THE APPLICATION OF LASER CLADDING TO MECHANICAL COMPONENT REPAIR, RENOVATION AND REGENERATION

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Abstract: *Thanks to shifting social paradigms and economic pressure, the repair and refurbishment sector of production engineering is currently booming. This chapter describes laser cladding technology, which is being increasingly applied in the repair and reconditioning of all kinds of mechanical components. We have sought here to describe the use of laser cladding technology and its basic principles. Its comparative advantages over other build-up technologies include better overall quality of coating, minimal dilution and distortion and customised surface parameters. The methods for applying additive material to the repaired surface are detailed, together with the three main types of lasers.*

The current stage of laser cladding technology implementation and trends for its industrial application are outlined with emphasis to the repair sector, including relevant equipment and powder delivery nozzles. An illustrative case study is included in the chapter to demonstrate how laser cladding could be effectively applied to in-situ marine crankshaft repairs. This includes an assessment of previous studies in the field, the sampling of laser-cladding machine designs and lessons learned. It is then possible to evaluate the advantages and disadvantages of laser cladding. Here we have defined the challenges to be addressed and summarized the emerging overall trends of this technology. It is noted that laser cladding is only in its early stages of implementation and commercialization. Finally we offer a brief overview of the relevant issues to be considered by engineering educators and policy makers.

Keywords: *laser cladding, repair, reconditioning, mechanical components, challenges for the future*

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1. Introduction

Society in general is becoming “greener” and we are witnessing fundamental changes in our attitude and usage of various technologies. Everyone appreciates the benefits of recycling and reusing resources, tools and gadgets, as long as there is no loss of quality in the end products. Engineers today have to create attractive new products that exploit all means of recycling and at the same time, have to be able to effectively reuse and repair already existing appliances. From past experience and with the ongoing economic difficulties in Europe and other industrially developed parts of the world, we know that we no longer have the luxury of being able to throw away everything which is slightly damaged. Yet the world over, commercial advertisements and marketing tools are pressuring society to buy the latest products. This is how the consumer society was created and is sustained, to the detriment of our natural resources. Fortunately, cooler heads in society and manufacturing industry understand that we have to reduce costs by repairing, regenerating and renovating. Industry does not have any “free” money to buy new machines; instead it needs and really depends on repairs. Even, if the resources are available, nobody is now prepared to throw their money to the winds. Thanks to these social changes, new attitudes and economic pressure, the repair and refurbishment sector of mechanical and manufacturing engineering is currently booming. The size and potential of this repair and renovation market is enormous.

Since the introduction of the diesel engine into the shipping world in 1912, the ship repair sector has been successfully refurbishing these engines (Woodyard, 2009). Over the past century, improvements have revolutionized the design and performance of diesel engines. Yet even today, among the most important elements of any diesel engine is its crankshaft – one of the most heavily used elements in the entire engine – which has extremely high precision manufacturing and servicing requirements.

The unremitting working conditions and intensive wear of marine diesel engine crankshaft main and crankpin journal surfaces, along with potential lubrication failures, cause various types of damage to the journal surfaces. Common faults in the journal surfaces are ridges, cuts, grooves, tears, marks and formation of a built-up edge. Wear also leads to insufficient geometrical clearances of the crankshaft journals, such as roundness and central alignment.

The aforementioned damage also affects the mechanical properties of journal surfaces. This may result in reduced hardness and rigidity or conversely, in excessive surface hardening. Regular repairs of marine diesel engine crankshaft main and crankpin journals surfaces are therefore needed in order to perform partial or complete renovation of the worn crankshaft journals. These repairs are carried out in the workshop, after removing the crankshaft from the engine and subsequently performing journal grinding on stationary machines. The crankshaft is usually fixed centrally and rotated around its central axis.

Where necessary, various other types of build-up operations are also carried out in specialist, onshore workshops. Subsequently the crankshaft journal is machined to the required dimensions, as per the manufacturer’s specifications.

Crankshaft journals can be renovated using various technologies, such as conventional TIG/MIG/MAG build-up welding, plasma coating welding and spraying. These surface refurbishing techniques are approved by most Ship Classification Societies, but are limited to use only within workshop (onshore) environments, are time-consuming and can be performed only with highly sophisticated machinery. Other manual operations (e.g. metal/plastics, grinding and lapping) can be conducted for emergency repairs and only provide a temporary solution (Torims , 2012).

At the same time, none of these conventional technologies can be used onboard the ship to fully build up worn crankshaft crankpin journal surfaces. However, crankshaft crankpin repairs frequently have to be carried out directly onboard the vessel or even at sea and not in the comfortable conditions of onshore facilities. Comprehensive research was carried out into how to deploy laser cladding technology for in-situ crankshaft repairs. The solution to this technological challenge was found to be to fix the laser nozzle to the already developed platform of the crankshaft journal in-situ grinding equipment (Torims et al , 2012).

Laser cladding offers many advantages over the aforementioned conventional coating processes. It can deliver a much higher quality of coating, with minimal dilution and distortion, offering enhanced surface quality parameters. The properties of the surface material thus obtained have similar or even better characteristics than originally. In general, the advantages of laser cladding are:

- reduced production time,
- enhanced thermal control;
- highly satisfactory repair of parts;
- Production of a functionally graded part;
- Production of smart structures.

The flexibility of laser cladding is being recognised by industry and research funders. The potential of this technology is massive, with research groups around the world continuing to contribute to its growth through research programmes, industrial applications and training students in laser cladding techniques (Toyserkani et al, 2010).

2. Description and Application of Laser Cladding Technology

A major application of laser cladding is in the repair and refurbishment of high-value components such us tools, turbine blades, gas turbine and internal combustion engine parts, as well as various components of a military nature. Its three fields of industrial application are surface cladding, repair welding and generative manufacturing. The process is a reliable macro-materials’ processing technology. One of its primary applications is the deposition of well-known wear-resistant and anti-corrosion coatings. Conventional methods use welding to renovate these damaged components. However, such conventional methods are in most cases destructive, due to the highly variable temperatures over the repair areas. This thermal stress leads to inferior mechanical quality, surface quality problems such as cracks and porosity, as well as shortening the lifetime of the repaired part. In addition, there are many other applications of laser-based direct material deposition, such as functional coatings, repair depositions, rapid design changes and finally, the direct generation of complex parts made from modern construction materials. The fabricated structures are very precise, possess the highest mechanical strength and have precisely tailored features (Nowotny, 2011, Toyserkani et al, 2010).

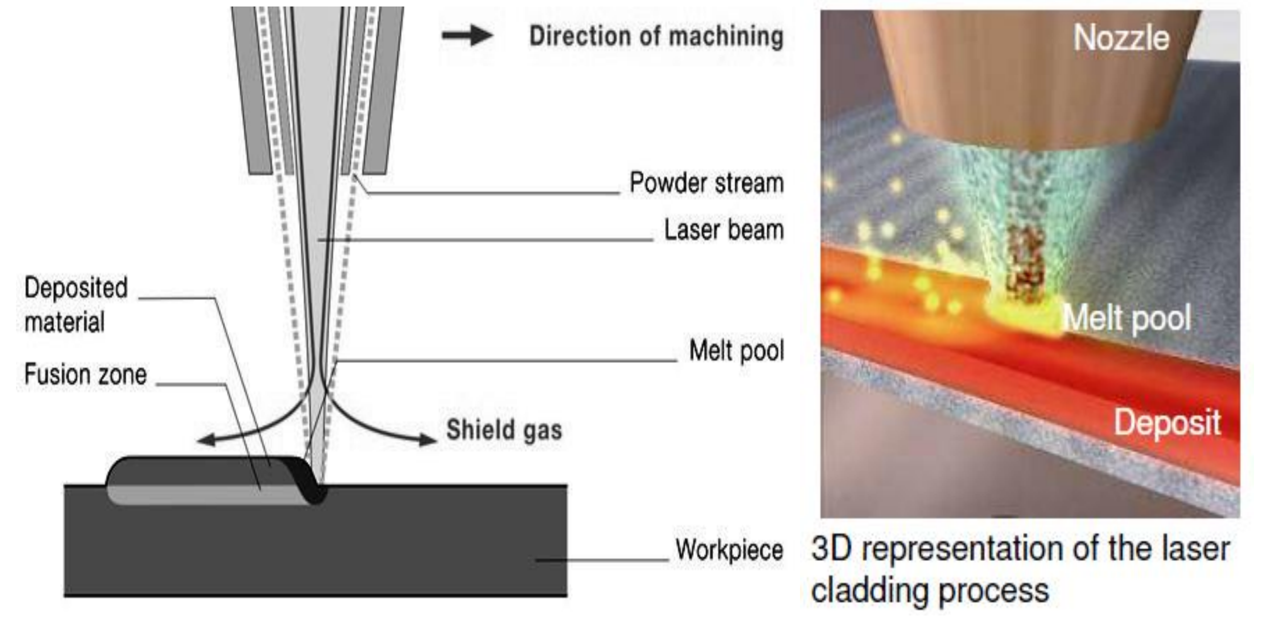

Fig. 1. Laser cladding process. Courtesy of TRUMPH

Laser cladding is a melting process in which the laser beam is used to fuse an alloy addition onto a substrate. It is the highest precision build-up welding technique. The additive material and a thin layer of the substrate are melted by the laser beam. This ensures a metallurgical bonding between layer and substrate. The alloy may be introduced into the beam-material interaction zone in various ways, either during or prior to processing. The additive material is either pre-coated onto the substrate or supplied in-situ. Pre-coating either by thermal spraying or galvanic deposition is time-consuming and expensive, and is thus efficient only for cladding over large areas. In-situ supply refers to the injecting of additive material into the interaction zone of the laser beam and the substrate, either in form of wire or powder. Powders are more common and popular due to their virtually unlimited potential to vary the alloy composition – see Fig. 2. The powders used for laser cladding should have a particle size of between 20 and 200 μm. The best feeding properties are achieved with a spherical form of the particles, typical for atomised powders. Very little of the substrate is melted, thus creating a clad with nominal alloy composition. Surface properties can then be tailored to a given application by selecting an alloy with the appropriate wear, erosion, oxidation or corrosion properties. The molten clad solidifies rapidly, forming a strong metallurgical bond with the substrate. Most substrates that tolerate laser melting are generally suitable for cladding: carbonmanganese and stainless steels, along with aluminum, titanium, magnesium, nickel and copper alloys. The type of laser used depends on the surface area to be covered, the thickness of clad required, and the complexity of the component. CO2 lasers are ideal for large areas requiring clads several millimeters in thickness over surfaces with a regular geometry. A robot-mounted diode laser beam, or Nd:YAG (neodymium-doped yttrium aluminum garnet; Nd:Y3Al5O12) laser light delivered via a fiber-optic cable, is more suitable for precision treatment of complex three-dimensional components requiring a coating less than one millimeter in thickness. The overall aim is to produce a clad with appropriate service properties, a strong bond to the substrate, maximum coverage rate with the minimal addition of alloy and minimal distortion (Ion, 2005, Nowotny, 2011, Weisheit, 2013).

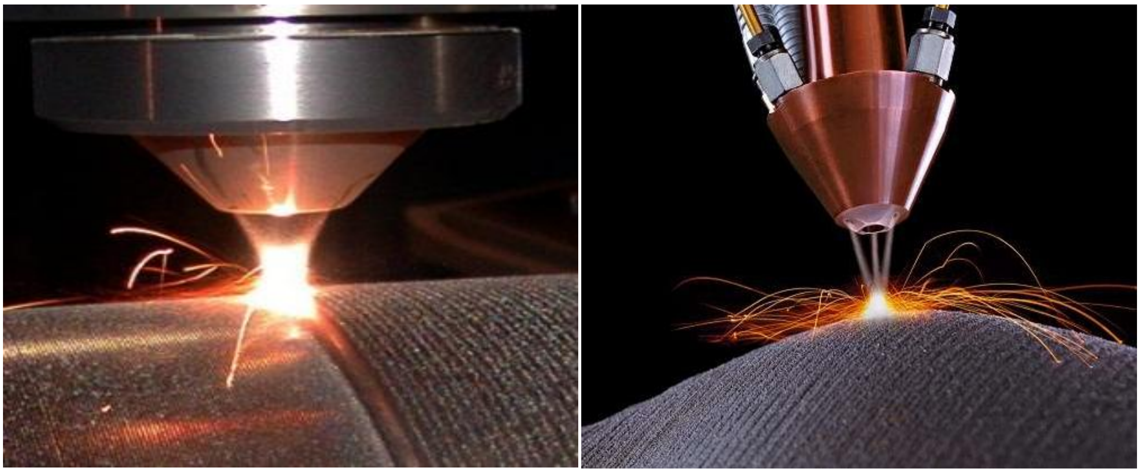
a) b)

Fig. 2. Laser cladding a) Laser welding solutions, b) Laser focus world.
Source: TRUMPH

The laser cladding energy cluster has a power density of around 100 W mm^{-2}. This is roughly ten times that required for solid-state heating, but slightly below that needed for other processes based on surface melting. The reason is that the alloy is introduced in the form of powder, wires or foils, which are melted more easily than a solid flat surface because of the larger surface area to volume ratio. In practice, a minimum beam power of around 2 kW is needed for efficient cladding. Insufficient power results in limited melting of the alloy addition, whereas excess power results in excessive melting of the substrate and an undesirable dilution of the clad. A beam interaction time in the order of 0.1 s provides sufficient time for mixing and homogenization of the clad, while enabling the surface to solidify and cool sufficiently quickly to form a fine microstructure with superior properties, compared with the larger-grained clads produced by conventional build-up techniques. The clad geometry is established by the surface properties required. A small, discrete region can be clad in a single pass, in which case the beam width is fixed by the required clad width and the traverse rate may be up to 1 m min^{-1}. If a large area is to be clad, the aim is to maximize the coverage rate by using the widest beam and highest traverse rate possible that satisfy the requirements of power density and interaction time. Overlapping, parallel tracks are often required in such cases (Ion, 2005)].

Using wires as an alternative to powders has a number of important advantages. For example, independent of part geometry, the material utilization is always 100%. The material delivery is not affected by gravity. It is a clean welding process, which is much less dangerous for operators and machines. The wires also have smaller specific surfaces, which provide advantageous conditions for processing materials prone to chemical reactions with the surrounding atmosphere, such as titanium and aluminium. It requires complex systems' technology to make the wire delivery independent from the welding direction. Therefore the repair of more complex, three-dimensional metal structures remains so far the exclusive domain of the established handheld laser guns. These are efficient and flexible, but suffer from subjective influences due to the operator's dexterity. Lower build-up rates and part dimensions also limit such potential repairs (Annual Report 2012)].

3. State of Play

With the rapid growth of laser applications and the reduced cost of laser systems, laser material processing is being successfully implemented in the automotive, aerospace, shipbuilding and ship repair, navy, defense and many other industries. Laser cladding is an emerging material processing domain, involving the effective interdisciplinary engagement of laser technology, CAD/CAM, robotics, sensors, controllers, powder metallurgy and machine design. In recent years, laser cladding has gained momentum due to the diversity of its potential applications: metallic coatings, high-value mechanical component repairs, rapid prototyping, layered metal deposition and nano-scale manufacturing (Toyserkani et al, 2010).

Conventional tool repair technologies rely mostly on destructive, high temperature welding processes. Conversely, laser cladding can be effectively and safely utilized for repairing various instruments and mechanical components—especially on critical contacting surfaces—as there are no destructive high temperatures, heat-affected zones or other damage. Indeed, laser cladding by powder metal injection can be effectively used for manufacturing, component repair, rapid prototyping and coating. (Toyserkani et al, 2010).

Since the development of high-power lasers, cladding has become a major research topic. Over the past fifteen years, basic and applied research has provided an in-depth understanding of the cladding process, as well as a variety of potential applications. However, industry has been rather reluctant to adopt this technology, mainly due to high investment and running costs. Since high-power diode lasers and diode-pumped Nd:YAG lasers were developed and introduced on the market, the situation has changed. One main advantage of these lasers is a significant reduction in running and maintenance costs. Apart from this, progress has been made in laser cladding automation and process layout. These developments have led industries to renew their interest in laser cladding, especially for repairing tools and turbine engine parts (Weisheit et al, 2013).

Laser material processing technologies in general, and more specifically laser cladding, are developing continuously. A distinctive field of current advances is the hand-operated laser processing heads, which allow, for instance, slight abrasion marks on forming or cutting tools to be refurbished by depositing just the right amount of material on the surface. Systems can be self-regulating, to compensate for unsteady motion during manual operation. The multitude of research activities in laser technology suggests on-going development of laser-assisted build-up welding and cladding. Even today, the relatively high cost of laser equipment limits the technology to niche applications, such as low-volume work with minimal post-treatment and/or special materials that rule out build-up welding using conventional techniques (Bach et al, 2006)].

Surface coating over large areas, requiring particular productivity and efficiency, are now coming to the fore. The trends are to use more power and to combine lasers with additional energy sources such as induction heating. Micro build-up welding, on the other hand, is expected to significantly reduce reproducible structure dimensions. Current research is focusing on expanding the selection of high-performance and highly temperature-stable materials (Nowotny, 2011).

Unlike in the 1980s and 1990s, when it was necessary to build complex laser machines for industrial use, today it is straightforward to integrate laser system technology into the end user’s existing machine tools. Laser technology is now available for the precise fabrication of functional and protective coatings, as well as for repairing components with complex shapes and forms, as well as the most expensive parts. Laser cladding is used for precise, functional coating as well as for fast surface repair. The technology is based on modern laser-beam sources and user-friendly optics, processing heads and software systems. The process has become established as a precision manufacturing technology in engine and turbine repair, as well as in the tool and die making industry (Institute for Scientific Publications)].

The necessary equipment is modular and includes the laser, optical components, the processing head, the powder or wire feeder and software. The laser processing heads are exactly tailored to the requirements of different industries. Powder nozzles with coaxial powder delivery (see Fig. 3.) are the predominant design, as they can perform the welding process in any direction. The use of powder typically accounts for between 60 and 80% of applications. Up to 98% of tasks can be achieved under ideal conditions when the melt pool is larger than 5 mm in diameter. Wire-based weld metal delivery is an alternative to the powder process. Modifications are also available for omni-directional material delivery (Nowotny, 2011).

Fig. 3. Coaxial powder nozzles. Source: Fraunhofer Institute of Material and Beam Technology (IWS)

Two-thirds of the industrial laser build-up welding business is undertaken by toll manufacturers. The remainder is performed by original equipment manufacturers in the areas of engine and stationary gas turbine manufacturing and the automotive industry. Typical applications in the area of surface technologies are anti-corrosion and abrasion coatings on long, hydraulic cylinders for offshore use, oil production and mining tools, and large screw conveyors. Aircraft engine technology is the primary application for repair and generative fabrication technologies. Examples are the repair of blades, disks and casings and titanium turbine disks and the generation of three-dimensional surface structures. It is also important to mention laser applications in mould and die making. Manual laser workstations are used to perform very precise repairs of injection moulds. Quick turnarounds are possible when changing the designs of large sinking dies for automotive body production. Frequently mobile laser technology is being used to perform in-situ repairs of stationary gas turbines (Nowotny, 2011).

The process principles are similar to those of other surface melting processes, enabling the microstructure and properties of the clad surface to be established from data, to achieve rapid solidification of the alloy. Practical processing has been simplified by the development of coaxial alloy delivery systems (see Fig.4.), which permit cladding of complex, three-dimensional components in various orientations. Analytical modelling aids in understanding the process principles, whilst empirical data can be used to calibrate parameter selection diagrams to particular cladding geometries. Novel manufacturing methods, notably rapid manufacturing by various means of direct metal deposition, have been developed based on this process (Ion, 2005).

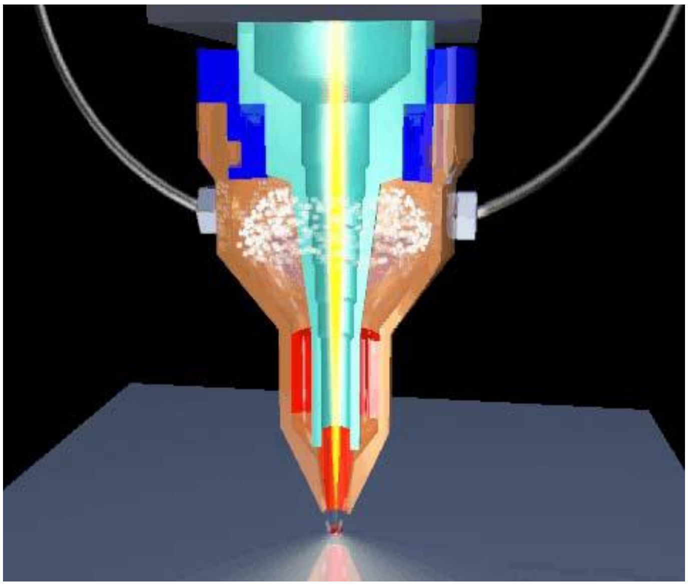

Fig. 4. Coaxial powder nozzle. Source: Fraunhofer Institute of Material and Beam Technology (IWS)

4. Case Study: Laser Cladding Application in Marine Crankshaft Renovation

The aim of the case study is to demonstrate how laser cladding can be successfully applied to in-situ renovation of ship crankshaft journal surfaces. The essence of this study is to demonstrate a functional platform for repairing and renovating crankshaft journal surfaces.

4.1 Assessment of previous studies

Thanks to the aforementioned advances in laser know-how, over 10-15 years this technology has also become commercially available and affordable for ship repairers. The ship repair industry and academia then started to consider the application of laser build-up welding and laser cladding to mechanical components of marine diesel engines, including crankshaft surface renovation.

In their article (Vishnevetskayai et al, 1996), the authors addressed material property issues, without however providing technical solutions or applications for the laser build-up technology itself. A further article (Koehler et al) describes a laser build-up technique for a crankshaft. However, the technique described is limited to workshop conditions and is not an in-situ technological solution.

Further research (Torims et al , 2012) outlined an idea to use the laser cladding technique for marine engine crankshaft bearing surface repairs. It proposed to use the previously developed technological platform, which is designed to perform shipboard crankshaft renovation (surface grinding) operations, inside the diesel engine.

A study (Torims et al , 2012) confirmed that laser cladding technology is indeed very well suited to marine crankshaft journal surface renovation. Among other clear benefits, laser cladding permits virtually unlimited varieties of alloys and ensures a full metallurgical bond (unlike thermal spraying). It revealed that cladding technology is the most appropriate solution, using commercially available CO_2 or a fibre-coupled diode laser through a coaxial powder nozzle.

Although some technical difficulties were identified, preliminary research concluded that machines could be built for shipboard, in-situ crankshaft bearing repairs using laser cladding. The study also revealed that this know-how can be applied to crankshafts with bearing diameters of at least 120mm.

The feasibility study (Torims et al , 2012) concluded that when constructed, tested and approved by the competent authorities, such technology would offer an innovative solution for shipboard crankshaft repairs. It could open up a new field of application to laser cladding and generate considerable economic benefits.

Today, laser cladding is deployed in manufacturing and repair industries, basically in three different fields: surface cladding, repair welding and generative manufacturing. These technologies have been closely associated with the commercial success of laser build-up welding over the past 15 years. The availability of ever-newer generations of laser beam sources have provided the decisive impetus for this successful development. A variety of manually guided laser systems is currently available for repair applications. These systems are fitted with compact, lightweight Nd:YAG solid-state lasers, including for mobile systems. This is very practical for the customer, since the laser can be transported to them. It is no longer necessary therefore to dismantle and transport expensive and heavy parts over land or to the workshop. Instead the repair process is performed on site, saving time and costs (Nowotny, 2011).

Another significant paper in the field (Brückner et al, 2012)] reviews recent progress in the productivity, precision and quality of laser-based cladding and additive layer manufacturing. Recently the “Fraunhofer Institute Material and Beam Technology IWS” demonstrated induction-assisted laser cladding. This novel, hybrid technology combines high deposition rates with excellent cladding properties. Direct, laser-based metal deposition is a novel concept for the fabrication and repair of components as well as geometrical surface modifications.

This analysis clearly demonstrates that laser cladding can be applied to in-situ marine diesel engine crankshaft repairs. The conceptual model of the laser cladding machine for in-situ crankshaft repairs has therefore been developed.

5. Principal Design of the In-Situ Laser Cladding Machine

The aforementioned goals are achieved by placing the laser cladding nozzle positioning and guidance device directly on the crankshaft journal fillets (Torims et al , 2013). These fillets as a rule are not damaged or worn and thus preserve the manufacturer’s original crankshaft dimensions (Torims, 2013). Thus they (see Fig. 5) can be used as a reference surface when positioning the laser build-up nozzle guidance platform.

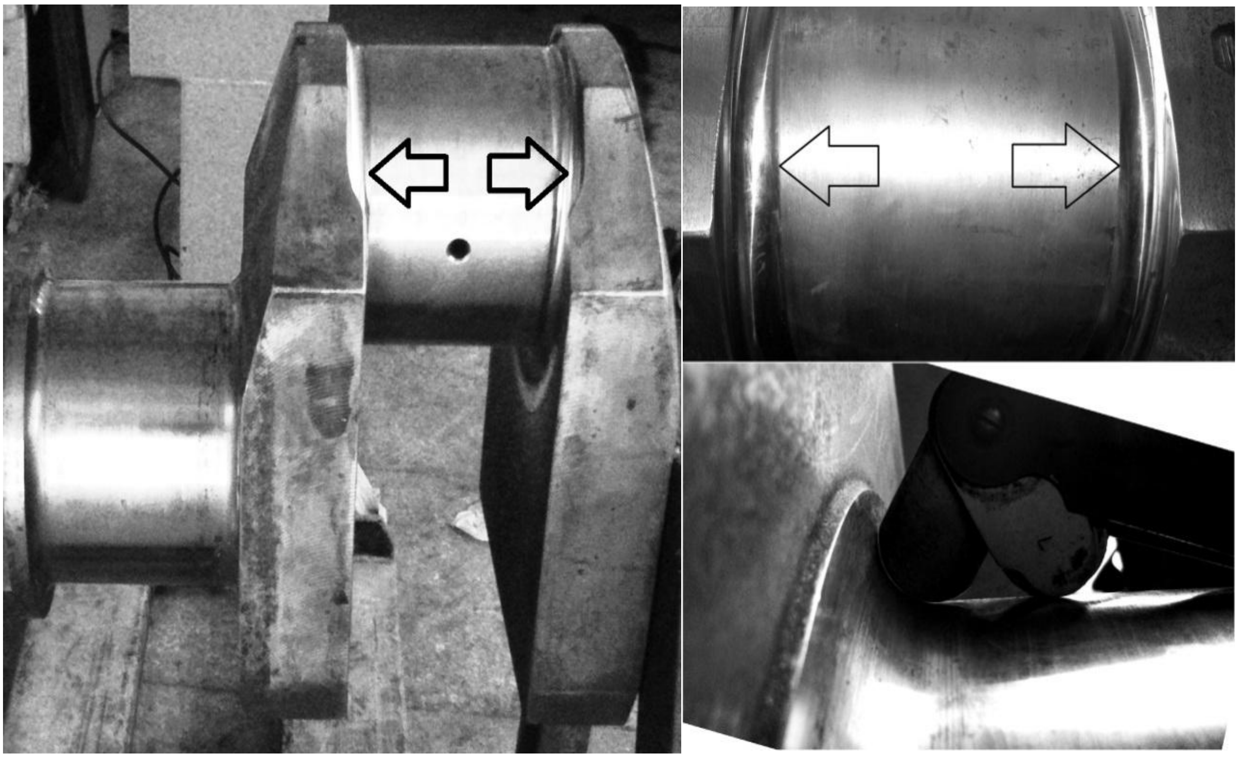

Fig. 5. Fillets of a marine diesel engine crankshaft

The device is composed of two guideways, for positioning it onto the crankshaft fillets, and two frame parts, each of which is fitted to its respective guideway – see Fig. 6. Additionally the device comprises two upper rods connecting the upper frame and two lower rods connecting the lower frame, so that both frame parts are fixed together rigidly.

The prototype device further comprises two carriages which are installed on the upper and lower rods, so that both carriages can slide along these rods. A laser cladding nozzle is installed on the first carriage. The drive elements are two control motors: the first control motor is installed in the first carriage and is physically connected to the laser cladding nozzle to control its pivoting angle; the second control motor is installed in the second carriage and is functionally connected to one of the two lower rods by means of a gear transmission mechanism, to control the longitudinal position of the laser nozzle.

The laser build-up process includes a step whereby cladding powder or any other cladding material is applied to the damaged journal surface. At the same time, the cladding powder is irradiated by the high-energy laser beam. Thus a metallurgical bond between the crankpin surface and substrate material is achieved by melting both the cladding material and the substrate. As a result, the worn or damaged surface is restored to its original configuration or to any other desired shape, to allow for subsequent mechanical machining.

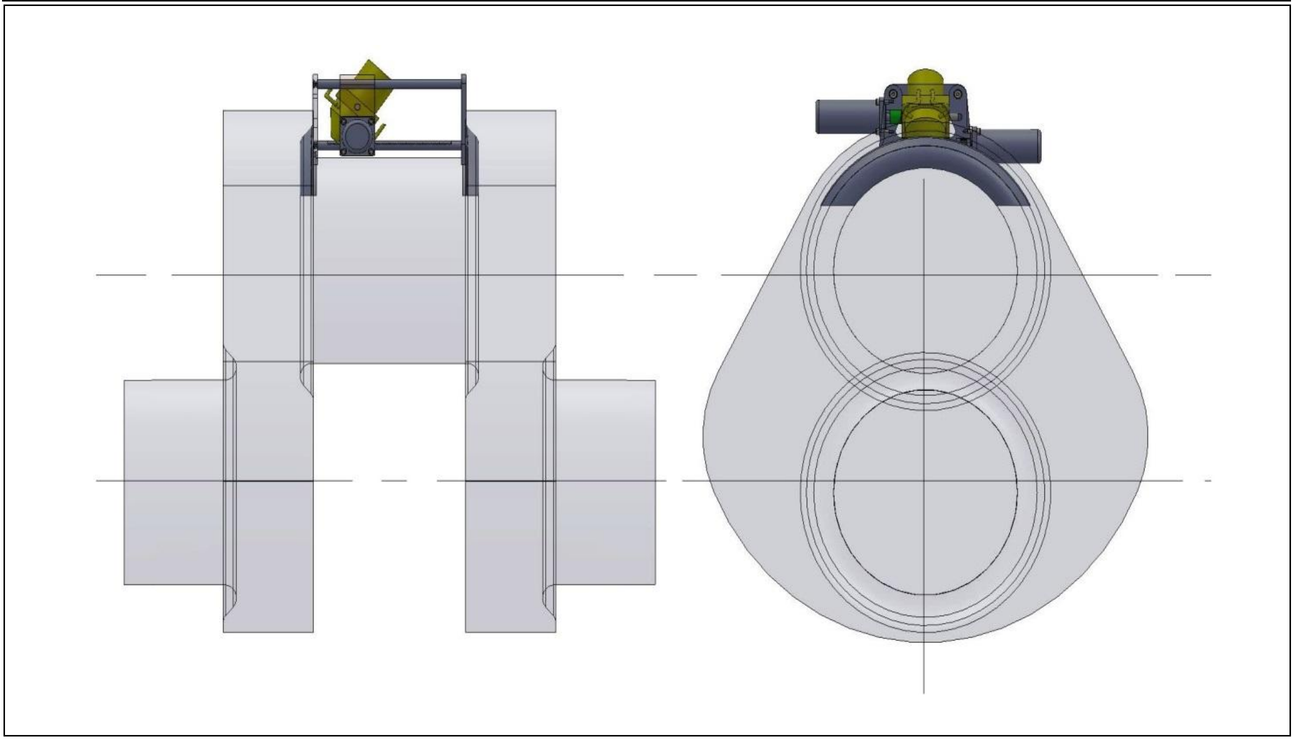

Fig. 6. Laser cladding device positioned on a crankshaft

The following parameters (feeding elements) are synchronised and digitally controlled: 1) Positioning of the first control motor– guiding the laser nozzle radial feed; 2) Positioning of the second control motor – guiding the laser nozzle angle; 3) Crankshaft rotation frequency; 4) Laser power; 5) Feeding of the welding powder, etc.

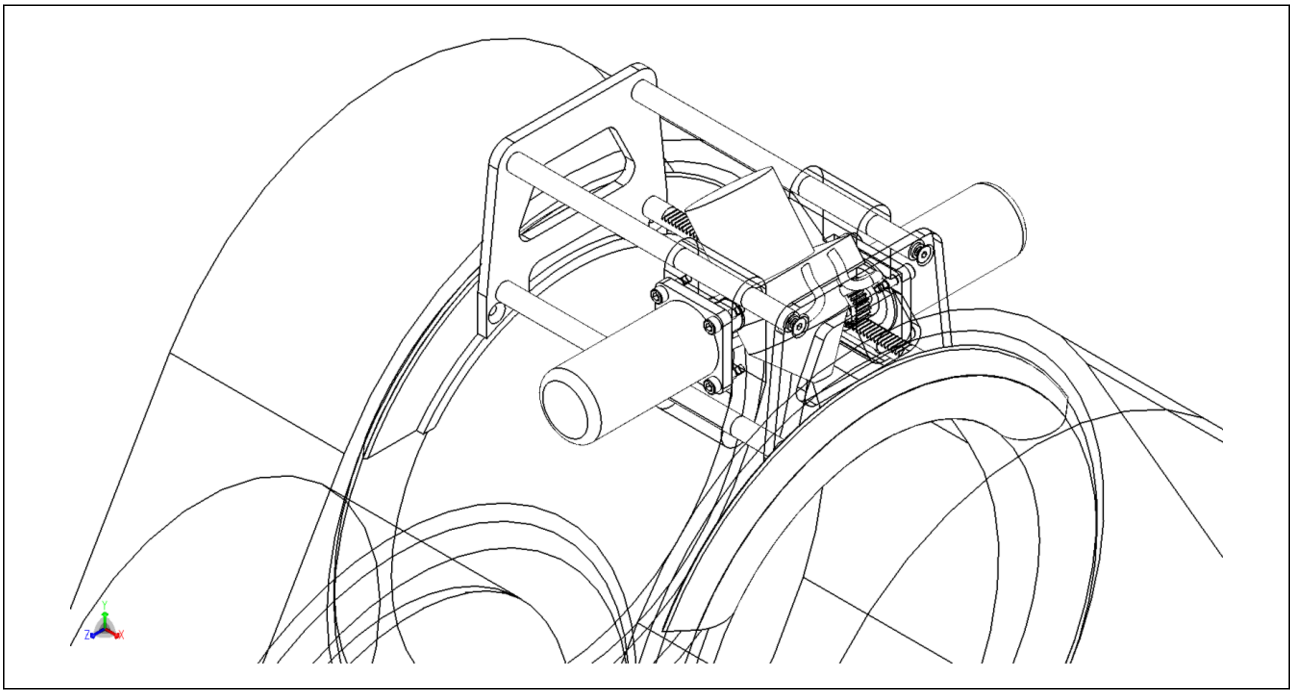

Fig. 7. Laser cladding guidance mechanism (Torims, 2013)

The gear transmission mechanism comprises a spur gear connected to the second control motor and a toothed rack, which is attached directly onto the lower rod. The first control motor is connected to the laser nozzle through a bush. Both the laser power fibre-optic cables and the cladding powder supply tubes should be flexible. They can then be deployed easily through the piston liner from the top of the engine. A potential method for repairing and renovating crankshaft journal surfaces using the aforementioned device is described as follows:

1. positioning of said device above a journal surface to be refurbished by means of said guideways;
2. applying a cladding powder onto the damaged surface of the journal;
3. positioning the laser nozzle above the journal surface by means of the two control motors;
4. irradiation of the cladding powder by a laser beam emitted from the laser nozzle;
5. repeating operations 2 through 4 until the damaged surface of the journal is cladded.

In operation 3, a pivoting motion of the laser nozzle is achieved by means of the first control motor and a longitudinal positioning of the laser nozzle is achieved by means of the second control motor and its gear transmission mechanism. In accordance with the developed technology, the crankshaft does not need to be removed from the engine or motor block in order to repair or renovate the crankshaft journal surfaces (Torims et al , 2013).

6. Outcome of the Case Study

The main issue of this research addresses how to deploy laser cladding technology for in-situ crankshaft repairs. A potential solution to the problem could be to fit a laser nozzle to the existing platform of the crankshaft journal grinding equipment. This platform can be placed directly on the crankshaft bearing surface to be repaired. By fitting a laser cladding head onto this platform, the crankshaft surface can be refurbished or build-up welding performed directly in the engine housing. In this case, repairs are naturally limited to the crankpin journals only. The proposed technology will have clear economic benefits and could be combined with an in-situ crankshaft grinding machine. Thus the entire process of in-situ crankshaft reconditioning can be performed on board the ship.

7. Advantages of Laser Cladding Technology

Optical energy is an ideal form of energy for surface treatment. The uses of laser surface treatment include surface heating, bending, scabbling, melting, alloying, cladding, texturing, roughening, marking, cleaning and layered manufacturing processes. The advantages offered by the laser are the highly localised, clean nature of the process, low distortion and the high-quality finish (see Fig.8). With the development of highly automated workstations and cheaper, more powerful, reliable and compact lasers, surface treatment by lasers is set to be the general trend in future decades (Steen & Mazumder , 2010).

Fig. 8. Laser cladding of camshafts. Courtesy of TRUMPF

As described above, laser cladding can achieve a permanent structural repair and refurbishment with a wide range of different alloys (e.g. aluminium alloys) which are generally considered by industry as impossible to weld by any conventional method. In turn, the advantages of laser cladding are small heat-affected zones, rapid solidification, increased cleanness, lower dilution and improved controllability over the depth of the heat-affected zone (Toyserkani et al, 2010).

In comparison with conventional build-up techniques, the energy input of laser cladding is low, which results in finer microstructures with superior properties, and minimal component distortion. In addition, in-service performance is improved because of the smooth clad surface, the lack of defects in the clad and the metallurgical bond to the substrate (Ion, 2005).

The low- energy input of laser cladding causes very little distortion to the component, which leads to a significant reduction in post-treatment machining operations. Close control of dilution with the substrate ensures the desired coating composition is achieved. The deposit is of high quality—laser clads can be made with low porosity and few imperfections. Rapid solidification and cooling rates result in fine, solidified clad microstructures offering superior wear and corrosion properties, as well as the formation of beneficial metastable phases and extended solid solubility, which also enhances properties. However, rapid cooling rates increase the sensitivity of the clad and heat-affected zone to cracking, and precautions such as preheating might be necessary (Ion, 2005).

This almost unique precision cladding technique offers a flexibility that is only just beginning to be explored. Not only can it clad with good fusion-bonded cladding in localised areas, but it also allows build-up of the clad to make precision castings. The high rate of mixing in the clad melt pool causes homogenisation of the melt, for speeds below a certain value, and hence alloys can be formed in situ from cheaper ingredients or alloy systems can be rapidly analysed using this process. The cooling rates are fairly swift in the small melt pool. This generates finer microstructures than competing processes (Steen & Mazumder , 2010).

As the beam can be delivered accurately, discrete regions of surfaces can be treated, which reduces the total energy input and contributes to reduced distortion. The use of expensive alloying elements can be minimized since they are used only in superficial areas, rather than throughout the mass. The clad thickness can be accurately controlled, which limits the amount of post-treatment machining required (Ion, 2005)].

The laser beam can be manipulated easily, quickly and flexibly, owing to the availability of a wide range of laser wavelengths, powers and energy, which in turn enables processing to be carried out in various thermal modes and for diverse penetration treatments. The technology is adaptable to automation and flexible manufacturing It offers numerous methods for optical beam delivery. It is possible to switch rapidly between different treatment geometries and process a wide range of shapes, through the ease of beam shaping. The process is therefore highly suitable for automation, including beam sharing and beam switching. The beam can be directed into otherwise inaccessible locations, either using mirrors or fibre-optic beam delivery. A variety of component geometries can be treated, by modifying software to generate an optimal beam and traverse path (Ion, 2005).

Higher productivity can be achieved with laser processing, through a reduction in processing time because of the low inertia of laser processing, the use of less and cheaper materials, a reduction in labour and equipment maintenance costs owing to the absence of tool wear, less scrap, a shorter process cycle time due to the minimization of post-treatment work, a reduction in order lead times, greater equipment availability time and a reduction in energy costs (Ion, 2005).

Last but not least, laser processing is environmentally friendly because it uses clean energy and few contaminating materials. Optical energy generates very little environmental disturbance (noise, external electrical and magnetic fields), which enables processing to be carried out in local, ergonomic surroundings.

8. Disadvantages and Challenges of Laser Cladding

Many opportunities arise from the inherent characteristics of laser processing. However some distinctive challenges related to the implementation laser cladding technology have been identified. In fact there are very few negative characteristics or clear disadvantages to note:

- relatively high equipment and running costs;
- a lack of knowledge of the technological and financial benefits;
- resistance from industry caused by negative past experiences with early, unreliable lasers;
- poor acceptance of a potential reduction in manpower;
- a need for retraining;
- unexplored technical difficulties.

The capital cost of the equipment is several times higher than many conventional techniques, and the learning curve is very steep. Applications have to be of sufficient volume or add sufficient value in order to be economically viable. A large number of competing techniques are available, many of which are more familiar to engineers and managers responsible for production decisions. It can be difficult to obtain the technical and economic information needed to present a convincing case for changing to laser cladding (Ion, 2005).

Yet another challenge is the laser cladding process itself, which is an interdisciplinary technology involving physics, material science, production engineering, design and manufacturing as well as mechatronics, robotics, sensors, controls and importantly also metallurgy.

A benefit might be possible with no change in technical specifications - a simple substitution of a laser cutting system for a conventional metal cutting system may provide the necessary improvements to the technological process economics to justify its implementation. Technical improvements in product quality often more than compensate for any increase in production costs. The most profitable scenario involves improvements in both technical and economic factors (Ion, 2005).

The maximum clad width is limited by the power density required for melting, such that overlapping passes are required for coverage of a large area. The process may be used both to build up coatings and add material to specific locations, for the purposes of modification or repair (Ion, 2005).

9. Emerging Trends and Way Forward

As a general trend, it is expected that laser cladding equipment and appliances will continue to become smaller, cheaper, more user-friendly and flexible.

New manufacturing opportunities arise from the nature of laser processing—as it is a non-contact process that causes no tool wear. It is also able to process conventionally untreatable materials and discrete portions of large components as well as precisely treat small components and selected areas. The laser beam is also able to access concealed locations (Ion, 2005).

Higher product quality, in terms of improved in-service properties, can be achieved through improved tolerances, accurate control of process parameters, selection of new materials and product redesign.

As a wider range of engineering materials are brought into use and the cost of lasers decreases, opportunities that once were neither technically nor economically feasible will become attractive. These advantages have enabled laser processing to gain footholds in a variety of conventional treatment fields (Ion, 2005).

Although laser cladding continues to be an efficient means of surfacing discrete component parts, the basic processing geometry has undergone modifications to create an industry in which parts can be manufactured rapidly and flexibly. In the field of laser thermal processing, more such developments can be expected, driven by the availability of even smaller, cheaper lasers (Ion, 2005).

Further application of laser repair and renovation technologies will depend mainly on the development of hardware and research related to the interaction between the various technologies involved. This will involve laser sources, power transfer and application technique solutions.

Major developments are likely to be centred on the differences in optical energy from other energy sources, as well as equipment developments which will alter the capital cost or processing capabilities. Some of the principal differences between optical energy and other forms of industrial energy are (Steen & Mazumder , 2010):

- current laser power densities are amongst the highest available to industry today;
- optical energy is one of the easiest forms of energy to direct and shape;
- this power can be delivered with very little signal noise, allowing a unique window into the process for automation and adaptive control;

- the laser beam contains properties as yet unexplored by material processing engineers but which are contributing to the rapidly growing "optical" applications of lasers. These may spill over into material processing.

There is little doubt that successful development of this promising technology will directly depend on the evolution of the technologies involved, a clear understanding of interactions across these technologies, process quality and correlations with the surface quality parameters (Toyserkani et al, 2010).

The next step will be the generation of complete prototype components and the geometric modification of expensive tools. In laser cladding, the supply of the additive material is one of the key factors controlling the process. The most advantageous method is powder injection. However, the available equipment was developed for the needs of research institutions. Further efforts are still necessary to provide equipment which meets the requirements of industry regarding aspects such as reliability, maintenance and lifetime (Weisheit et al, 2013).

Opportunities exist in many areas for growing the business of industrial laser material processing. Developments in the fields of laser systems, materials and processes are generating conditions for innovation: the availability of a new laser source can underpin a novel process, a new material might lead to an original application of an existing source or an innovative process might demand the development of a new material and laser source. Industry sectors have characteristic drivers for change, mostly resulting from the need to sustain growth and maintain competitiveness (Ion, 2005).

Applications are broadening to various technological processes and mechanical parts. Innovative, multi-material and multi-layer concepts are being developed. In the area of cladding, development is aimed at new system and process technologies. The integration of nanoparticles into the deposited coatings as well as the development of online process monitoring and control techniques are opening up new applications for both of these areas (Institute for Scientific Publications).

Laser cladding technology is in the early stages of commercialization and will offer a revolutionary new production technique to manufacturing industry. Due to its promising features, many industries are concentrating their attention on this technology. Research groups and companies involved in the development of the technology may focus their efforts in several directions to resolve the current shortcomings of this technology. The main focus of research efforts should be the development of autonomous machines for the laser cladding process that can not only deposit a wide range of alloys, but also make complex shapes without the need for the presence of engineers. The development of an automated machine may not be possible without a string of collaborations between researchers from different disciplines.

The development of a knowledge-based controller for such a machine requires the expertise of scientists with control, automation and also metallurgical backgrounds. Dedicated research efforts will focus on increasing the speed of the process, as the current processing speed is relatively slow compared with conventional technologies. The investigation of laser cladding and its effects on applications requires an understanding of the process and the relationship between laser energy, process speed and powder feed rate, as well as mechanical and metallurgical properties. Efforts should therefore be dedicated to modelling the process (Toyserkani et al, 2010). This reasoning also applies to marine engine repairs and renovation solutions for highly complex machine components.

For example, the National Research Council of Canada has successfully tested laser cladding technology for its use in the manufacturing of space-related structures, such as the main parts of a robotic arm. These tests resulted in the production of robotic arm components with excellent mechanical properties, which is a straightforward indication of the potential of laser cladding technology for in-space manufacturing facilities. Researchers are commencing studies on strategies for developing a reliable in-space transportation infrastructure, which may eventually include permanent refuelling stations and maintenance platforms in space, as well as cargo vehicles that haul supplies across the shipping lanes of space.

A discussion of the characteristics of laser cladding technology identified its potential to lead in space manufacturing processes, as it would allow space explorers to quickly design and produce replacement parts in space. It is therefore anticipated that the laser cladding process will play an important role in the development of possible in-space manufacturing methods in the near future (Toyserkani et al, 2010).

Market developments should be taken into consideration as a crucial issue for manufacturing sectors to explore the technology. A number of industries still consider the laser to be a "fancy" device, resulting in a major technological barrier between conventional and advanced manufacturing products. This obstacle has to be overcome through close co-operation between researchers and manufacturers, also involving end users. It is quite probable that breakthroughs in laser cladding will require a merger of advanced and conventional techniques, which may not be possible without close interaction across the entire spectrum of specialists on one side and industrial users on the other (Toyserkani et al, 2010).

New laser sources will continue to be developed. Existing resources will be made more compact, efficient and cheaper. Enhanced sophistication of the process monitoring and control systems will continue to facilitate the migration of laboratory applications into the production environment (Ion, 2005).

Significant improvements can be made through developments in optical components. Lenses capable of concentrating the low-quality beam from diode lasers provide numerous opportunities for processing. Novel designs, such as dual-focus optics, lead to improvements in cutting. Work is being conducted in the field of diffractive optics, which enable a low-quality beam to be transformed into an appropriate tool for a variety of processing mechanisms. Adaptive optics compensate for irregularities in beam propagation, thereby improving processing performance (Ion, 2005).

Lightweight, compact lasers are ideal tools for autonomous, flexible, robotic systems for material processing, which enable small groups of tailored components to be rapidly fabricated. Robot-mounted lasers are well suited for this purpose and we can expect to find them in an increasing number of engineering sites in the future (Ion, 2005).

Quick and accurate control of the power intensity will allow precise thermal properties to be engineered. This will allow greater control over cooling rates, stirring action, time above certain temperatures and the weld bead profile (Steen & Mazumder , 2010).

The laser market is in fact an elastic market, which could grow much faster if equipment costs are reduced, yet it requires mass production rather than the current custom-made systems. The invention of fibre and disk lasers has created a high-brightness laser that is compact, lightweight and efficient. The intrinsic cost of such lasers is low, since there is relatively little construction work involved in their designs, which are based mainly on solid-state diodes and doped fibres. As the price of such lasers comes down, so the market will expand (Steen & Mazumder , 2010).

Hand-held laser devices for the art and do-it-yourself markets seem an obvious development: desktop laser erasers, along with microcladding, welding or cleaning lasers will spawn a surge of small businesses. Diode-pumped solid-state lasers and phase-matched diode arrays are among other contenders for the leading choice of laser, with the diode laser having the greatest potential future. Diodes are efficient, compact and simple to operate; understanding their cavity optics and controlling their mode output could make them the device of the future (Steen & Mazumder , 2010).

Automatic beam-guidance systems, which are currently receiving some research interest, will lead to the simple control of laser beams over long distances, allowing a new field of applications to develop. Finally, the development of beam and workpiece translation equipment, including the possibility of remote processing using long depths of focus, combined with high-speed software and user-friendly programming, is an on-going vision for many engineers (Steen & Mazumder , 2010).

10. Relevant Issues for Modern Engineering Education

Education of highly qualified specialists in this area can reduce the current technological gap between the advanced and conventional manufacturing sectors. Unfortunately current laser material processing programs in universities are very limited, most likely due to the lack of teaching knowledge and availability of high-power laser “schools”. Too few universities are equipped with high-power lasers, therefore the opportunities for studying laser material processing in most cases lack any practical training. In addition, the field is multidisciplinary and requires training in a number of different scientific fields, such as laser, optics, automation, control, robotics and material science (Toyserkani et al, 2010).

Sales of laser systems have increased exponentially over the last fifty years. Annual double-digit growth was common during the 1980s and 1990s, tempered only by the economic turbulences of the early 1990s and the recent economic crisis. At the turn of the millennium, about 125,000 industrial lasers had been sold. If sales continue to rise at the same rate in the coming years—as is expected—the number of systems will more than double every five years (Ion, 2005).

The importance of teaching the subject of laser material processing has only recently been acknowledged. The number of hours devoted to university teaching in the subject is relatively small in comparison with conventional manufacturing technologies, and its growth has lagged behind the increase in industrial applications. Engineering undergraduates might receive a few hours of instruction in the use of laser-based fabrication and its technical advantages. There are opportunities for industries and vocational education centres to join forces and devise relevant courses to meet future needs. The rapid rate of change in laser-based industries means that qualifications will require constant updating. Conferences and industrial workshops are of paramount importance in spreading the capabilities of laser-based fabrication among existing practitioners and interested parties, to meet the demand for innovative and sustainable solutions to manufacturing problems (Ion, 2005).

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