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Laser Beam Cladding: A Flexible Tool for Local Surface Treatment and Repair

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The versatility of the laser beam cladding process as a means of localized surface treatment is highlighted in this article with an emphasis on applications in the field of repair and regeneration. A newly developed cladding technology using low power Nd:YAG lasers is also introduced. Small dimensions and minimal heat input allow high precision cladding. Short interaction times and good control of the process enable the generation of graded composite coatings. Application examples in the field of regeneration of components are given. An industrial case study presents the CO_2 laser repair of large engine components.

Keywords CO_2 laser, graded layers, gradient materials, hard facing, laser beam cladding, Nd:YAG laser, precision cladding, regeneration, repair

1. Introduction

Conventional materials and surface treatments often fail to meet the increasing demands of today's engineering components. In order to find new engineering solutions, research has been conducted in the field of laser surface treatment. In surface engineering, laser beams are being used as a high intensity heat source for hardening, alloying, and cladding (Ref 1-3). Characteristic features of the laser processes are high localized heating and cooling rates, short interaction times, and a very low overall heat input. Laser beam cladding has mainly been applied on steel substrates utilizing multikilowatt CO_2 lasers and conventional hardfacing powder materials such as NiCrBSi, Stellite, and WC/Co. More recently a wider range of materials has successfully been clad, for example, oxide ceramics on steel and aluminum substrates and composite claddings containing diamonds and other hard particles sensitive to heat damage (Ref 4-6). The latter was possible with the use of solid state Nd:YAG lasers that allow improved control of the cladding process at low intensities.

In laser beam cladding, powder is either predeposited, or more commonly, fed continuously into a melt pool on the surface of the substrate. The melt pool is generated and maintained through an interaction with the laser beam; it forms a clad track after solidification, as the substrate is scanned relative to the beam (Fig. 1a). A cladding is produced from single tracks, laid side by side by means of oscillating or straight rows (Fig. 1b). The surface of the substrate is melted to a certain extent (in the micrometer range), to obtain metallurgical bonding between the substrate and cladding material. The dilution, A, of the cladding with substrate material is given by the area ratio $A = A_2/(A_1 + A_2)$, which can be measured in the cross section (Fig. 1b). In order to retain the properties of the cladding material, dilution is often kept below 5%.

The development of a cladding strategy for a given component must cover all requirements concerning the cladding suitability of the materials, the cladding possibility of the process, and the service requirements of the construction (Ref 7). In the case of regeneration and repair of technical components, the construction with its service requirements and the substrate material are given, limiting the choice of suitable cladding material and process parameters.

Large area surface cladding and coating is widely applied in industry using either welding or thermal spray techniques. In this field, despite its noticeable technological advantages, the laser cladding process suffers from the disadvantage of being

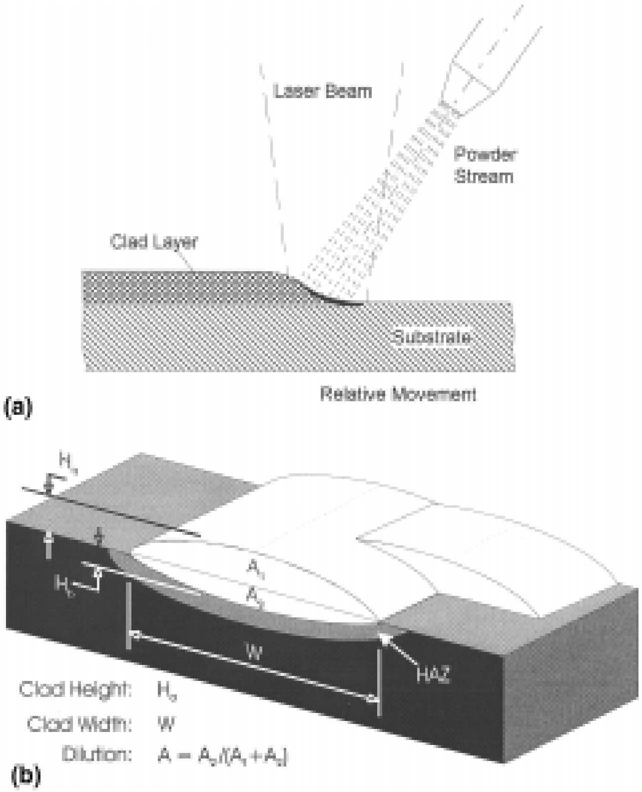

Fig. 1 (a) Principle of the powder-fed laser beam cladding process. (b) Geometrical parameters of the cladding

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comparatively slow and cost intensive and hence, often uneconomic (Ref 8). There is, however, a certain market where conventional processes cannot be successfully applied because of technological shortcomings. Moreover, if cladding is only required locally on a component (such as in repair and recovery of components), the laser process may be economically competitive.

In this article, the precision cladding technique is introduced, and application examples are given for both Nd:YAG and CO_2 laser cladding.

2. Precision Cladding Using Nd:YAG Lasers

2.1 *Experimental Setup*

The principle of precision powder-fed cladding using Nd:YAG lasers is similar to that known from the CO_2 laser process. Differences arise due to changing process conditions as a result of the shorter wavelength of Nd:YAG laser radiation (1.064 μm) compared to CO_2 lasers (10.6 μm). For metals, the absorption of laser energy is higher at shorter wavelengths (Ref 9), thus the process efficiency is higher with the Nd:YAG laser. Furthermore, the radiation from a Nd:YAG laser can be delivered through an optical fiber, allowing a simplified beam guiding system and providing a higher degree of flexibility when cladding three-dimensional contours with a robot.

The processing head consists of the focusing system, a cross jet, and the powder nozzle with its adapter (Fig. 2). These components are accommodated and positioned by the focusing head. The diverging laser beam is first collimated and then focused by different lenses. Protective glass and a cross jet prevents contamination of the lenses. An exhaust system must be applied to remove any powder and dust from the air.

For metering and feeding of the powder, a commercially available pneumatic powder feeder is applicable, although for a number of applications it may have to be modified to enable powder feed rates as low as 1 g/min. It is important to maintain a continuous powder stream free of pulsing. Furthermore, a stream of gas flowing coaxially with the powder stream shields the melt pool from the ambient atmosphere.

For precision cladding, low power cw-Nd:YAG-lasers operating at powers in the range of 150 to 500 W were used. This allowed working very close to the focus point (i.e., at a distance, z_f, of only 0.5 to 2.5 mm between the focus point and the surface of the substrate). Power densities (10^8 to 10^{10} W/m^2) are below the threshold of plasma formation. Fine clad tracks with a height of less than 100 to 300 μm and a width of 300 to 600 μm were obtained. Fine microstructures result from extremely short interaction times (4 to 80 ms) at scan velocities of 10 to 100 mm/s, one order of magnitude higher than normally applied in laser beam cladding.

2.2 *Influences on the Cladding Results*

The geometry of the cladding and the dilution, beside microstructural features, are essential quality aspects. Both are mainly influenced by processing parameters such as laser power, powder feed rate, track overlap, and scan velocity of the laser relative to the workpiece.

The height of the cladding depends mainly on the heat input, most appropriately described by the line energy, which is defined as the quotient of laser power and the scan velocity (Fig. 3a). The clad width is determined predominantly by the focal position, that is, by the width of the laser beam (Fig. 3b). The unavoidable dilution of filler material with melted base material (necessary for the metallurgical bonding) affects the properties of the cladding, such as hardness and corrosion behavior. Dilution can be kept low by balancing line energy and powder feed rate to achieve a high quality cladding. As an example, Fig. 4 illustrates the changes of the hardness profiles for different degrees of dilution.

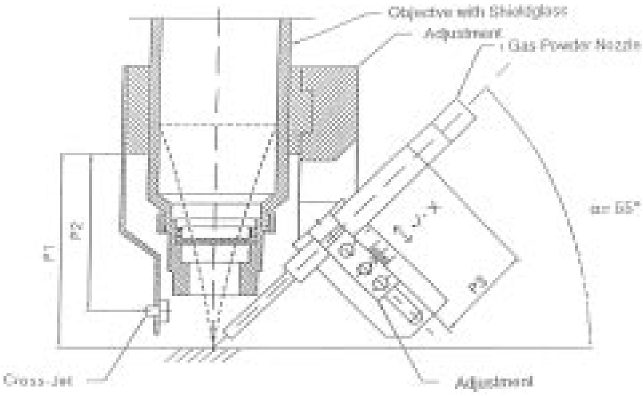


Fig. 2 Processing head for precision powder-fed cladding (schematic)

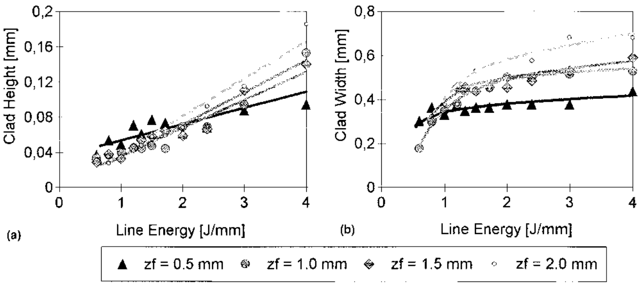


Fig. 3 Effect of line energy and focal position on (a) clad height and (b) clad width for precision cladding of NiCrBSi on mild steel

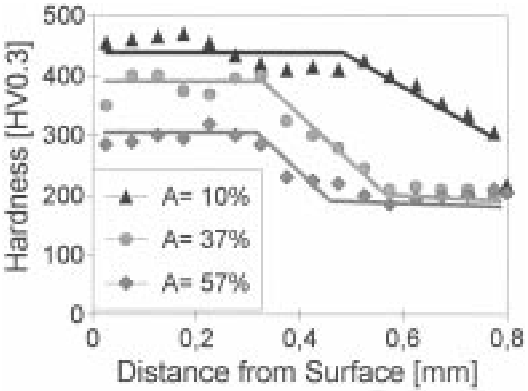
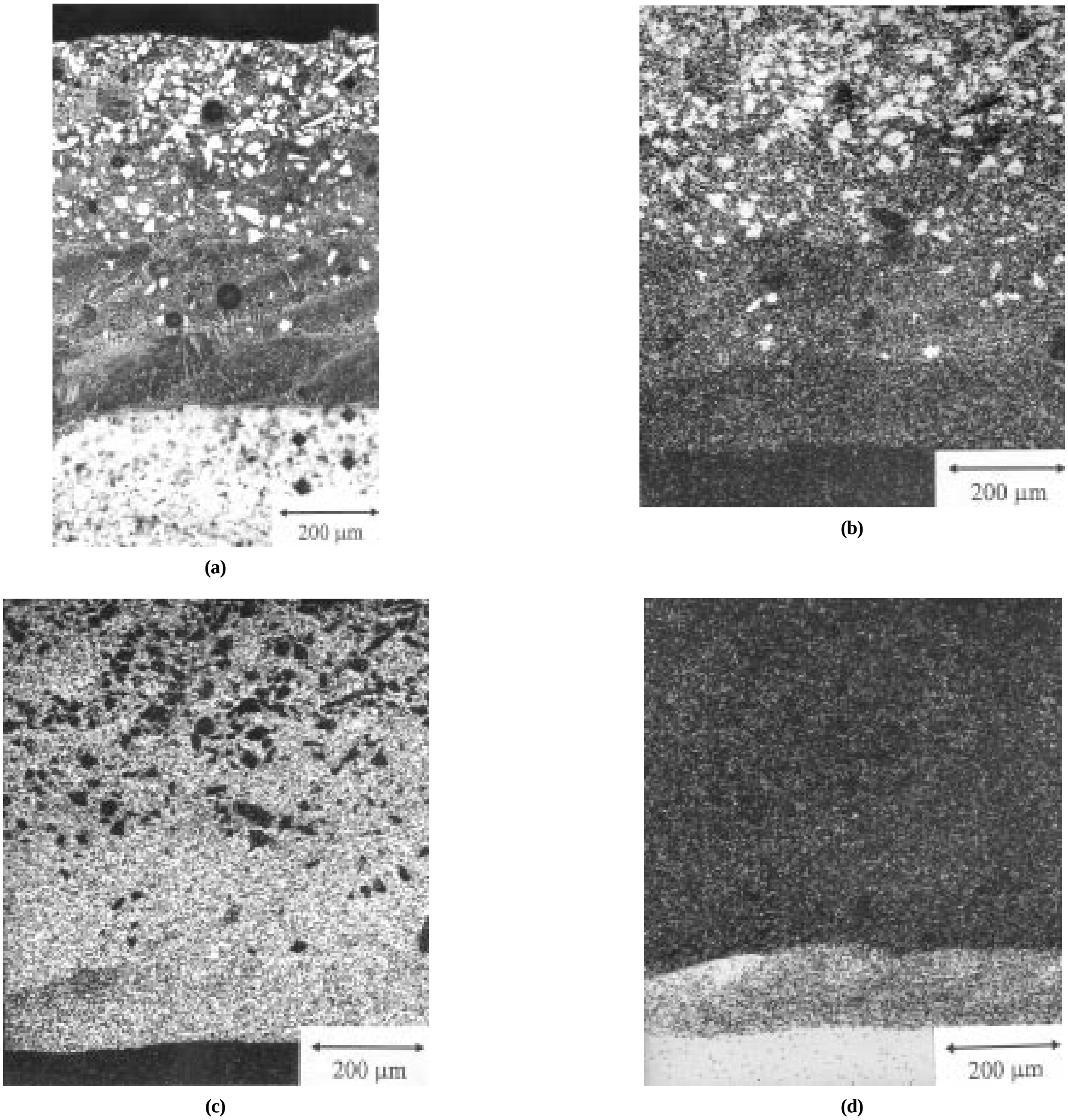


Fig. 4 Hardness profiles for different degrees of dilution, *A*, for precision cladding of NiCrBSi on mild steel

2.3 Deposition of Graded Layers Using Nd:YAG Lasers

For both load bearing thermal protective systems and wear resistant coatings, ceramic and cemented carbide type coatings are used. The goal of graded layer coatings is to overcome the stress-related failure of composite coatings at the interface that results from a sharp contrast of properties, such as thermal expansion behavior. Therefore, efforts have been made to generate functionally gradient materials (FGMs) and graded coating systems, particularly in the field of thermal spray (Ref 10, 11). By the laser process, thin graded, three-layer claddings were obtained using predeposited powder, thereby suppressing Marangoni effects and controlling melt pool convection mainly through buoyancy forces (Ref 12). When aiming to clad multiple layers with increasing content of the nonmetallic component, however, the powder-fed laser process has been reported to have shortcomings concerning distribution and dissolution of carbide particles (Ref 13).

In this study, four layer claddings of NiCrBSi alloy with increasing content of Cr_3C_2 (0, 10, 30, and 50 vol%) were produced on a steel substrate using the powder-feed process. Each layer was approximately 0.2 mm thick. Line energy was varied in the range of 7 to 13 J/mm to compensate for the effect of compositional changes. In the cross section of the claddings (Fig. 5a), the increase of carbide content toward the surface is evident. The carbide distribution is very promising, that is, homogeneous within each layer. Moreover, it appears that thermal damage to



(a)

(b)

(c)

(d)

Fig. 5 Cross section of graded four layer cladding of NiCrBSi with Cr_3C_2 (0, 10, 30, and 50 vol%). (a) Light microscope view, etched in HNO_3/HF. (b) Chromium concentration map. (c) Nickel concentration map. (d) Iron concentration map (and the degree of dissolution of) the carbides was kept low. Furthermore, the structure of the underlying layers remained unaffected by the thermal load of multiple cladding. Area maps of the element concentration obtained from qualitative energy dispersive x-ray (EDX) analysis supported this finding (Fig. 5b-d). The corresponding concentration profiles (Fig. 6) perpendicular to the surface revealed the desired increase of chromium content toward the surface, whereas the content of nickel (representing the matrix alloy) decreased accordingly. Only the first layer was to some extent diluted with iron, but its concentration was negligible in the outer three layers.

The hardness of the carbide particles, measured at a load of 50 g, was between 2100 and 2300 HV 0.05. The matrix alloy, by contrast, was found to be in the range of 370 to 550 HV 0.05. The hardness of the matrix alloy was not affected significantly by the carbide content of the layer, although it may be reduced slightly when tempered by the heat of the subsequent layer. At a load of 300 g, a larger volume of material is affected, hence, an average hardness number for both carbide particles and matrix alloy was measured. The measured hardness profile reflected the increase of carbide particle content toward the surface where the maximum hardness exceeded 800 HV 0.3 (Fig. 7).

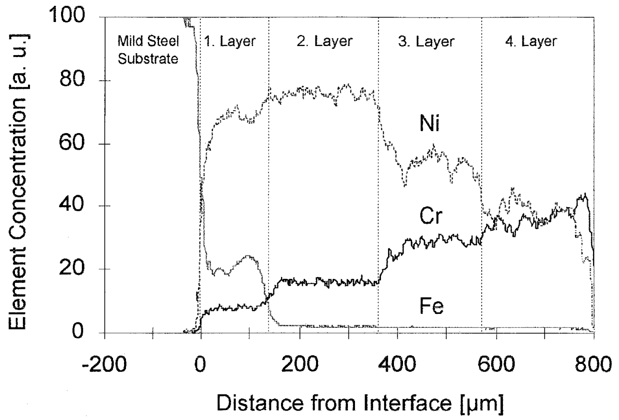


Fig. 6 Concentration profiles of graded cladding (NiCrBSi with Cr_3C_2)

The surface roughness was typically $R_{Z,ISO}$ = 10 µm for single layer claddings of NiCrBSi. Because the chromium carbides had a particle size 10 to 45 µm, an increase of the roughness to $R_{Z,ISO}$ = 30 to 35 µm could not be avoided for the graded 0.8 mm layers.

Although some porosity was present, it was concluded that the precision laser beam cladding process using low power Nd:YAG lasers was well suited for the generation of graded metal/carbide layers. The process characteristics (small melt pool dimensions, short interaction times, and low heat input) maintained reasonable carbide particle distribution and low dissolution.

2.4 Freeform Shapes

Components and tools often have to be modified by adding material to meet changing service requirements or extend service life. In rapid prototyping and tooling, there is a strong demand for versatile processes that enable the direct generation of near net-shape metallic components. Simple cylinders with a

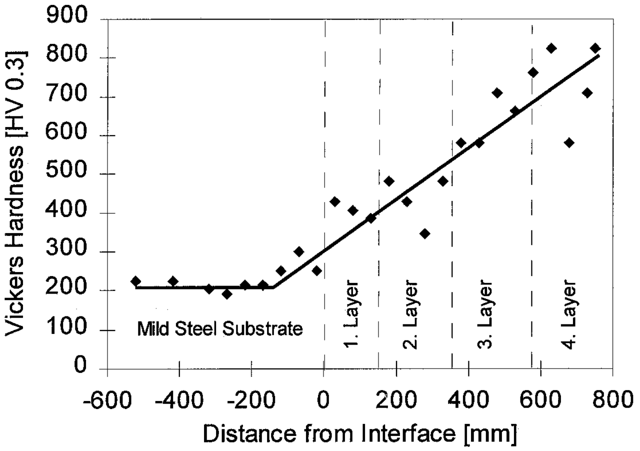


Fig. 7 Hardness profile of graded cladding (NiCrBSi with Cr_3C_2)

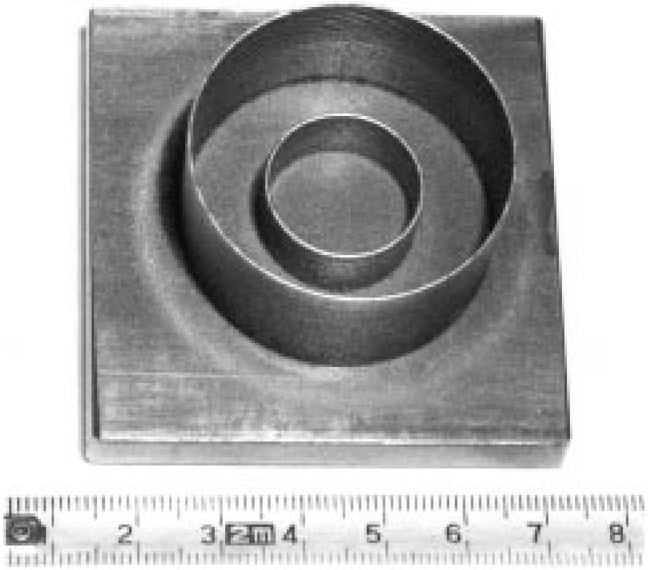


Fig. 8 Example of freeform shape of Stellite produced by laser cladding

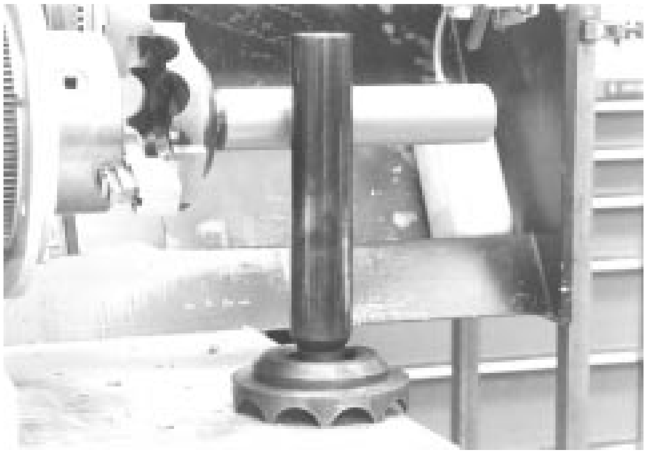


Fig. 9 Repaired and worn (standing) plungers (base material 31CrMo12, cladding material NiCrBSi)

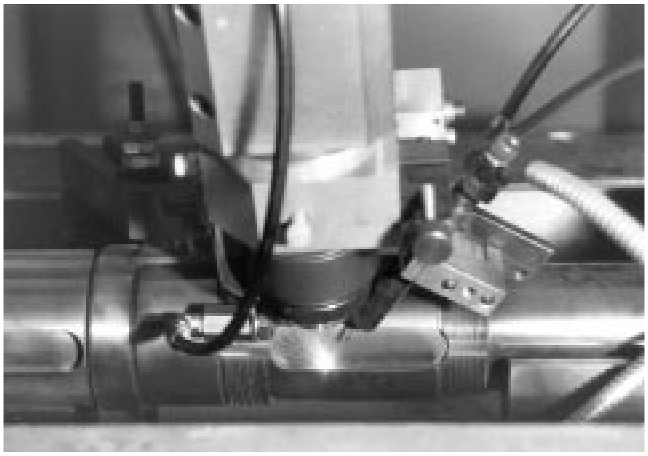


Fig. 10 Precision laser beam cladding of oversized groove in a finished shaft (base material 0.45% carbon steel, cladding Stellite material)

uniform wall thickness of only 0.7 mm were built up from a Stellite alloy (Deloro Stellite, Inc., St. Louis, MO) to demonstrate the potential of precision laser beam cladding for the production of freeform shapes (Fig. 8).

2.5 Application Example: Repair of Plungers

Pump plungers of a large diesel engine fuel injection system have to be replaced when worn by hard particles scoring the surface. These plungers cannot yet be repaired because neither welding nor thermal spraying techniques have met the service requirements. Due to the low heat input, precision laser cladding using Nd:YAG lasers enabled the deposition of a NiCrBSi hardfacing alloy of the desired thickness (approximately 100 μm), leaving the steel substrate (31CrMo12) virtually unaffected. The cladding was metallurgically bonded to the substrate; it was pore and crack free and well suited to withstand corrosive and abrasive environments. Figure 9 shows a worn and a repaired plunger.

2.6 Application Example: Repair of Mismachined Components

During different manufacturing steps, deviations from specified dimensions of components, for example, caused by mismachining, often occur. If these faults occur as undesired loss of material in the later stages of production, they frequently cannot be repaired by means of conventional filler welding because the heat input would lead to unacceptable distortion. Correction of these faults is desirable, especially for small-lot and single-part production, when high costs have already been incurred. For this application, the precision powder-fed cladding using Nd:YAG-lasers with the possibility of cladding precisely (that is, locally limited with cladding heights down to 100 μm) and with a very low heat input offers a promising basis for the recovery of components previously classified as scrap.

Figure 10 shows an example of a cladding of an oversized groove in a finished shaft made from a 0.45% carbon steel. It was possible to recover the shaft by precision powder-fed cladding using a Stellite filler alloy. After cladding, no deformations were measured, and no considerable reworking was necessary.

3. Industrial Case Study: Repair of Diesel Engine Components Using CO_2 Lasers

The low power Nd:YAG laser is a suitable tool for localized precision cladding with minimal heat input. There are, however, limitations in processing speed, particularly when thicker layers or larger areas are to be clad. In this case, CO_2 laser cladding may be a suitable process. In the field of CO_2 laser regeneration of engine components, some promising results have been obtained in recent years (Ref 14).

Two components of a large ship engine were found to be defective in the final stages of manufacture, thus, a laser cladding strategy had to be developed for repair. The cross-head gudgeons, each weighing 4.2 tons and made of 0.45% carbon steel, had defects on the functional surface that were machined out to give a groove 6 mm deep, 15 mm wide in the ground, and 80 and 100 mm long, respectively, with a 30° flank angle.

The cross-head gudgeons transmit a force of 7500 kN in a 30 MW engine. The service load on the functional surface of the components is extreme, hence, they are examined closely by the classification societies. Due to the oscillating movement of the component, the lubricant film between the cross-head gudgeon and its bearing is below 1 μm; thus, the maximum surface roughness is 0.05 μm, which is in the quality range of optical mirrors for CO_2 laser beam guiding.

Both components could neither be preheated nor afterheated, and any distortions or undercuts had to be avoided because the oversize for machining was below 0.15 and 0.05 mm, respectively. Furthermore, the cladding material and process had to be selected carefully to obtain a cladding capable of bearing the service load and the residual stresses resulting from the temperature gradients and the geometrical constrained conditions.

Laser cladding had to meet the following criteria:

- Need to fill in the given geometry and volume of the groove
- Heat input and heat flow that guaranteed a crack-free cladding and minimal heat affected zone (HAZ)
- Sufficient heat input to temper the preceding clad track and its HAZ in order to reduce hardness
- Surface hardness maintained below 450 HV to enable machining of the contour within narrow tolerances and uniform behavior in service
- Scalability of the process, considering a 4.2 ton component would behave as a large heat sink

For the choice of the cladding material, it was important to consider:

- Relative thermal expansion behavior of cladding and substrate
- Sensitivity to hardening
- Strength, ductility, and toughness
- Possibility of reducing or releasing the residual stresses
- Suitability of the material for laser cladding

To fill up the groove, a 5 kW CO_2 laser with 6 mm line focus and a cobalt-base alloy (Stellite 21) were chosen. A defect free (that is, no pores and cracks), fine dendritic microstructure of the

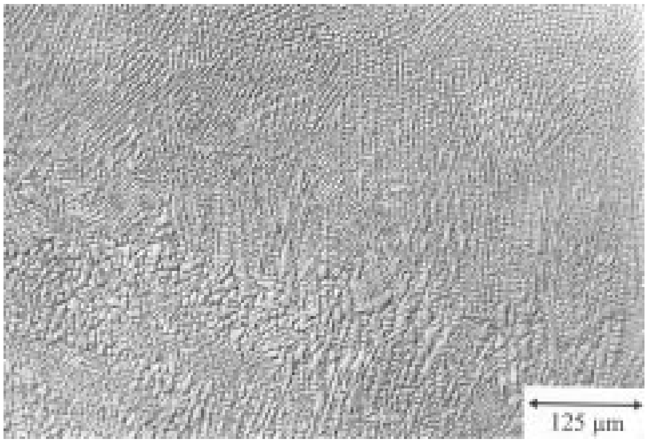


Fig. 11 Microstructure of a CO_2 laser cladding. Filler material: Stellite 21, etched in HCl/HNO_3

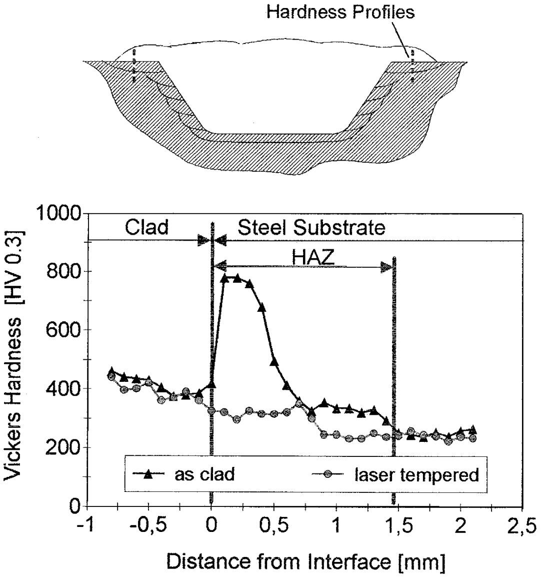


Fig. 13 Effect of laser tempering on the hardness profile of heat affected zone (0.45% carbon steel)

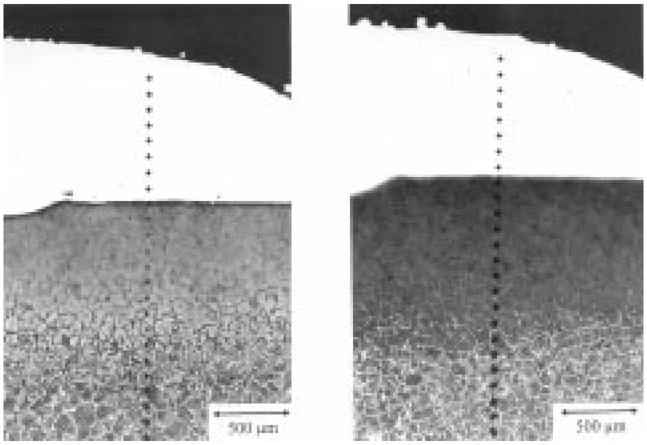
cladding was achieved (Fig. 11). Furthermore, a subsequent CO_2 laser heat treatment was performed locally to temper the microstructure of the heat affected zone at the very surface, as illustrated in Fig. 12(a) and (b). This resulted in a smooth hardness profile and a reduction of the peak hardness of the steel from 780 HV 0.3 to below 400 HV 0.3 (Fig. 13). Figure 14 shows an as-clad component.

After rebuilding, the two laser clad engine components have been approved and met the requirements in the acceptance test run of the engine.

A general approval of the repair of cost intensive large engine components by the laser beam cladding process is now being formulated in collaboration with the standardization and testing societies.

4. Conclusions

The following conclusions can be drawn:



(a) (b)

Fig. 12 Cross sectional view of heat affected zone (0.45% carbon steel, nital etched).(a) As clad. (b) Laser tempered after cladding

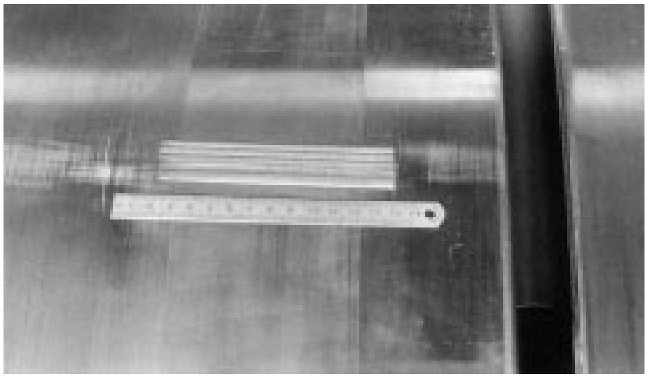


Fig. 14 Detail of diesel engine component repaired by CO_2 laser cladding

- Precision powder-fed cladding using Nd:YAG-lasers has been shown to be a flexible technique suitable for cladding and repairing machine components. Due to the very low heat input, distortion was reduced to an insignificant degree. Nevertheless, a sound metallurgical bond between base material and filler material was obtained. This resulted in excellent adhesion of the claddings.
- The developed technique has opened new possibilities for the recovery of components with strict requirements regarding accuracy, such as components with manufacturing defects that have occurred in the later stages of production. Up to now, such components either could not be repaired, or only with a highly uneconomically expenditure.
- The precisely controllable heat cycle also enables the production of functionally gradient materials (FGMs) and graded coatings. Thus, the powder-fed laser beam cladding process allows the combination of the technological advantages of metallurgically bonded claddings and graded layers.
- Despite the noticeable advantages of Nd:YAG laser precision cladding, CO_2 laser cladding is still the method of choice if the volume to be clad or filled in is larger and heat input is less critical because the overall processing speed is

higher. In addition to the wide field of repair and regeneration, application areas are cladding for temperature, corrosion, and wear protection where metallurgical bonding is required and clad heights in excess of 0.5 mm are desired to meet extreme service conditions.

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