and CO$_2$ lasers. Engineering assistance with weld joint design is also available. Materials clad include dissimilar materials. Markets served include aerospace, automotive, circuit boards, decorative designs, power generation, medical and petrochemical.

- **Preco Incorporated** - Laser cladding services using high power CO$_2$, Nd:YAG, diode and fiber lasers.

- **Titanova, Incorporated** - Diode laser cladding services.

- **Nuvonyx Incorporated** – Manufacturer of custom high power industrial laser systems for cladding and other applications

- **Alabama Laser** - Laser cutting, cladding, welding, etching/marking, heat treating/hardening, & micromachining services. Custom laser systems, specialized laser research services & process development also available.

- **Stork Technical Services** - Provides turnkey approaches for laser cladding services needed at customer sites. Suitable for complex, high demanding systems which are difficult and expensive to dismantle or to transport.

- **Hardwear Laser Surfacing** – Mobile laser cladding system that can be transported to a site for refurbishment of large components or parts and components which are costly to disassemble and/or transport such as Turbine blades, Valve seats, valve chests, etc.

- **Laser Cladding Technologies** – Laser cladding process based on diode laser technology, patented Tungsten Carbide wear resistant materials and other metallic compositions, that offer superior material deposition solutions which are tailored to meet the extremities of customers’ requirement.