

High-Performance Laser Coatings for Manufacturing and Maintenance of Industrial Components and Equipment

Petri Vuoristo and Jorma Vihinen

Introduction

Laser coating is an advanced coating technology for improving surface properties of various components and equipment. Laser coatings are surface coatings with an extremely dense, crack-free and non-porous structure. Laser coatings show excellent metallurgical bonding to the base material, have uniform composition and coating thickness. Laser coating produces also very low dilution and low heat input to the component.

Laser coating of new components gives them surfaces with high resistance against wear, corrosion and high temperatures. Besides new manufacturing, the process has shown its importance also in maintenance and repair of worn components, often resulting in component performances superior to those of uncoated ones.

Research and development of laser coating processes, properties of coated structures, and industrial applications has been very active during the last years in Finland, primarily due to the rapid development of high power laser technology and recent launching of industrial laser coating activity. Industrial use of laser coatings is expected to increase markedly during the following next years.

High power laser equipment for coating and surface treatment

Several basic properties of lasers make them very useful for a number of industrial applications including laser materials processing. These properties include directionality, monochromaticity, coherence, and high brightness of the laser light. Laser equipment operating with high power levels, i.e. the "high power lasers", can produce highly energetic and well focusable laser beams that are usable in marking, drilling, cutting, welding, hardening and laser coating. **Table 1** presents the characteristics of different type of high power lasers available for materials processing.

Carbon dioxide (CO₂) lasers are the most traditional high power lasers and are available in power levels up to several tens of kW's. CO₂ lasers have characteristics of very high power and power density, moderate efficiency, reliable operation and excellent beam quality (low "beam-parameter-product" number). The high wavelength of 10.6 μm results in a relative low absorption of the laser beam by metals, e.g. steels. It is common that an absorption enhancing pretreatment, such as graphitizing of the metal surface, is frequently needed in surface hardening by a CO₂ laser.

Solid-state lasers, e.g. Nd:YAG lasers, operate at a still lower wavelength (1.06 μm), which markedly improves the absorption characteristics, i.e. the metal surface absorbs now significantly better energy from the Nd:YAG laser beam. However, these lasers operate at significantly lower electrical/optical efficiency, which makes the equipment bulky and costly to run. Fiber coupling of the laser allows the beam to be carried easily through optical fibers from the laser beam supply to the work station.

Table 1. Characteristics of high power lasers for laser materials processing.

Property	Laser type			
	CO ₂	Nd:YAG lamp-pumped	Nd:YAG diode-pumped	HPDL
Wavelength (μm)	10.6	1.06	1.06	0.8 - 0.94
Efficiency (%)	5 - 10	1 - 3	10 - 12	30 - 50
Power (kW), max	40	5	5	6
Average power density (W/cm ²)	10 ^{6...8}	10 ^{5...7}	10 ^{6...9}	10 ^{3...5}
Service period (h)	1000-2000	200	5000-10000	5000-10000
Fiber coupling	No	Yes	Yes	Yes
Beam-parameter-product (mm x mrad)	12	25 - 45	12	100 - 1000

High power diode lasers (HPDL) were introduced fairly recently. These equipment are available at maximum 6 kW power level. HPDL equipment represent the newest generation of high power lasers for materials processing; especially for welding (heat conduction welding), coating and surface treatment, polymer welding, brazing and soldering, etc. The still even lower wavelength (typically 0.8 and 0.94 μm) improves further the absorption characteristics of the laser beam. Due to the very high electrical/optical efficiency (30-50%), HPDL equipment are remarkably smaller in size than other lasers of the same kW level. The poor beam quality (high beam-parameter-product number) is not key factor when using HPDL equipment for laser coating and surface hardening.

Laser coating process

Among all laser materials processing methods, laser surface engineering is still significantly less used than for example laser marking, cutting or welding. Surface engineering by lasers involves primarily transformation hardening of steels, and laser coating, which is also called "laser cladding". Several modifications of laser surface coating and treatment exist. These can be classified as follows:

1. Laser transformation hardening of steels and cast irons
2. Surface modification: remelting (e.g. cast iron), surface alloying, impregnation (e.g. with carbides)
3. Laser coating:
 - 2-step process: remelting of pre-placed or pre-deposited layer (2-step process, melting/alloying); "pre-placed" layer of powder, with/without organic binder
 - 1-step process: laser coating with powder or wire; laser coating with coaxial or off-axis powder nozzles
4. Laser assisted hybrid processes
 - laser surface cleaning with thermal spraying
 - laser assisted thermal spraying; hybrid spraying

Laser transformation hardening is a relatively straightforward process and involves rapid heating of the steel surface to the austenite region, which is then followed by self-quenching to form a martensitic case of high hardness. Laser hardening allows hardening of local well-defined areas, high-intensity local heating and very high self-cooling rates with good hardenability of various ferrous alloys.

Laser coating is an overlay deposition process, where the coating material, a powder or wire, is applied on the surface of the base material through a melting process. **Figure 1** shows the principle of laser coating. **Figure 2 a)** and **b)** show two different laser coating equipment with co-axial and off-axis powder feeding principles, respectively. In laser coating, a fine powder, e.g. 50-150 μm in size, is injected with a carrier gas to the laser beam traversing on the surface of the material or component to be coated.

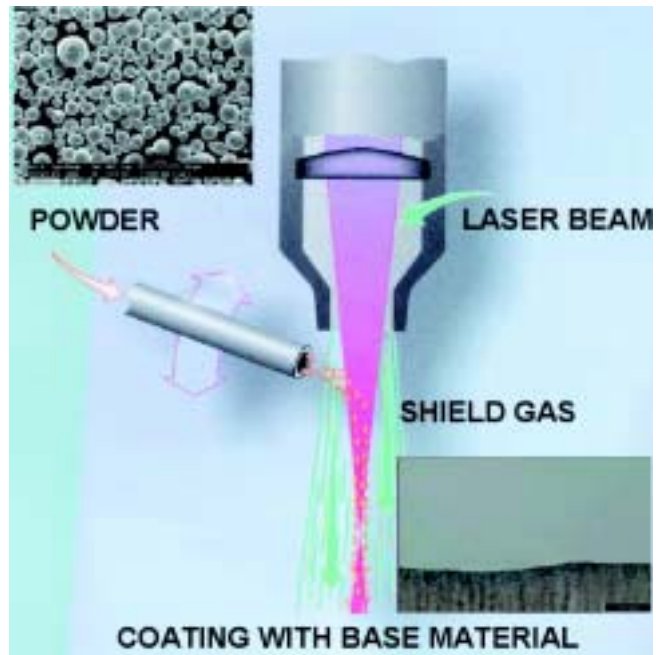


Figure 1. Principle of laser coating.

The powder absorbs energy from the laser beam, starts heating and melting in-flight, and deposits on the surface of the base material. Part of the energy is also absorbed by the surface causing controlled melting of a thin layer of the base material. This ensures formation of a real metallurgical bonding between the coating and the base material. In laser coating a melt pool of the coating material is formed, which in turn results in coatings without porosity. The mixing between the two materials (coating and base material), i.e. dilution, must be as small as possible to utilise the properties of the coating material most effectively.

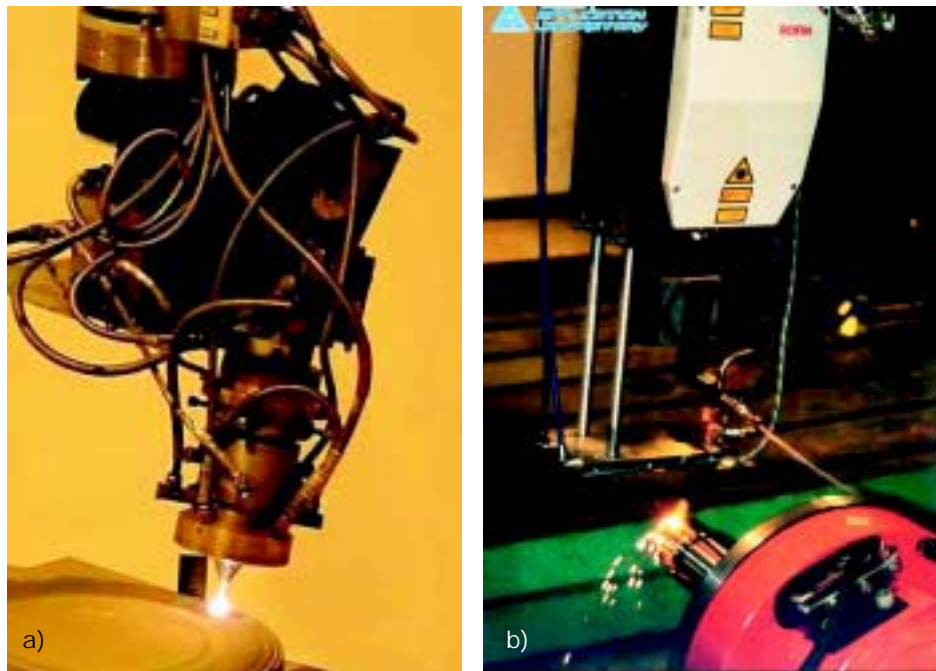


Figure 2. Two types of laser coating processes in operation:
 a) 6 kW CO_2 laser coating with coaxial powder nozzle at Fortum Service Oy Laser Coating Centre, LaserCo KETEK; b) 6 kW diode laser coating process with off-axis powder feeding at Laser Application Laboratory, Tampere University of Technology.

Table 2 compares the characteristics of laser coating with conventional weld surfacing and coating by thermal spraying. It is apparent that such characteristics as:

- high intensity, well focusable and controllable heat source
- excellent coating properties obtained
- low dilution
- minimum changes in base material due to low heat load
- controllable coating thickness
- reasonable productivity and cost make laser coating attractive for industrial coating of new components and in repair.

In laser coating careful control and optimisation of several important parameters and deposition conditions are needed, for example:

- type of laser (CO₂, Nd:YAG, HPDL)
- power level, power density
- beam size, geometry and quality
- working distance
- geometry of powder injection
- surface velocity (m/min)
- feed (mm/r) or step (mm)
- deposition angle
- coating geometry and order
- overlapping, number of layers.
- powder properties - composition, particle size and distribution, impurities
- powder feed rate (g/min)
- surface pretreatment
- pre-heating and temperature during coating
- cooling and post heat-treatment
- post-machining.

Coating materials and properties

Laser coatings can be prepared on several types of base materials. Most commonly the base materials used are unalloyed steels, alloy steels, hardenable steels, stainless steels, nickel or cobalt based alloys. Also various cast irons can be coated successfully by laser process. Laser coating on copper and its alloys, on aluminium alloys and even on titanium alloys have been reported.

Laser coating offers a wide range of possible coating materials. **Table 3** gives an overview of coatings which can be prepared by laser coating. Most commonly used laser coatings are various cobalt base hard alloys, e.g. Stellite 6 and 21, nickel based superalloys, e.g. Inconel 625, self-fluxing alloys, e.g. NiCrBSi, and stainless steels. In order to improve the wear resistance, hard carbide particles, e.g. WC, Cr₃C₂ or TiC, can be added. Also some hardmetals with high carbide contents can be prepared by the laser coating process. Ceramic coatings can also prepared, e.g. Al₂O₃-TiO₂ on aluminium alloys.

Table 3. Examples of coating materials in laser coating.

Metals and alloys:

- Unalloyed and alloy steels
- Self-fluxing alloys (NiBSi, NiCrBSi, etc.)
- Stainless steels (AISI 304, 316, 420, etc.)
- Nickel and nickel based superalloys (Inconel 625, Alloy 59, NiCr, NiCrAl, NiCu, etc.)
- Cobalt alloys (Stellite 6, 12, 21, Triballoys, Ultimet, etc.)
- Copper alloys (Aluminium bronze), light metals

Carbide containing alloys and composites; ceramics:

- WC, Cr₃C₂, TiC, SiC + metal alloys - carbide-metal- blends (max. 50 vol.% carbides)
- Hardmetals WC-Co, Cr₃C₂-NiCr, TiC-Ni/Co, etc. - composites (max 80...90 vol.% carbides)
- Ceramic/metal - composites Al₂O₃/Ni, TiB₂/CrB₂-Ni etc.
- Ceramics Al₂O₃-TiO₂, Al₂O₃-ZrO₂

Figures 3, 4a) and 4b) show examples of laser coatings. **Figure 3** shows an optical micrograph (cross-section) of a high chromium Ni-Cr alloy laser coating prepared by the 6 kW HPDL coating process. The laser beam used was 20 mm wide, the traverse speed 400 m/min and the powder feed rate 100 g/min. By using overlapping, large surfaces can be coating effectively.

Figure 4 presents the microstructures of two different laser coatings; Fig. 4 a) is an SEM micrograph of a microstructurally dense Stellite 21 coating on steel; Fig. 4 b) is NiCrBSi self-fluxing alloy coating containing hard WC particles as reinforce-

Table 2. Comparison of thermal spraying, weld surfacing and laser coating.

Coating process	Thermal spraying	Weld surfacing	Laser cladding
Property			
Heat source	Combustion flame, electric or plasma arc	Combustion flame, electric arc	High intensity laser radiation
Bond strength	Low to moderate*; mechanical bonding	High; metallurgical bonding	High metallurgical bonding
Coating structure	Lamellar; from porous to nearly dense*	Dense; cracks and pores may exist*	Dense; crack and pore-free layers
Heat load to workpiece	Very low to moderate*	Very high	Low to moderate
Dilution	Nil	Moderate to high*	Low
Coating thickness	0.05 – some mm's	Several mm	Typically 0.5 – 3 mm
Coating materials	Wide range of metals, alloys, hardmetal, ceramics, polymers*	Metal and alloys; alloys with hard particles	Metal and alloys; alloys with hard particles; hardmetals; ceramics
Productivity	Low to high	Low to very high	Low to moderate/ (high)*
Cost	Low to high*	Low to moderate	Moderate to high

* depends on the type of process.

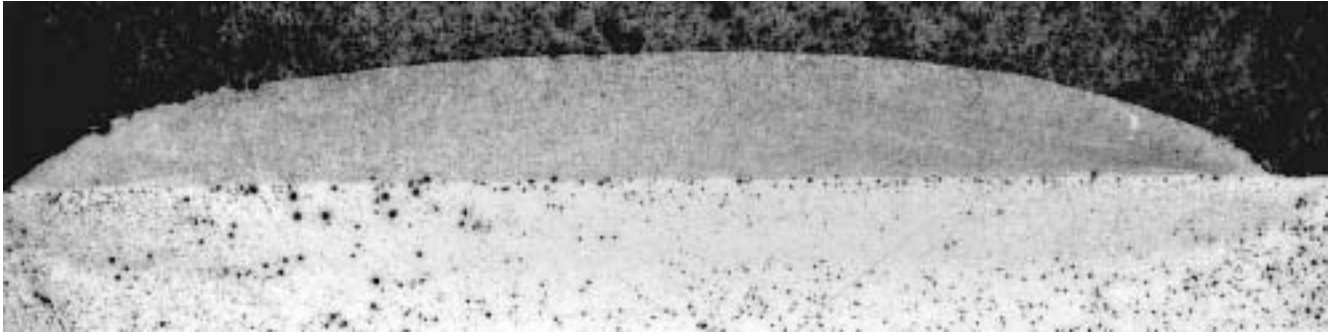


Figure 3. Cross-section of high chromium Ni-Cr alloy laser coating layer 20 mm wide and 2 mm thick. The coating was prepared by 6 kW HPDL system with a powder feed rate of 100 g/min.

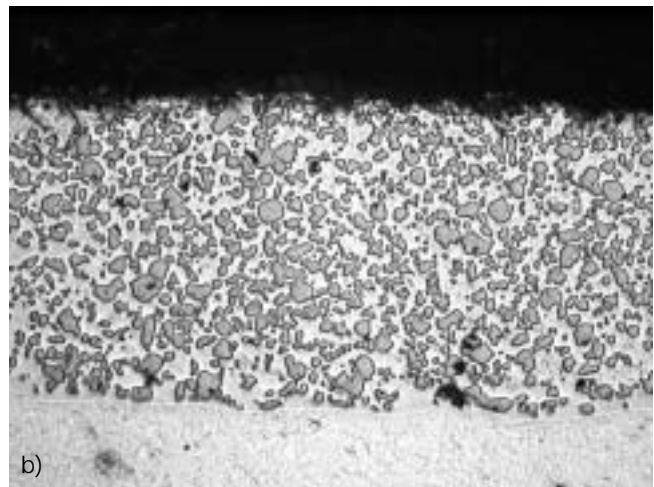
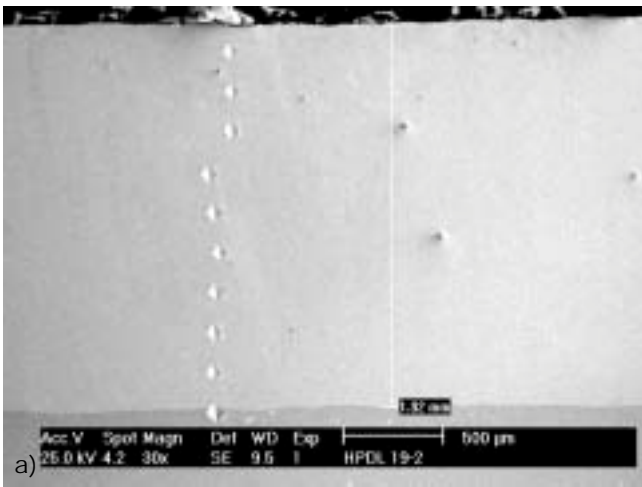


Figure 4. Microstructures of high-quality laser coatings: a) Stellite 21 and b) WC+NiCrBSi.

ment and for improving the wear resistance.

Laser coatings can be regarded as real corrosion barriers, which can protect non-corrosion resistant base materials (steels) from corrosion. Figure 5 compares the corrosion properties of steel Fe 37, wrought nickel base superalloy Inconel 625 (Ni-Cr-Mo alloy) and two Inconel 625 coatings; one prepared by thermal spraying (HVOF – high-velocity oxy-fuel spraying) and the other prepared by laser coating process. The test samples were immersed in 3.5 % NaCl solution (sea water) for several hours simultaneously measuring the potential of the sample versus time.

Fe 37 steel corrodes actively, which can be seen as a change of the potential towards negative values. Wrought Inconel 625 alloy is resistant in these conditions; the potential moves to positive values with time, indicating passive behaviour. HVOF sprayed Inconel 625 coating is not resistant against corrosion in NaCl solution and the corrosion potential tries to follow the curve of the base material Fe 37. However, Inconel 625 laser coating behaves similarly with the corresponding wrought alloy; this indicates a high corrosion resistance of the laser coating.

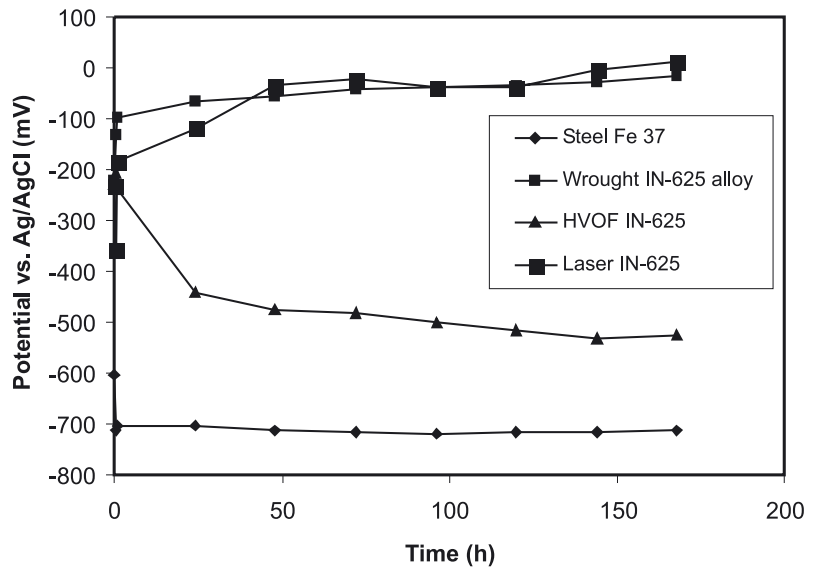


Figure 5. Open circuit potential vs. time for steel Fe 37, HVOF sprayed Inconel 625 coating, Inconel 625 laser coating and wrought Inconel 625 alloy.

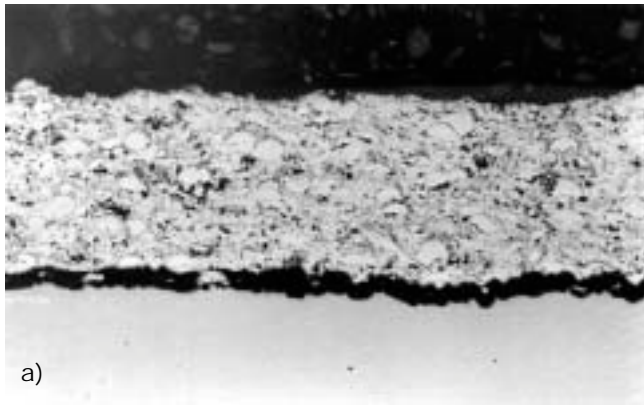


Figure 6. Inconel 625 coatings after corrosion test in 3.5 % NaCl. a) HVOF coating and b) laser coating.



Microstructures of the two Inconel 625 coatings after the sea water immersion test are presented in Fig. 6. The HVOF coating had corroded inside the coating material and in the base material, mainly at the coating/base material interface, see Fig. 6a). Laser coating is still intact and shows no signs of corrosion in the coating or in the underlying steel, Fig. 6b).

Selection of a laser coating can usually be done on basis of the properties of corresponding bulk material. Laser coating powders, laser parameters, and various pre- and post-treatments, e.g. machining, heat-treatments (if needed), need to be optimised for the specific coating and substrate material pair, and for the type of component to be laser coated.

Industrial applications

Laser coating applications include new production, spare part manufacture and as well as maintenance and repair of worn components and equipment. Laser coatings are used to produce surfaces which are resistant against abrasive, erosive and adhesive wear, wet corrosion, high temperature oxidation and corrosion, etc. Typical applications of laser coatings are:

- shafts, rods and seals
- valve parts, sliding valves and discs
- exhaust valves in engines
- cylinders and rolls
- pump components
- turbine components
- wear plates
- sealing joints and joint surfaces
- tools, blades
- moulds

Industrial laser coating was started recently by Fortum Service Oy Laser Coating Centre (Kokkola, Finland). Laser coatings are prepared by using a 6 kW CO₂ laser coating equipment shown in Fig. 7. The powder head is based on coaxial powder feeding principle.

Figures 8 to 12 present some examples of industrial components coated by laser.

A by-pass valve spindle used in power plants is shown in Fig. 8. Several areas of the valve spindle are coated by laser to make the component resistant against high temperature, corrosion and wear.

Figure 9 shows a small and thin-walled (2 mm) tube coated by laser. This example clearly demonstrates the low heat input from the laser coating process to the workpiece. Figure 10 shows laser coating of a large shaft sleeve with a diameter of 1.5 m.

Laser coating repair of a 4.5 m long cooling water (sea water) pump shaft is presented in Fig. 11. In this application, a thermally sprayed (plasma) coating could work only for a very short period; detachment of the sprayed coating occurred

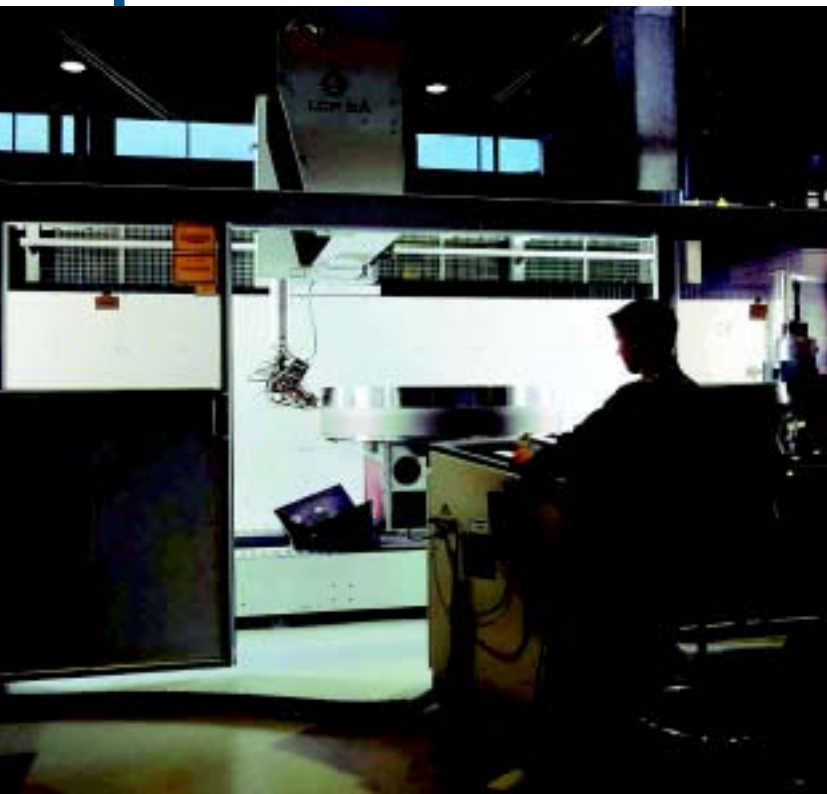


Figure 7. Industrial laser coating cell with 6 kW CO₂ laser at Fortum Service Oy Laser Coating Centre (Kokkola, Finland). Operation dimensions: 4000 x 1000 x 600 mm.

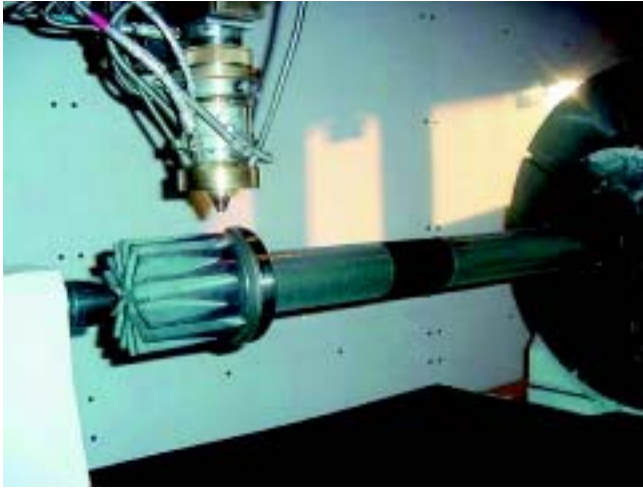


Figure 8. Laser coated by-pass valve spindle.

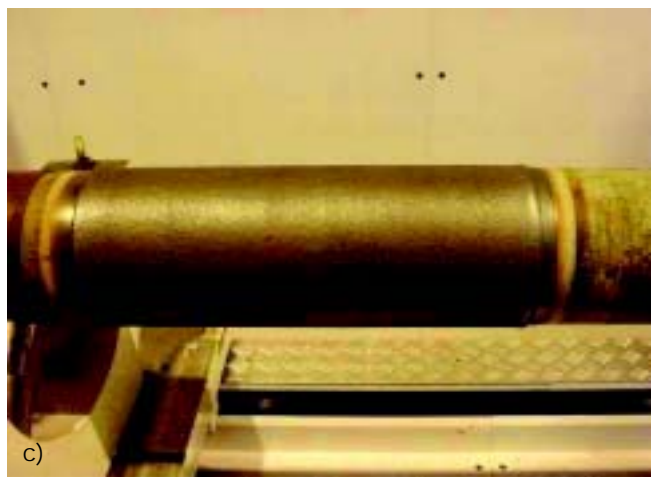


Figure 11. Laser coating of a 4.5 m long cooling water (sea water) pump shaft.
 a) thermally sprayed coating with severe detachment due to heavy corrosion of the coating and the base material beneath the coating,
 b) laser coating of the shaft after removal of the worn surface,
 c) laser coated surface ready for post-finishing by turning.

The shaft was laser coated with a 6 kW CO₂ laser, first with a build-up layer and then with a functional corrosion and wear resistant top coating (Photo: Fortum Service Oy Laser Coating Centre).



Figure 9. Thin walled (2 mm) stainless steel tube with a laser coating (Photo: Fortum Service Oy Laser Coating Centre).

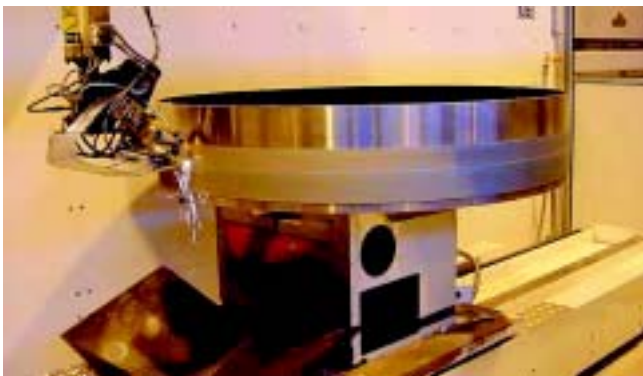


Figure 10. Laser coating of a large shaft sleeve 1.5 m in diameter (Photo: Fortum Service Oy Laser Coating Centre).

after an unexpectedly short time due to heavy corrosion of the coating and the base material beneath the coating. The sprayed coating was not found to be protective in the conditions where the shaft operates. Prior to laser coating, the worn coating was removed by machining. Selected areas of the shaft were then coated with a build-up layer and finally with a functional top layer. No corrosion of the laser coating has occurred so far in this application.

Figure 12 shows a hydraulic piston, which was coated by the HPDL coating process.

The selected industrial application presented here show that laser coatings can be applied on a variety of different components; both on small sized parts as well as on large components.

Laser coating research and development

Laser coating research and development was strengthened recently in Finland when two organisations, Tampere University of Technology (TUT) in Tampere and The Central Ostrobothnia Technology Service Centre KETEK in Kokkola, signed a collaborative agreement. The aim of the joint collaboration is to form a noticeable research unit in the area of laser coating with a sufficient critical size. Laser coating research is lead by a joint professor in surface engineering. Laboratories participating are "Surface Engineering Laboratory" and "Laser Application Laboratory" at TUT and Laser Coating R&D unit "LaserCo" at KETEK. In the following a short presentation of the two laser coating laboratories will be given.



Figure 12. Laser coated hydraulic piston. The piston was laser coated by using a high rate 6 kW HPDL laser coating process with a corrosion resistant coating (Photo: Laser Application Laboratory, Tampere University of Technology).



Figure 13. Overview of the Laser Application Laboratory (LAL, Tampere University of Technology). Two high power lasers (6 kW HPDL, 4 kW Nd:YAG) are used for surface hardening, laser coating and for laser welding research and development. Centre: HPDL with robot; bottom: powder feeder; left: power supply for HPDL; right: Nd:YAG with robot.

Laser Application Laboratory – LAL (Tampere, Finland)

LAL uses two high power lasers for various laser materials processing purposes. A general view of the laboratory is presented in Fig. 13. The lasers are used primarily for surface hardening, laser coating and for some welding R&D. The first high power laser equipment, a 4 kW continuous wave fiber coupled Nd:YAG laser, was installed in 1998. The most advanced high power diode laser, a 6 kW HPDL equipment was installed in 2001. Laboratory LAL acts as a scientific and technical laboratory environment for the joint research and operation at TUT. The most important research topics are laser hardening and coating, both processes especially for large surface areas. The research topics performed at LAL are challenging both from scientific and technological point of views. The main areas of research are divided into the following topics:

- development of HPDL technology for surface engineering applications
- optimisation coating materials and laser processing; off-line simulation of hardening and coating process
- structure and properties of laser clad and hardened surfaces
- mechanisms of laser surface treatments
- diagnostics of laser cladding process
- development of the laser surface treatment (process, equipment, control, laser surface treatment cell, integration into industrial production lines)
- industrial demonstrations and application development
- education and training

LAL has developed an advanced laser coating technology, which is based on using a 6 kW HPDL laser system, an industrial robot, computer controlled powder feeder unit, special powder feeding principles to reach high powder feed rates (e.g. 100 g/min for 20 mm wide beam), fully computer controlled laser cladding process and off-line programming of coating and hardening process.

LaserCo - KETEK (Kokkola, Finland)

LaserCo is also a relatively young laser coating research and development laboratory. The full activity of the laboratory was started from the beginning of this year. The main tasks of LaserCo are as follows:

- research and development of laser coatings, coating process and applications
- publication and distribution of research results in the area of laser coating and other laser processes
- providing measurement, testing and analysis services
- increase the use of lasers in materials processes in the region
- education and training

Authors

Petri Vuoristo, Dr.Tech., Tampere University of Technology (Tampere, Finland) and LaserCo KETEK (Kokkola, Finland), is professor in surface engineering and specialises in metallurgical coatings and coating processes, including laser coating and thermal spraying.

Jorma Vihinen, Lic.Tech., is manager at Laser Application Laboratory of Tampere University of Technology (Tampere, Finland), and specialises in manufacturing technology including laser processes and robotics.