- usually they are applicable only to large crankshafts, more than Ø 200 mm;
- they are closely guarded know-how;
- they require highly-qualified operators – engineers;
- they are not capable to rebuild the surface.

In the same time, medium speed four-stroke diesel engines are maintaining their dominance in the propulsion of smaller ships as well as larger specialist tonnage such as cruise vessels, car/passenger ferries and Ro-Ro freight carriers. Crankshaft journal diameter of these engines often is below 200 mm [6].

Although the surface grinding technology has been ascertained to be highly efficient and money-saving, it does not address damaged crankshaft surface material build-up solutions. Furthermore grinding has certain problematic aspects related with the surface properties, including reduced hardness and stiffness. Grinding into smaller diameters also requires tailored (repair size) bearing shells – these are not always easily available on the spot. Therefore crankshaft journals grinding should be accompanied by applying technologies which are restoring the original bearing diameters and even improving original surface properties. The following conventional methods for shipboard crankshaft journal renovation are currently used in marine engine crankshaft bearing repairs:

- conventional TIG/MIG/MAG build-up welding
- plasma coating (welding and spraying)
- metal-plastics, e.g. Devcon Plastic Steel®
- surface hardening and nitrating
- annealing (to remove excess hardness)

These surface refurbishing techniques are approved by most Ship Classification Societies, but are limited to use only within workshop (onshore) environments. Others can be applied for emergency repairs and only as a temporary solution. None of these technologies can be used fully on board the ship.

Taking into account the above mentioned considerations and challenges it has been decided to consider application of the laser build-up welding and/or cladding technologies to in-situ marine crankshaft repairs. Indeed, laser technologies are around already for many years, but only within last 5-10 years these technologies became truly reliable and accessible [7]. Since laser cladding ensures local heat input and low surface distortion, it can be successfully applied to crankshaft journals refurbishing. Moreover, within the past decade the laser build-up process has gradually advanced and in particular in domains of high power diode and fiber lasers [8]. For this particular research it is important that quality of the new coating is superior to the bearing journal surfaces manufacturers' technical specifications. Required mechanical properties like hardness, stiffness and tribological behavior can be adjusted accordingly by choosing tailored materials.

Application of laser build-up welding and cladding for the crankshaft journals surface renovation is considered by industry and academia. In particular the development of a laser cladding process in preparation for the industrial application of crankshaft reconditioning has been scientifically evaluated [9, 10, 11]. Several repair companies already offer laser cladding as an option for crankshaft journal renovation [12, 13]. Yet laser build-up and cladding technologies to be applied for true in-situ marine crankshaft repairs – without dismantling the whole marine diesel and removing crankshaft itself from its bed in engine housing.

Hence research has been done on how to deploy laser cladding technology for in-situ crankshaft repairs. A potential solution to the problem could be to fit laser nozzle to already existing platform of the crankshaft journal grinding equipment

This platform is placed directly on the crankshaft bearing surface to be repaired and ensures a solid base. Theoretically, if one finds a way to fit a laser cladding head onto this platform, the crankshaft surface refurbishing, including build-up welding, can be achieved directly in the engine housing. In this case, repairs would logically be limited to the crankpin journals only. This would have enormous economic benefits and could be combined with an in-situ crankshaft grinding machine. Thus in order to achieve the aforementioned goals, a comprehensive overview is needed, including laser build-up and in particular cladding technologies.

2. DEVELOPED IN-SITU CRANKSHAFT JOURNAL MACHINING TECHNOLOGY

A new technological approach has been developed. It significantly simplifies machining processes and provides that crankshaft journals grinding can be done directly inside the engine housing. Thus there is no need to remove the crankshaft from engine. This new technology results in significant savings of financial and human resources. On top of that much less overall repair time is needed for the ship diesel engine repairs. The latest is a very important argument for the ship owners and shipping management companies [14].

The designed grinding device is an electro-mechanical hand instrument, the principal construction of which is relatively simple and safe. Its main parts are the following: drive mechanism, reduction gear, positioning and adjustment system, grinding stone (in protective casing), control gauge etc. Originally the grinding device was designed for the machining of the crankshafts crankpins. The grinding device is based directly on crankshaft crankpin radii R (see Figure 4). It requires previous removal of the connection road and bearing liners [2, 14].

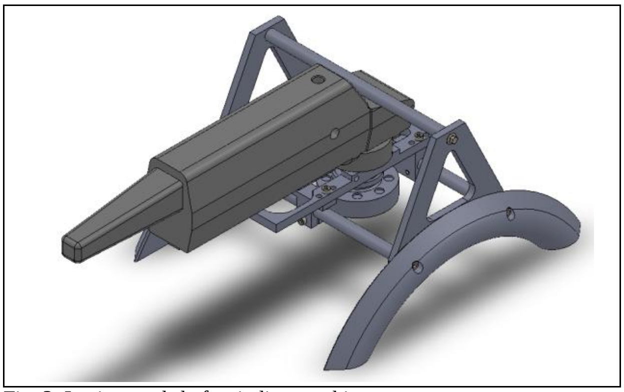


Fig. 3. In-situ crankshaft grinding machine

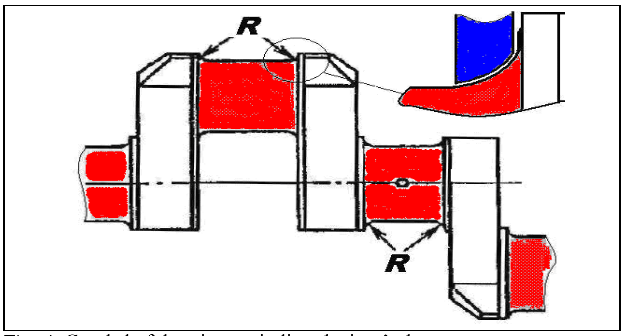


Fig. 4. Crankshaft bearings grinding devices' placement

Nevertheless, during experiments the device proved to be easily applicable also for the grinding of crankshaft main bearings. In this case crankshaft should be previously dismantled form the engine and centered in the turning machine. This grinding device has been extensively tested and proved its capability to ensure that crankshaft bearings surfaces are renewed according the prescribed geometrical and surface roughness parameters.

In principle by simple constructive adjustments this grinding device can be applied eventually to any type of crankshafts. However additional difficulties occur when very small or very large (bearings with Ø > 350 mm) crankshafts have to be renewed. Actually due to the spatial limitations this device cannot be used for bearings less than 100 mm in diameter – see Figure 5.

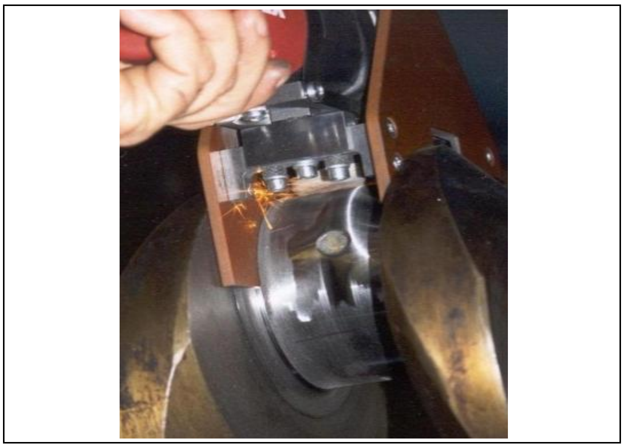


Fig. 5. In-situ crankshafts grinding device. journal with ∅ 120 mm

The renewable crankshaft bearing surface is abrasively processed by the flat surface of grinding stone. This kind of abrasive stone position is rather unusual for grinding operations. However, only in this manner it is possible to carry out crankshafts grinding in the very limited space of the engine housing. This is the main advantage of this elaborated equipment in comparison with other available grinding devices in the ship repair facilities. Relatively small diameter and specific position is compensated by the very high rotation speed of the grinding stone.

Feeding motion of grinding device is ensured manually by an operator, who steady moves the device in parallel to machining surface and in the same time performs cyclic round-shape motions. The grinding depth is fixed by the special adjustment plates and screws. In exceptional cases, when at the end of machining it is necessary to achieve a smooth surface it is possible to use the special polishing discs and polishing wax.

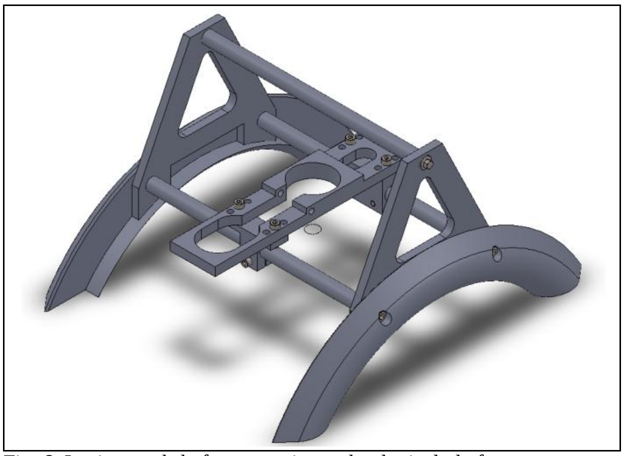


Fig. 6. In-situ crankshafts renovation technological platform

Taking into the above described particularities of the novel technology, its advantages and its limitations, it is evident that the technological platform itself (see Figure 6.) could be extended to the laser cladding. Hence more detailed analysis of laser cladding technology and its application is needed – see the following chapters.

3. BUILD-UP WELDING TECHNOLOGIES

Build-up welding in comparison with other material deposition technologies generally provides coatings with higher adhesion due to metallurgical bond created by partial or fully molted materials. The joint between coating and substrate is usually the strong and are thus particularly appropriate for applications with heavy wear conditions (e.g. marine crankshaft journals). Additionally these built-up joints show high edge strength [15].

Depending of type build-up welding usually provides single new layer up-to 1-6 mm. Further application of multiple layers is theoretically unlimited, but certainly suites well engine crankshaft surface renovation needs. A fusion metallurgical bond always creates a mixture of coating and substrate materials. The degree of fusion, or ratio of molten substrate material to the total volume of molten material, is a characteristic value, in percent:

$$= \quad / \quad \cdot 100 \qquad (1)$$

Practical measurements of the degree of fusion involve either planimetric methods on cross sections, or spectrometric analysis of substrate and coating material. For bigger accuracy, spectrometric calculations focus on the allying element with the greatest variation between the two materials, in percent:

$$= \frac{\quad -1}{\quad -1 \; +1} \cdot 100 \qquad (2)$$

ρ_c – density of coating material;

$\rho_{substrate}$ – density of substrate material;

m_c – % by mass of alloying element in coating material;

m_{fc} – % by mass of alloying element in fused coating.

If the difference in density of substrate and coating material is negligible, calculation of the degree of fusion simplifies to, in percent:

$$= \ 1 - \frac{}{} \ \cdot 100 \qquad (3)$$

Fusion dilutes the coating material and changes its properties. The degree of fusion is characteristic of an applied build-up welding technique and parameters. Processes with high energy density (e.g. laser build-up welding) in the operating beam produce the lowest degrees of fusion.

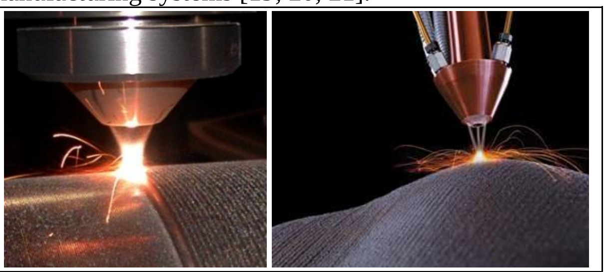
Without any subsequent machining, geometries produced by fusion build-up welding are adequate for applications with low requirements in terms of geometrical accuracy. Applications with precisely defined geometry, e.g. build-up welding of crankshaft journals, require mechanical post-processing of deposited coatings [15].

4. LASER BUILD-UP WELDING AND CLADDING

Laser beam build-up welding is technologically comparable to plasma build-up welding and plasma spraying. One of the advantages of this technology is its potential application in cases where the component is heavily stressed (e.g. crankshafts). Compared with conventional build-up welding, laser machinery has exact controllability of the welding process and composition of the layer, as well as the precise localization of the build-up material [16].

Laser beam welding uses a high-power laser beam as the source of heat to produce a fusion weld. Because the beam can be focused onto a very small area, it has a high energy density and deep penetrating capacity. The beam can be directed, shaped and focused precisely on the exact part of the workpiece. Laser beam welding provides good quality results with minimum shrinkage or distortion. Laser welds have good strength and are generally ductile and free of porosity. Build-up welding, high temperature brazing and cladding nowadays are frequently used for refurbishment of machine components with high intrinsic value and elevated replacement costs. Cladding is rapidly taking its place for rebuilding of gas and aviation turbines, heavy duty and hard material shafts, etc [17, 18].

The high-energy beam creates intense heat input and thus allows low degrees of fusion. Furthermore, heat input to the part is minimized and distortion remains low. The heat input into the workpiece is lower compared with MIG/MAG or plasma welding, whilst guaranteeing metallurgical bonding to the substrate. The accuracy of the resulting structures, in the range of 0.1 mm, is the highest possible in the group of build-up welding techniques. On the other hand, the available system expertise (lasers, powder feeders and nozzles) permits easy, successful integration of the laser technology into manufacturing systems [19, 20, 21].



a) b)

Fig. 7. Laser cladding, source: a) Laser welding solutions, b) Laser focus world

Several build-up welding laser platforms are currently already available on the market [22]. Table 1 summarises the technological features and parameters of shipboard diesel engine crankshaft renovation needs.

Type of laser	Maximal output power in KW	Wavelength
CO_2	20	10.6 μm
Nd:YAG	4	1064 nm
Diode	4	808 and/or 940 nm
Surface layer geometry in a single operation (for a 6 kW-CO_2 laser)		
Built-up layer width. *L*	0.5 to 8 mm	
Built-up layer height. *H*	0.2 to 2 mm	
Single layer thickness. *B*	0.3 to 3 mm	
Deposition rate	up to 1 kg h^{-1}	

Tab. 1. Laser build-up welding technical parameters

Laser beam build-up welding and cladding in particular is rapidly expanding in all domains of industrial manufacturing. The new fiber laser applications are allowing reach difficult welding positions. Within the last decade, a new compact coaxial powder nozzle for fiber laser build-up welding has been developed. This nozzle features in particular a compact design for improved accessibility and a smaller powder focus. The powder distribution within the nozzle is segmented into four, independent powder injectors. Thus the powder delivery becomes almost independent of gravity. As a result, the nozzle can be used to perform cladding in any direction which is of paramount importance for in-situ crankshaft cladding [23].

Fig. 8. Coaxial powder nozzles. Source:Fraunhofer Institute of Material and Beam Technology (IWS)

With side-blown powder there is a strong directional impact on the clad bed shape and the alignment of the powder stream with the melt pool is crucial. The coaxial system avoids these difficulties and is behaving like a laser pencil, capable of writing in metal on the surface within necessary pattern and shape. It is important to note that design of these nozzles is ensuring that the powder does not meet the beam until it is outside the nozzle orifice [24, 16]. It is to avoid clogging.

The design of coaxial nozzle with blown powder is provided in Figure 9 [23]. Up to four powder components are blown into an expansion chamber. There a powder-gas-cloud is formed, which is distributed homogeneously around the laser beam. After this, the powder stream passes through specially shaped channels, which transfer it into a quasi-laminar flow parallel to the axis of the laser beam. Finally, the ring-shaped slit of the nozzle tip focuses the powder stream onto the laser spot. Blown powder cladding is conducted over small melt pool area, which is traveling over surface of the substrate. The thermal penetration can be controlled by the speed, power – spot size. The clad layer usually is hawing residual tensile stress that may reduce overall tensile strength (e.g. of crankshaft) up to 50 % [25, 26].

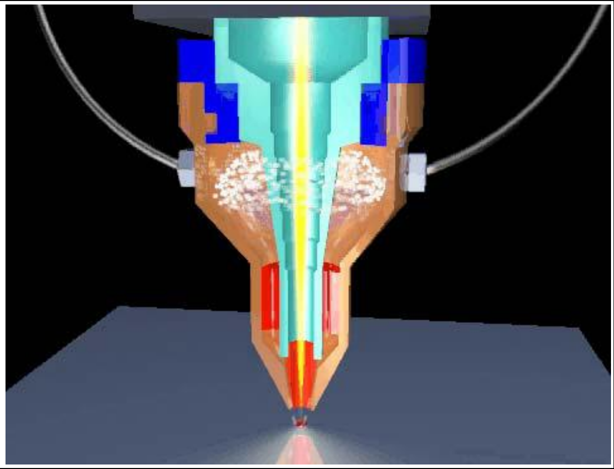


Fig. 9. Coaxial powder nozzle. Source: Fraunhofer Institute of Material and Beam Technology (IWS)

5. APPLICATION OF THE TECHNOLOGY

The possible integration of coaxial powder nozzle onto the crankshaft in-situ renovation platform is illustrated in Figure 10 and 11. The nozzle can be oriented manually and/or mechanically. Sufficient accessibility has to be confirmed and there should be no "blank spots".

This technical solution cannot be applied to very small crankshafts owing to space limitations, or to very large diameters. Already at the outset, there are clear advantages of such a technical solution: mobility, productivity, high surface quality with little finishing needed. Yet there are also certain problematic aspects and inherent difficulties:

– high initial cost of equipment;
– marine diesel engine crankshafts renovation by means of laser cladding is not yet approved by the classification societies;
– material deposition rates remain low compared to conventional build-up welding techniques;
– highly qualified operators are needed;
– high voltage power source (not a problem on vessel);
– separate station for welding powder or wire deposition;
– the influence on mechanical properties can neither be predicted nor has been investigated sufficiently.

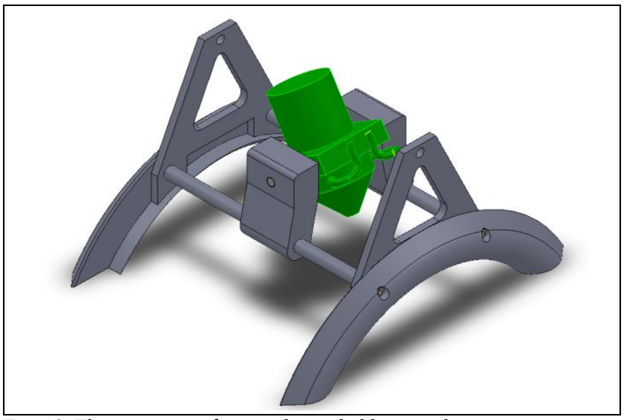


Fig. 10. The prototype of in-situ laser cladding machine

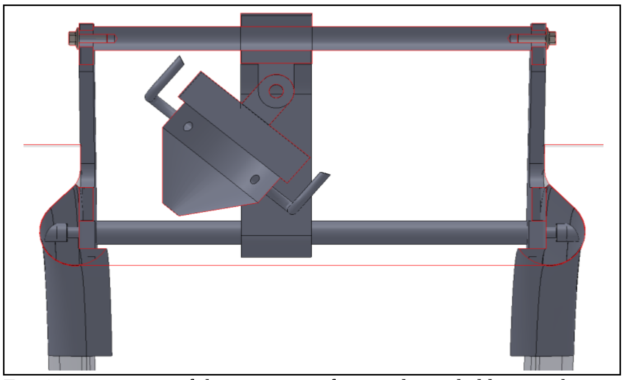


Fig. 11. positioning of the prototype of in-situ laser cladding machine

An additional technical challenge is not to damage the technological platform during cladding operations. In practice, this means that particular attention should be taken so as to not touch the crankshaft bearing technological radii –see Figure 4.

Currently commercially available laser power (fibre-optic) lines are flexible as well as cladding powder supply pipes are flexible. They can be deployed through piston liner from the top of the engine.

Another aspect to bear in mind is that laser cladding of outer surfaces of bearings will be achieved at a certain angle - α and that respective laser power corrections will be needed to ensure homogenous deposition of the new surface layer(s). For crankshafts with external technological radii, subsequent manual application of some material might be needed to compensate "black" area left by the laser nozzle angle.

At this stage no major technological or constructive obstacles could be detected which could prevent laser cladding coaxial powder nozzle application to the said technological platform. Initial studies and modelling revealed rather optimistic results.

6. FUTURE DEVELOPMENTS

This article is solid base for further studies which can be directed to the full-scale prototype machine development. Such device shall be built and tested both in laboratory and in-situ on board the ship. Upcoming tests should focus on verifying the surface quality and integrity obtained. Special attention shall be given to the safety aspects of the high energy lasers application on board the ship.

Proposed technical solutions require in-depth testing and would be possible using the real crankshafts which should be renovated in the relevant ship repair companies. Ineviatbly the initial faze of these trials will be carried out in confined laboratories with the appropriate technological equipment for the actual cladding and provided with adequate results measuring and recording equipment.

Furthermore, laser economic costs, pros and cons of said technology as well as practical benefitsalso have to be scrutinized too.Indeed project of such scale will require enhancedcooperation and involvement of the entities that possess the laser cladding know-how and entities that are having technical solutions of the in-situ ship repair technologies.

7. CONCLUSIONS

This article outlines an idea to use the laser cladding technique for marine engine crankshaft bearing surface repairs. It proposes to use the previously developed technological platform which is designed to perform renovation (surface grinding) operations inside an engine.

This study has confirmed that indeed laser cladding technology is very well suited for marine crankshaft journals surface renovation. Among other clear benefits, laser cladding offers virtually unlimited alloys varieties and ensures full metallurgical bound (not like in thermal spray). It revealed that the most appropriate would be cladding technology with commercially available CO_2 or fibber diode laser trough coaxial powder nozzle.

Although some technical difficulties where identified, a machine for shipboard crankshaft bearing in-situ repairs using laser cladding could be built. Study also revealed that this know-how can be applied to crankshafts with bearing diameters starting from 120mm. When constructed, tested and approved by the competent authorities, such a device would offer an innovative solution for shipboard crankshaft repairs. It opens up a new field of application to laser cladding and would generate considerable economic benefits.

8. ACKNOWLEDGEMENT

The study on which this paper is based is being developed, within the framework of the scientific research project “Laser cladding application to in-situ repairs of the marine engine crankshafts”, financially supported byRiga Technical University, Latvia.

9. REFERENCES

[1] Woodyard D. (ed.). (2009). Pounder's Marine Diesel Engines and Gas Turbines, 9th Edition. Butterworth Heinemann, ISBN 0750689846, Oxford, UK

[2] Torims. T. (2006) Researches on machining of diesel engine crankshaft journals surfaces. Doctoral Thesis. Riga Technical University,Latvia, Riga

[3] *** (2012) http://www.goltens-insitu.com/ *accessed on* 05.08.2012

[4] *** (2012) http://www.abcgrinding.com/ *accessed on* 05.08.2012

[5] *** (2012) http://www.in-situ.co.uk/ *accessed on* 05.08.2012

[6] Molland A.F. (Ed.). (2011). The Maritime Engineering Reference Book. ISBN 978-0-7506-8987-8. pp. 390. 399.Elsevier,Oxford, UK

[7] Ion. J.C. (2005). Laser Processing of Engineering Materials. Elsevier Butterworth-Heinemann. ISBN 008097189 X. Elsevier, Oxford, UK

[8] VollertsenF., Partes K., Meijer J. (2005).State of the art of Laser Hardening and Cladding, Proc. of the Third Int. WLT-Conf. on Lasers in Manufacturing. AT-Verlag. Munich, Germany

[9] KoehlerH., PartesK., SeefeldT., VollertsenF. (2010).Laser reconditioning of crankshafts: From lab to application. Physics Procedia, Volume 5, Part A, 2010, pp. 387-397, ISSN 1875-3892, 10.1016/j.phpro.2010.08.160

[10] VishnevetskayaI. A, Denisov V. A. and SolovyovA. V. (1996).Tribotechnical efficiency of journal-bearing connection of crankshaft renewed by laser built-up welding. Proc. SPIE 2713, 301, pp 301-305, ISSN 0277786X

[11] KoehlerH., PartesK., SeefeldT., VollertsenF. (2011).Influence of Laser Reconditioning on Fatigue Properties of Crankshafts. Proceedings of the Sixth International WLT Conference on Lasers in Manufacturing Lasers in Manufacturing 2011 - Volume 12, Part A. Physics Procedia, pp. 512-518, doi:10.1016/j.phpro.2011.03

[12] *** (2012) http://www.laserbond.com/.au *accessed on* 05.08.2012

[13] *** (2012) http://www.ere-shiprepairs.gr *accessed on* 05.08.2012

[14] Torims T., et al. (2009).New approach for the crankshafts grinding and determination of the 3D surface roughness model for the crankshaft bearings. The 20th DAAAM International Symposium Intelligent Manufacturing & Automation: Theory, Practice & Education. ISBN 9783901509704, pp 1563-1565.Vienna, Austria

[15] BachF.W, LaarmannA., WenzT.(Ed.). (2006) Modern Surface Technology. WILEY-VCH Verlag Gmbh& Co. ISBN 3-527-31532-2. Weinheim, Germany

[16] Steen, W &Mazumder, J. (2010) Laser Material Processing. Springer.ISBN 978-1-8499-6061-8. London, UK.

[17] *** (2012) http://www.sulzer.com/ *accessed on* 05.08.2012

[18] *** (2012) http://www.hardwear.com.au/ *accessed on* 05.08.2012

[19] Nowotny, S. (2007). Laser Beam Build-Up Welding: Precision in Repair, Surface Cladding, and Direct 3D Metal Deposition. Journal of Thermal Spray Technology, Vol.16, No.3. Sept.2007.pp344-348, DOI: 10.1007/s1166600790285

[20] *** (2012) http://www.laserweldingsolutions.com/ *accessed on* 05.08.2012

[21] *** (2012) http://www.laserfocusworld.com/ *accessed on* 05.08.2012

[22] Fraunhofer Institute for Material and Beam Technology, Laser Beam Build-up Welding.IWS Dresden. 2011. Available from: *** (2012) http://www.iws.fraunhofer.de/ Accessed: 05.08.2012

[23] Nowotny S.,Scharek S., Kempe F., Beyer E. (2003) COAXn: Modular System of Powder Nozzles for Laser Beam Build-Up Welding. Proceedings of ICALEO 2003. October 13-16, 2003. Jacksonville, Florida USA.

[24] Lin J. and Steen W. M. (1998) Design characteristics and development of a nozzle for coaxial laser cladding. Journal of Laser Application.Vol. 10, Issue 2.1998.Detroit, LIA Orlando. doi:10.2351/1.521821. pp 27 -36

[25] Steen W. M. (1988) Laser Surface Cladding, Proceedings of the Indo US. Workshop on Principles of Solidification and Materials Processing, SOLPROS, 1988, p. 163 - 178

[26] Habedank G., Theiler C., Grupp M., Kohn H., Sepold G., Vollertsen F. (2003). Laser beam cladding of steel with high power diode lasers, Proc. of the Third Int. WLT-Conf. on Lasers in Manufacturing.AT-Verlag. Munich, Germany