Laser coating and thermal spraying - process basics and coating properties

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The paper describes the some differences of laser coating (laser cladding or laser spraying) process in comparison to thermal spraying. Laser coating is a novel coating process, which produces coatings with high density, metallurgical bonding and low heat input to the substrate. Laser coating types and coating properties are reviewed and compared with thermally sprayed coatings. Typical application areas of laser coatings are presented.

1 Introduction

Laser coating, also referred as “laser cladding” or “laser spraying” (note: in this paper the process is called laser coating), is an advanced coating technology for improving surface properties of various components and equipment. These coatings have extremely dense, crack-free and non-porous microstructures. Laser coatings show also 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 [1-3]. 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 f.ex. 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.

2 Laser coating as a coating process

2.1 High power lasers for surface treatments

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 (CO_2) lasers are the most traditional high power lasers and are available in power levels up to several tens of kilowatts. CO_2 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 laser transformation hardening of steel surfaces by a CO_2 laser.

Tab. 1. High power lasers for laser materials processing.

Property	**Laser type**			
	CO_2	**Nd:YAG, lp**	**Nd:YAG, dp**	**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	4	4	6
Average power density (W/cm^2)	$10^{6\ldots8}$	$10^{5\ldots7}$	$10^{6\ldots9}$	$10^{3\ldots5}$
Service period (h)	2000	200	10000	10000
Fiber coupling	No	Yes	Yes	Yes
Beam-parameter-product (mm x mrad)	12	25-45	12	100-1000

lp – lamp-pumped, dp – diode-pumped

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 (substrate, coating powder) absorbs now significantly better energy from the Nd:YAG laser beam. However, these lasers operate at significanly 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 workstation.

High power diode lasers (HPDL) were introduced 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 energy. Due to the very high electrical/optical efficiency (30-50%), HPDL equipment are remarkably smaller in size than other lasers of the same kilowatt level. The poor beam quality (high beam-parameter-product number) is not key factor when using HPDL equipment for laser coating and surface hardening. The HPDL equipment can be regarded as ideal for laser coating processes.

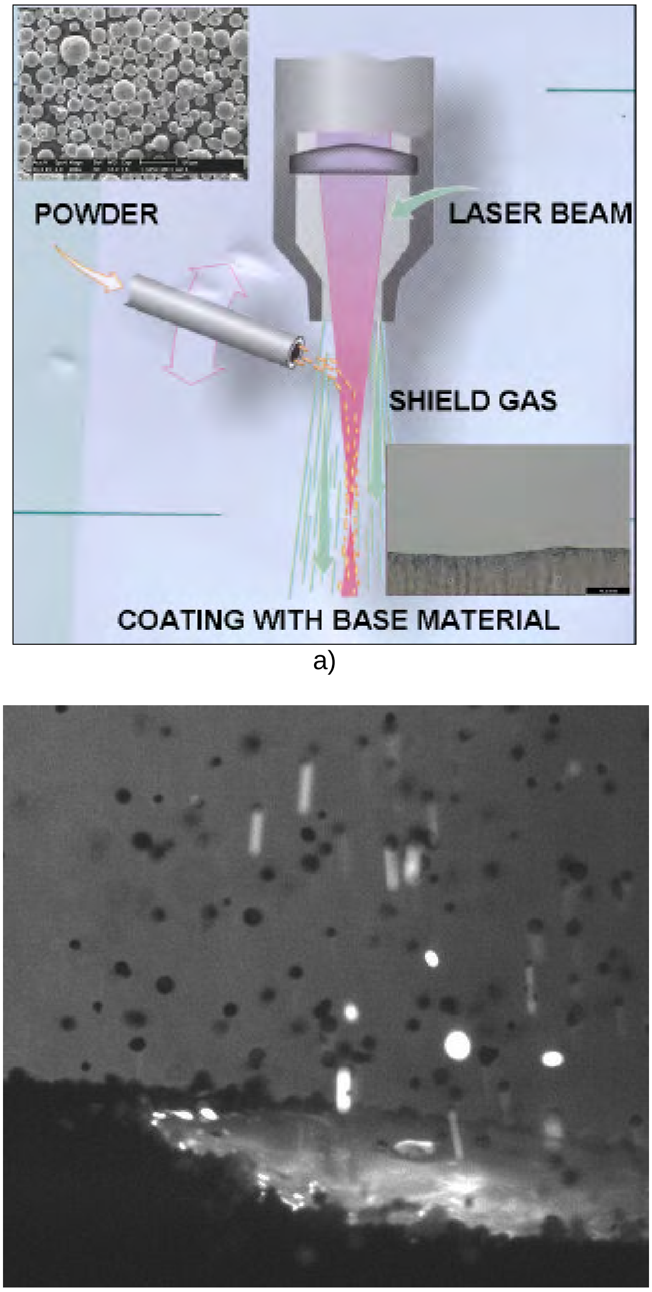
2.2 Laser coating process

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. 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 (laser cladding or laser spraying):
    - 2-step process: remelting of pre-placed or pre-deposited layer; ”pre-placed” layer of powder, with/without organic binder
    - 1-step process: laser coating with powder or wire; laser coating with coaxial/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 a) shows the principle of laser coating. The process has many similarities with thermal spray processes, i.e. the feedstock material (powder) is heated by using a special heat source. In laser coating the energy is received from the laser light, whereas in thermal spray processes the energy source can be a combustion flame (flame spray, HVOF), electric arc (arc spray), or plasma discharge (plasma spray, PTA). In laser coating, a 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. The powder absorbs energy from the laser beam, starts heating and melting in-flight, and deposits on the surface of the base material, see Fig. 1 b). 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.



a)

b)

Fig. 1. Laser coating process: a) schematic presentation, b) visualisation of a real laser coating process with heated powder particles arriving to the melt pool on the surface.

Figure 2 shows a laser coating process with coaxial powder feeding principles. This particular process is based on a 6 kW HPDL equipment (Tampere University of Technology). The special powder nozzle has been recently developed in collaboration between Tampere University of Technology and Fraunhofer Institute for Materials and Beam Technologies (Dresden, Germany). The aim of the work is to increase the use of HPDL equipment in laser coating of highly corrosion and wear resistant coatings.

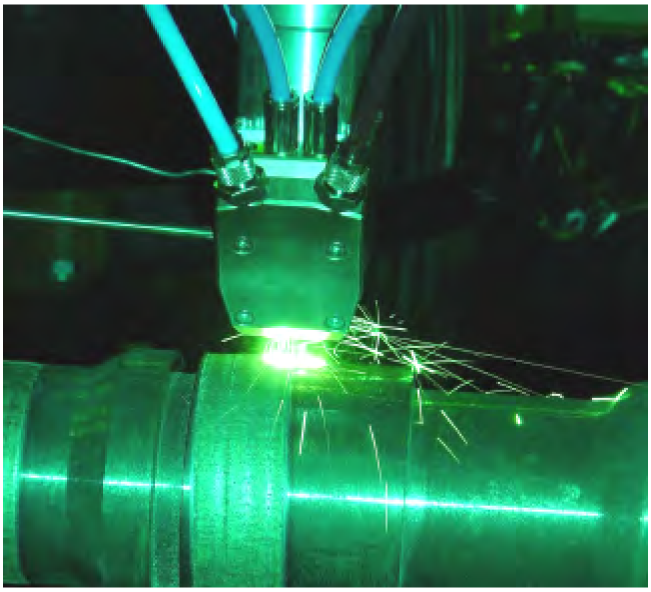


Fig. 2. Laser coating of a rod with 20 mm wide bead and high powder feed rate using a 6 kW high power diode laser (Laser Application Laboratory, Tampere University of Technology).

Table 2 compares the characteristics of laser coating with thermal spraying. It is apparent that such characteristics as:

- high intensity, focusable and controlled heat source
- excellent coating properties obtained
- low dilution (min. 1-5 %)
- minimum changes in base material due to low heat load
- controlled coating thickness
- reasonable productivity and cost

make laser coating attractive for industrial coating of new components and in repair.

Tab. 2. Comparison of thermal spraying and laser coating.

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

* depends on the type of process.

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

- type of laser (CO_2, 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 increment (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

2.3 Laser 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, Cr_3C_2 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. Al_2O_3-TiO_2 on aluminium alloys.

Tab. 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.)
Cobal alloys (Stellite 6, 12, 21, Triballoys, Ultimet, etc.)
Copper alloys (Aluminium bronze), light metals

Carbide containing alloys and composites; ceramics:
WC, Cr_3C_2, TiC, SiC + metal alloys – carbide-metal-blends (max. 50 vol.% carbides)
Hardmetals WC-Co, Cr_3C_2-NiCr, TiC-Ni/Co, etc. - composites (max 80...90 vol.% carbides)
Ceramic/metal – composites Al_2O_3/Ni, TiB_2/CrB_2-Ni etc.
Ceramics Al_2O_3-TiO_2, Al_2O_3-ZrO_2

Figures 3, 4a) and b) 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 coated effectively. The powder feed rates obtained with the novel HPDL process are approaching some thermal spray processes. The high powder feed rates with high deposition efficiencies are together with the investment costs such key factors, which can make laser coating to enter some industrial application areas of thermal spray coatings.

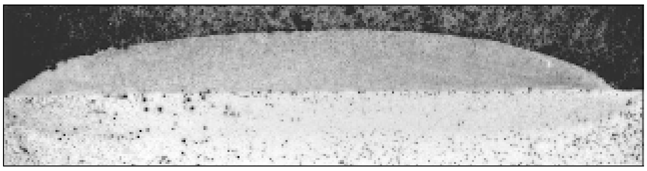
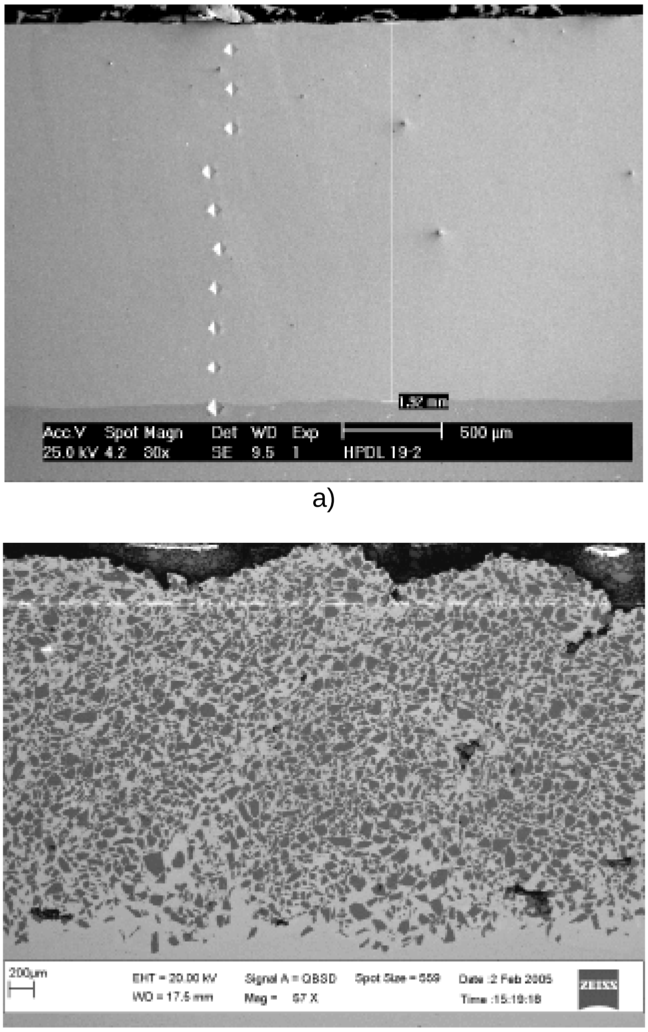


Fig 3. Cross-section of high chromium Ni-Cr alloy laser coating layer 20 mm wide and 2 mm thick. The coating was prepared by 6 kW HPDL system with a powder feed rate of 100 g/min.

Figure 4 presents the microstructures of two different laser coatings; Figure 4 a) is an SEM micrograph of a microstructurally dense HPDL deposited Stellite 21 coating on steel; Figure 4 b) is a dp-Nd:YAG laser deposited tool steel M2 coating coating containing a high volume percentage (80 vol.%) of hard TiC particles as reinforcement 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 [4,5]. 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 spraying) and the other prepared by laser coating. The test samples were immersed in 3.5% NaCl solution (sea water) for several hours with simultaneous measuring of the free potential of the sample surface.

Fe 37 steel corrodes actively, which can be seen as a change of the potential towards very 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 due to exiting through porosity 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. Microstructures of the two Inconel 625 coatings after the sea water immersion test are presented in Figures 6 and 7. The HVOF coating had corroded inside the coating material and in the base material, mainly at the coating/base material interface, see Figure 6. Laser coating is still intact and shows no signs of corrosion in the coating or in the underlaying steel, Figure 7.



a)

b)

Fig. 4. Microstructures of high-quality laser coatings (SEM micrographs): a) Stellite 21 and b) tool steel M2+ 80vol%TiC.

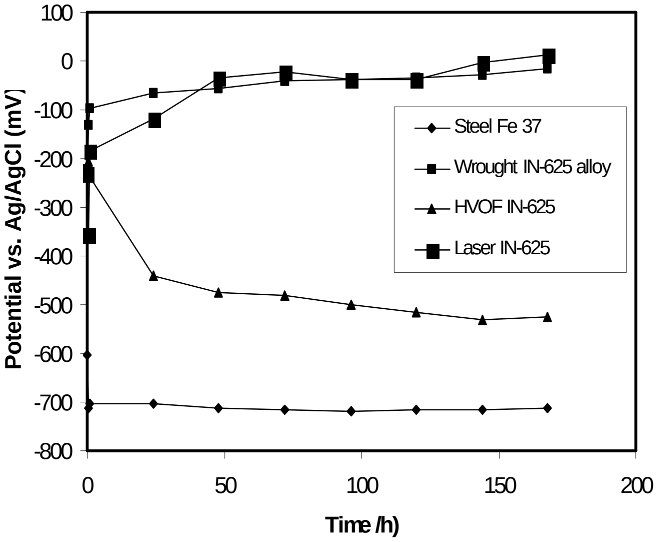


Figure 5. Open circuit potential vs. time for steel Fe 37, HVOF sprayed Inconel 625 coating, Inconel 625 laser coating and wrought Inconel 625 alloy.

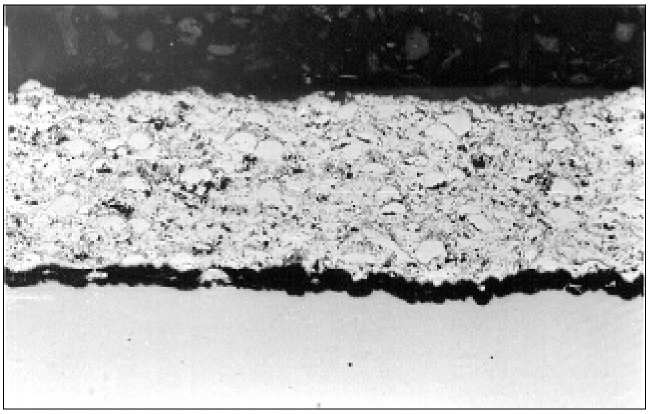
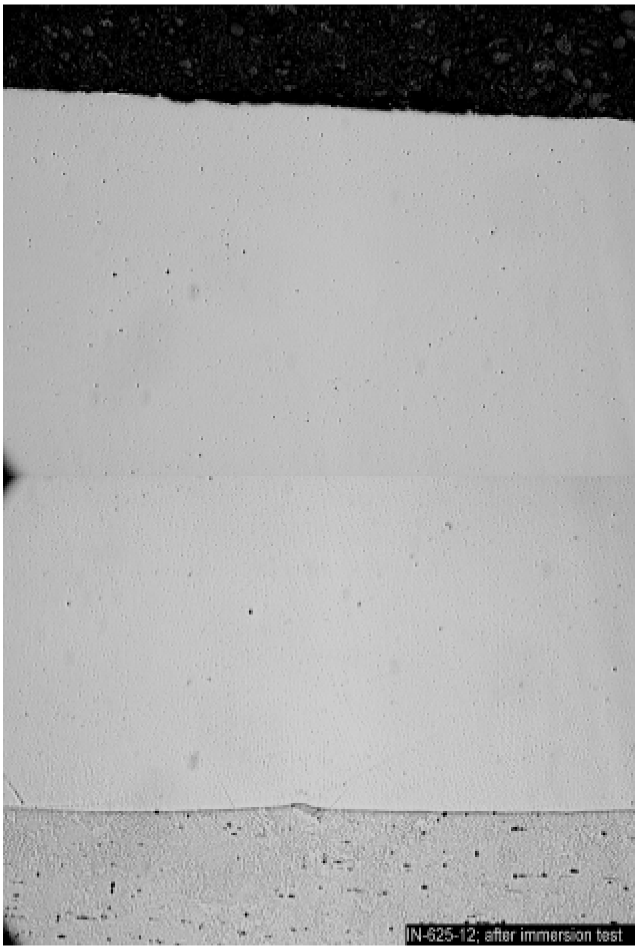


Figure 6. HVOF sprayed Inconel 625 coatings after corrosion test in 3.5% NaCl. The coating has been corrodes by chloride ions; also the substrate is corroded due to penetration of the electrolyte.



b)

Figure 7. Laser coated Inconel 625 coating after corrosion test in 3.5% NaCl. The coating hows no signs of internal corrosion of the coating itself; also the less corrosion resistant steel substrate remains unaffected.

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

3 Industrial applications of laser coatings

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 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 operation is usually based on high power CO_2 laser, which are regarded as reliable equipment. Also newer laser types, such as Nd:YAG lasers and HPDL systems, have been taken to industrial use recently. An example of an industrial laser coating workstation is shown in Figure 8. This system is based on a 6 kW CO_2 laser. The powder head is based on a coaxial powder feeding principle.

Figure 8. Industrial laser coating cell with 6 kW CO_2 laser (Kokkola LCC Oy, Finland).

Figures 9 to 13 present some examples of industrial components coated by laser. A by-pass valve spindle used in power plants is shown in Figure 9. Several areas of the valve spindle are coated by laser to make the component resistant against high temperature, corrosion and wear. The component was originally uncoated, but after laser coating the performance and lifetime was significantly improved from the original uncoated one. Figure 10 in shows laser coating of a large shaft sleeve with a diameter of 1.5 m. Such relatively large surfaces can also be economically coated by laser.

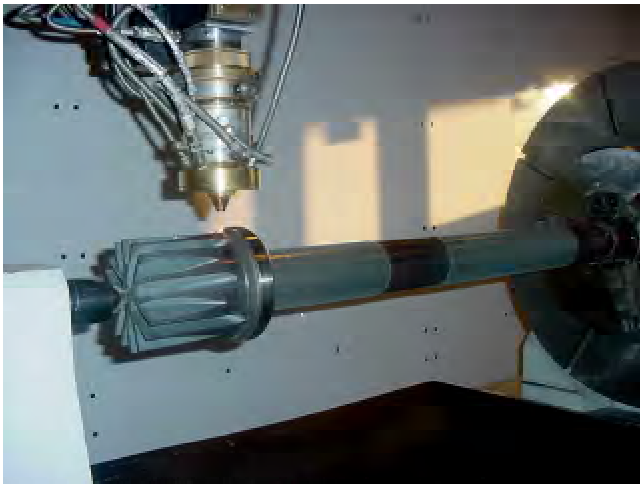


Fig. 9. Laser coated by-pass valve spindle.

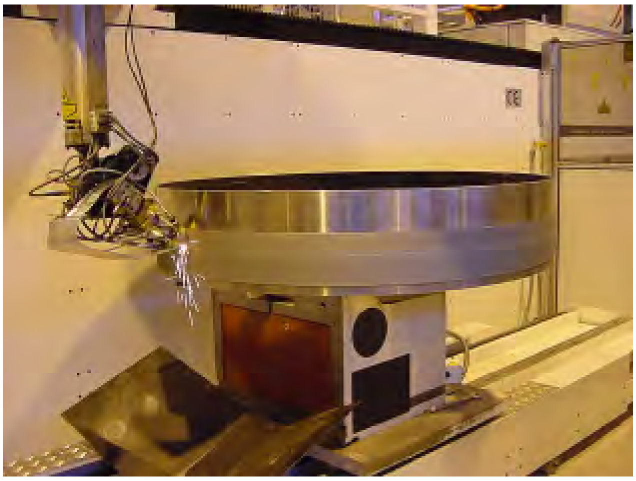
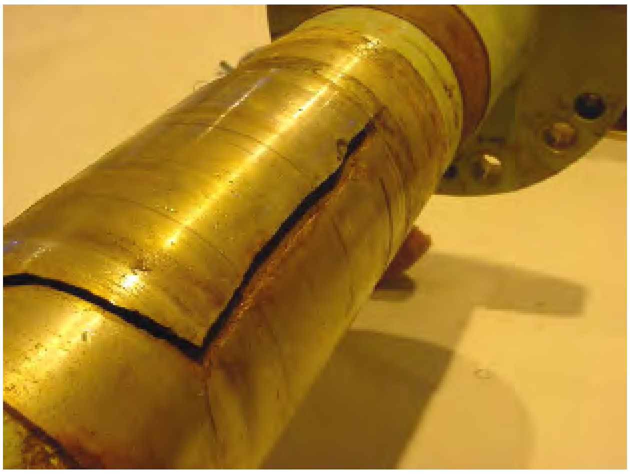
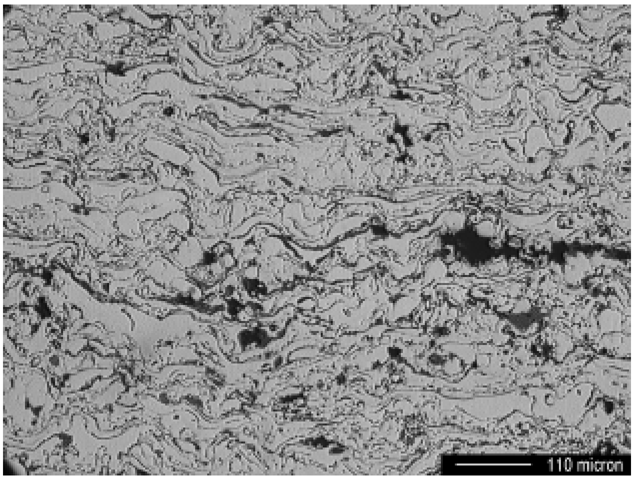


Fig. 10. Laser coating of a large shaft sleeve 1.5 m in diameter.

Laser coating repair of a 4.5 m long cooling water (sea water) pump shaft used in a nuclear power plant is presented in Figures 11 a) – d). This is an example in which a plasma sprayed coating did not work satisfactorily but in which a laser coating gives a working solution and a significant lifetime improvement for an important component of a nuclear power plant.

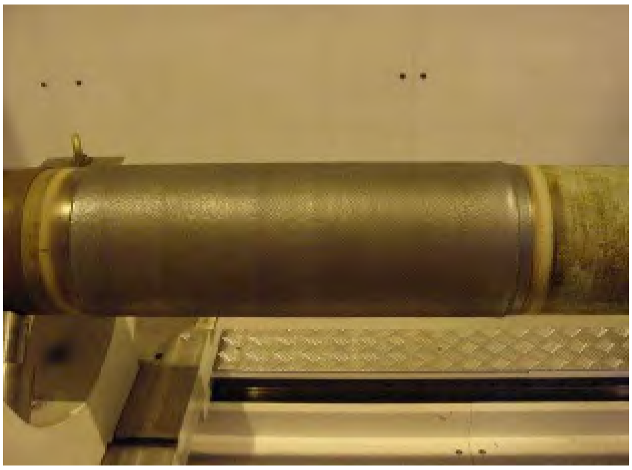


a)



b)

c)



d)

Fig. 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) microstructure of the plasma spray coating with insufficient corrosion resistance, c) laser coating of the shaft after removal of the worn surface, d) laser coated surface ready for post-finishing by turning. The shaft was laser coated with a 6 kW CO_2 laser first with a build-up layer and then with a functional corrosion and wear resistant top coating

The plasma sprayed corrosion resistant metallic coating could work only for a very short period (some months); detachment of the sprayed coating occured 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. A micrograph of the plasma sprayed coating is presented in Figure 11 c). It is obvious that sea water is too corrosive to such an inhomogeneous coating and better resistant coating should be used.

Prior to laser coating, the worn plasma sprayed 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 and several shafts have now been laser coated instead of using plasma spray coatings in this application. In case of such large components it is evident that the normally higher cost of laser coatings is counterweighted by the markedly better performance and increased lifetime of the critical components.

Figure 12 shows a hydraulic rod, which was coated by the HPDL coating process. In this application the previously used thermally sprayed coatings, including HVOF coatings, suffered from corrosion by aggressive chemicals. A highly corrosion resistant nickel based alloy was selected to the application for the coating material. Standard solution is now a laser coating prepared by CO_2 laser coating process. However, the novel HPDL coating process is highly interesting because of 3-5 times faster laser coating speed [6].

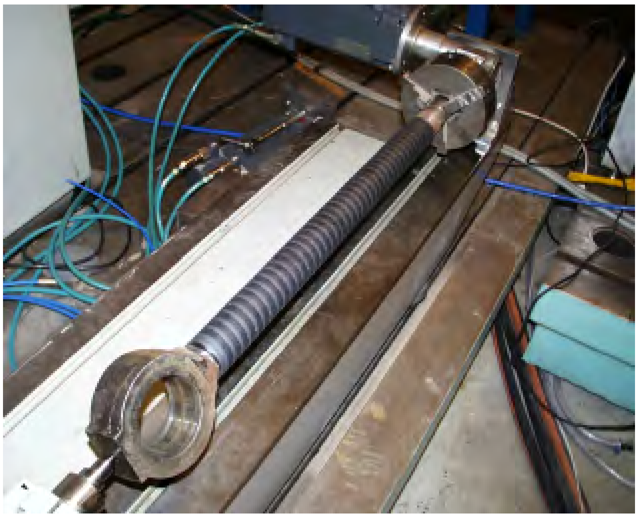


Fig. 12. Laser coated hydraulic rod. The piston was laser coated by using a high rate 6 kW HPDL laser coating process with a highly corrosion resistant coating.

Figure 13 presents a laser coated sleeve, which has a proprietary „*Resistant*“ two-component coating with superior corrosion resistivity in concentrated phosphoric acid environments. Conventional thermal sprayed coatings normally showed lifetimes varying from some hours to some months, whereas the new laser coating is known to be in a good condition even after two years of operation. The new coating consists of elements with high wear resistance and a highly alloyed metallic alloy for providing corrosion resistance.

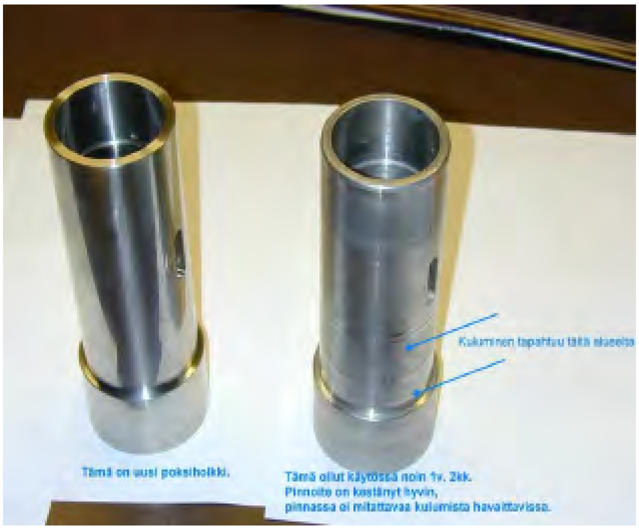


Fig. 13. Laser coated sleeve for highly corrosive 80% phosphous acid application. Left: unused laser coated sleeve; right: laser coated sleeve after 1 year and 2 months of operation.

The selected industrial application presented here show that laser coatings can be applied on a variety of different components. It is evident that in some cases laser coating has given a coating solution to such applications in which even state-off-the-art thermal sprayed coatings can not perform satisfactorily. In general, the application areas of thermal sprayed and laser coatings do not significantly overlap. However such overlapping applications exist and in these cases the laser coatings can be used if the somewhat higher cost level is balanced by the outstanding coating performance and increased component lifetime. An interesting thing will be also the possibility of the novel laser types with their higher production rates to increase the use of laser coatings in general. Also other factors such as taking laser coatings into more active standardisation processes may also increase the use of laser coatings in the near future.

4 Conclusions

The aim of the present paper was to describe briefly the basic differences of laser coating (also called laser cladding or laser spraying) process and thermal spraying, and to highlight the potentials of laser coatings and the laser coating processes. Laser coating is a novel coating process, which produces coatings with high density, metallurgical bonding and low heat input to the substrate. Laser coating types and coating properties were reviewed. Corrosion properties of laser coatings were then compared with thermally sprayed coatings. Main benefits of laser coatings are their significantly improved corrosion properties and coating adhesion Typical application areas of laser coatings were also presented.

5 Acknowledgements

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