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Procedia Engineering 100 (2015) 559 – 568

Procedia Engineering

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25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

Development of Technological Equipment to Laboratory Test In-Situ Laser Cladding for Marine Engine Crankshaft Renovation

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Abstract

This article presents the development of novel technological equipment for laboratory testing marine diesel engine crankshaft renovation using an in-situ laser cladding device. It outlines the technology and method devised to perform crankpin journal renovation operations directly in the engine housing, without removing the crankshaft from the engine. Firstly it describes marine crankshafts and the common faults of their main and crankpin bearings. There follows an analysis of conventional crankshaft repair methods, along with their limitations. The principles of laser cladding nozzles are then described, outlining the benefits of laser cladding technology for in-situ marine crankshaft repairs. The paper goes on to assess previous studies in field and the laser cladding repair solutions currently proposed for marine crankshafts. It also indicates the view taken by Classification Societies towards laser-cladding crankshaft repairs. The development of the in-situ prototype equipment is detailed, along with full-size prototype design steps, accompanied by the relevant analysis and considerations. In addition, appropriate calculations for the laboratory test device are given. The technological process and method described in this article are an innovative application of additive manufacturing technology to the crucial requirements of modern, ship-repair enterprises. In-situ crankshaft laser cladding is a promising technology with good financial prospects.

Peer-review under responsibility of DAAAM International Vienna

Keywords: laser cladding; crankshaft; marine; in-situ; tests

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Peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2015.01.405

1. Common marine diesel engine crankshaft failure modes and journal damage

Nomenclature

v	cladding speed
b	cladding width
L	crankpin journal bearing surface circumference
d	crankshaft journal bearing diameter
n_{min}	minimum crankshaft rotation speed
n_{max}	maximum crankshaft rotation speed
$\mathrm{i_w}$	worm transmission
$\mathrm{i_s}$	spur gear transmission
$\mathrm{i_{box}}$	gearbox transmission rate
f_{max}	frequency of inverter unit for maximal crankshaft rotation
f_{min}	frequency of inverter unit for minimal crankshaft rotation
V_{Amax}	maximum axial movement speed of laser head over crankpin journal surface
V_{Amin}	minimum axial movement speed of laser head over crankpin journal surface
m	tooth modulus
z	number of teeth
n_{ASmax}	maximum rotation speeds for axial drive stepper
n_{ASmin}	minimum rotation speeds for axial drive stepper

Marine diesel engines, like any other internal combustion engine, convert the power of a controlled explosion into a reciprocating motion. This linear motion is converted into a rotary motion that can be used to rotate a crankshaft. The crankshaft is continuously subjected to the force from the explosions, whose energy it transmits to the engine flywheel (cf. Fig. 1, 1), which is in turn transferred to a shaft connected to the principal machinery. Crankshafts are the most crucial part of any engine. They are therefore designed to be rigid, with high torsion strength that can withstand extreme force. [1]

A crankshaft has three main components:

- A crank pin journal (2) which receives the energy produced by the controlled explosion within the engine.
- A main journal (3) which carries the crankshaft within the main bearings.
- The crank webs (4), which connect the two journals together.

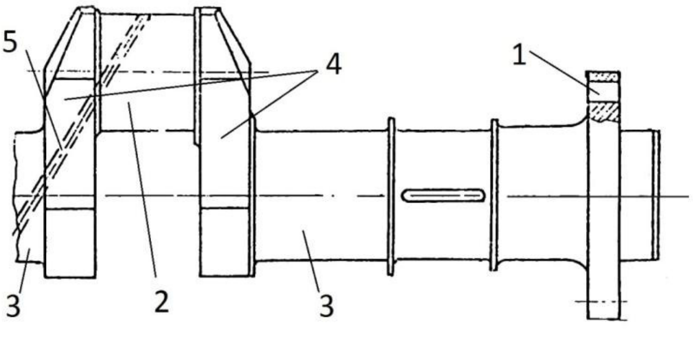


Fig. 1.Principal crankshaft components.

The crankshaft also carries lubricating oil to the crank pin journals, crossheads, top-end bearings and pistons. This involves complex and highly polished oil passages (5) through the crankshaft without reducing rigidity or strength, or causing areas of high stress. There are four main types of modern-day crankshaft:

1. Built crankshafts where the crankpin journal, main journal and crank webs are all manufactured separately and then fitted together by shrink fitting and relying on friction to prevent slippage.
2. Semi-built crankshafts where webs and main journals and/or crank webs and crank pin journals are forged as one piece and then shrunk fit together. These methods are essential in large engines as it is impossible to build a very large crankshaft from one piece of metal.
3. Welded crankshafts which were patented by MAN-B&W. These consist of a web, a half main journal and half crank pin journal which are welded together.
4. Smaller engines have fully forged crankshafts constructed from one piece of metal. Crankshaft journals (being running surfaces) are hardened.

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 (see Fig. 2). Wear also leads to insufficient geometrical clearances of the crankshaft journals, such as roundness and central alignment.

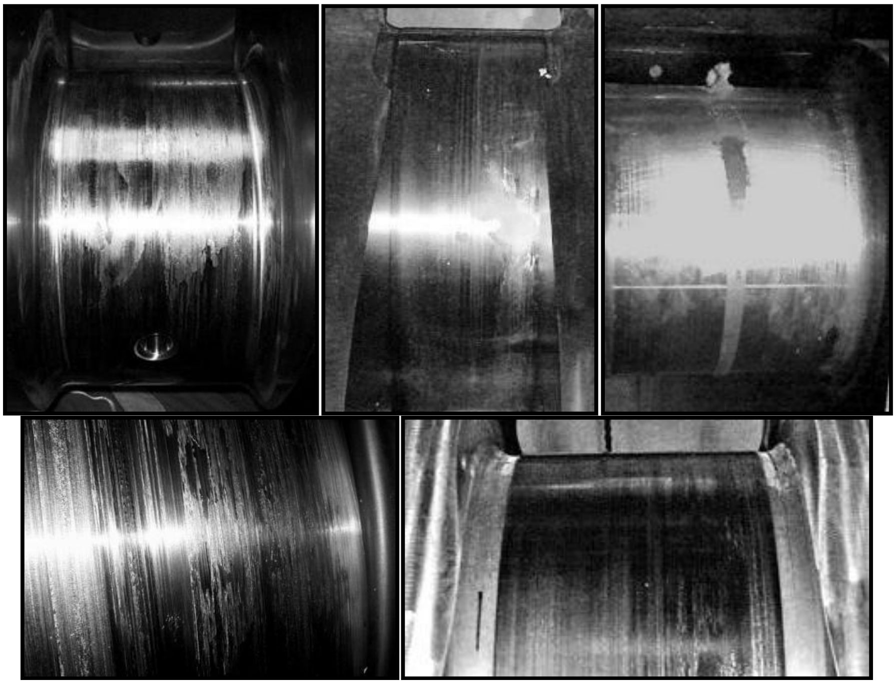


Fig. 2. Common faults of diesel engine crankshaft journals.

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. Marine diesel engine crankshaft main and crankpin journal surfaces therefore need regular repairs in order to partially or fully renovate the worn crankshaft journals. Such repairs are habitually 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 refurbishment 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.

At the same time, none of these conventional technologies can be used on-board the ship to fully build up worn crankshaft crankpin journal surfaces. However, crankshaft crankpin repairs frequently have to be carried out directly on-board 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 [2].

Laser cladding offers many advantages over the aforementioned conventional coating processes [3]. It can deliver a much higher quality of coating with minimal dilution and distortion, offering enhanced surface quality parameters. The resulting surface material has characteristics similar to or even better than the original. In general, the advantages of laser cladding are: a) reduced production time; b) enhanced thermal control; c) highly satisfactory repair of parts; d) production of a functionally graded part; e) production of smart structures. The flexibility of laser cladding is gradually 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 by training students in laser cladding techniques [4].

2. Assessment of previous studies and current laser cladding repair solutions in the ship-repair sector

Over the past 10-15 years, laser technology has 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 [5], the authors addressed material property issues, without however providing technical solutions or applications for the laser build-up technology itself. A further article [6] 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. The feasibility study [7] 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.

Another significant paper in the field [8] 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 manufacture 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. Development of technological equipment for laboratory testing of marine diesel engine crankshaft renovation with an in-situ laser cladding device has therefore commenced.

Although laser cladding repairs of the marine machinery and diesel engine parts are not yet fully accepted by the relevant Classification Societies (see chapter below), several ship-repair enterprises around the world are currently offering laser cladding services. For instance, the German enterprise Gall & Seitz System GmbH proposes to recondition worn and damaged parts (e.g. pistons, shafts and other rotating parts) by laser powder cladding. This company also offers a mobile robot unit for laser powder cladding of large, immobile or relatively inaccessible parts, in other workshops, ships, industry plants or even in the field [9]. Another European ship-repair company which is known to offer laser cladding services is the Greek KIMI SA [10]. This company offers to recondition various engine components in their workshop, including crankshafts, duplex stainless steel impellers and 4-stroke piston rebuilding. The Dutch company Stork Gears & Services BV [11] is offering similar services for various shaft modifications and repairs, including fast on-site laser cladding services and repairs by mobile robot system, analogous to the Gall & Seitz System.

The aforementioned examples clearly illustrate the interest of ship repair, oil and gas and offshore industries in mobile laser cladding applications. Yet none of them offer a true in-situ solution for marine diesel engine crankshaft cladding.

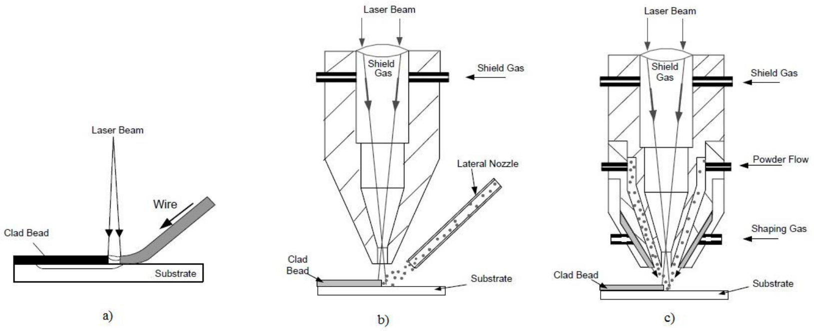
3. The laser cladding technological process and its state of play

Laser cladding is become a significant tool for industrial world applications, including repair technologies as well as new part improvement and production. In standard applications, several components are used to carry out the laser cladding process: laser source, laser optical fibre, required optic, cladding head for powder or wire delivery, guidance and processing software [12, 13].

The main application proposed in this paper is repair technology. More specifically, it focuses on in-situ repair technology for marine crankshaft journals. This crankshaft repair technology is in its primary development stage, and this article is devoted to the selection of the cladding nozzle. In the case of in-situ marine crankshaft journal repairs, the laser nozzle and material supply equipment has to fulfil particular requirements [14]:

- good accessibility;
- equipment suitability for lengthy processing;
- high material supply efficiency;
- flexibility, possibility to integrate the laser cladding equipment;
- capacity for multi-directional movements during processing.
- result should be reliable and of high quality.

Processing heads – several types of nozzles are used to adapt to different material forms (powder and wire) (Fig. 3), laser spot formation (round, square and rectangular), size and material delivery direction.



a) b) c)

Fig. 3. Laser cladding [4].

Overall the type of nozzle, the angle of the powder stream profile and powder stream dimensions on the melt pool area all influence powder cladding efficiency [15]. Fig. 3 shows the process head types which are most frequently used for a wide range of laser cladding applications.

The wire feeding process head (Fig. 3a)) offers high material efficiency and good process cleanliness. But these process heads result in the smallest cladding rates when compared with powder nozzles. Wire can be delivered to the melting pool from the side (FIG.3 a)) or for multi-directional cladding heads, the wire is perpendicularly delivered on melting pool and, optically splited laser beam is concentrated around wire. Special optics are used on the head, which is why the process head dimensions, without any modification, are not suitable for crankshaft renewal application [13].

Lateral injection nozzles (Fig. 3 b)) provide cladding in a single direction. Efficiency and cladding rates are the poorest in contrast with other powder process heads; moreover the stream is directed at one point, which may increase the risk of defects. The symmetrical latent powder injection nozzle helps achieve at least two cladding directions, when two injectors are used. The process has higher cladding rates and efficiency compared with systems a) and b). One drawback of this kind of system is the difficulty in providing effective cooling where separate elements are used. And effective cooling is a key factor during lengthy processes to protect equipment in operating conditions.

The universal coaxial nozzle system (Fig. 3c)) is useful when several modifications are required. These mostly involve different powder injectors, separate powder channels or ring slit, which are used for various spot sizes and forms. The ring slit is designed for smooth, stable powder delivery on flat and slightly tilting surfaces. Unlike a ring slit type nozzle, separate powder channels allow a lower angle of the processing head, yet quality of powder supply then is affected. The most common is symmetrical powder delivery, all set on one compact body (Fig. 4), where effective cooling can be provided. The coaxial powder system process is more effective and cladding rates are higher. Furthermore, additional safety gas flow can be ensured with this nozzle system, to help produce better quality cladding and form a powder stream that contributes to even higher efficiency. Safety gas is used as standard for powder transportation and also for optical element protection against process-reflecting particles that may damage the equipment. All of these benefits explain why coaxial system nozzles are widely used in industrial applications. Approximately 60-80% of industrial cladding applications are carried out using powder supply nozzles. Moreover research suggests that up to 98% of conventional tasks can be performed using coaxial nozzles [14, 8].

Fig. 4. Coax series nozzles from Fraunhofer IWS [15].

The powder system's advantage is its potential to simultaneously combine in the powder distributor and deliver up to four different powder materials (e.g. Fe-, Ni- or Co-based) and carbides (e.g. WC, VC, TiC), as well as ceramics. The aforementioned nozzle systems are suitable for production needs with up to 10 kW of laser power.

All of these benefits explain why coaxial nozzles are the most widespread of ship crankshaft journal renewal technologies. For the first stages of the in-situ renewal technology, the available equipment, without substantial modifications, will be used. Furthermore the available space of the coating area might even yield modifications in the nozzle design to improve accessibility. We may even look forward to seeing different spot forms, such as rectangles or squares. Despite the high efficiency of powder, not all powdery materials can be placed on the crankshaft. Hence wire-based weld metal delivery with full filler material utilization may be used as an alternative to the powder process.

4. Laser cladding technology for in-situ marine crankshaft repairs

A full-scale functional prototype of the in-situ laser cladding apparatus has been designed for the renovation and repair of crankshaft journal surfaces (see Fig. 5). The principles of this application are outlined in the Patent of the Republic of Latvia no. B24B5/42 - Device and method for the in-situ repair and renovation of crankshaft journal surfaces by means of laser build-up [16] and are the subject of the International Patent application PCT/LV2013/000006 of 18.07.2013 – Apparatus and method for in-situ repair and renovation of crankshaft journal surfaces by means of laser cladding [17].

The damaged crankshaft journal surface is renovated by fitting the laser cladding nozzle positioning and guidance device directly on the crankshaft journal fillets. This prototype device is currently being constructed. The main considerations of this project are provided below.

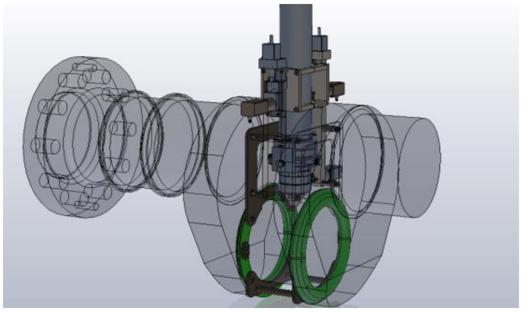


Fig. 5. Prototype of the laser cladding device for in-situ marine crankshaft repairs.

5. Current opinion of classification societies regarding the laser cladding of crankshaft journals

The authors of this article inquired with selected Classification Societies (IACS – International Association of Classification Societies members) as to their position concerning the application of laser cladding technology to marine diesel engine repair. The relevant technical requirements for crankshaft repairs—main and crankpin journal refurbishing and renovation—were sought.

Bureau Veritas recommended inquiring with the diesel engine makers, as these aspects are not handled by Class. The expertise lies with the engine manufacturers. Presumably the size of the engine will also matter when implementing this technology. The repair procedure is submitted to the class and they decide accordingly on a case-by-case basis, depending on the repair method. Typically the class defers to the maker's expertise on this subject.

Lloyds Register said that currently the only processes that have been applied to crankshafts are electrolytic plating with nickel, chromium or iron and thermal spraying. The firms undertaking repairs on crankshafts of engines installed in vessels classed with Lloyd's Register have to be approved by Lloyd's Register. For thermal spraying, each application is considered on a case-by-case basis. At present laser cladding is not an accepted repair process for crankshafts or main propulsion shafts, as being a fusion process, there is a risk that the heat-affected zone could have high hardness and result in detrimental residual stress.

Det Norske Veritas – Germanischer Lloyd (DNV-GL) has been involved in relevant research projects. Both are dealing mainly with repair welding of crankshafts by means of laser powder-clad welding. DNV-GL's welding department is involved. DNV-GL said that there is no particular technical specification concerning laser cladding (repair/build-up) of marine diesel engines crankshafts journals within the system. The main reason for this is because DNV-GL generally considers this issue to be ultimate responsibility of the manufacturer. In each case, a similar repair has to be done and the relevant procedure will be reviewed/evaluated separately by the Class (provided that we are invariably given consent by the maker's specialist). There are certain requirements within internal systematics, mostly involving acceptance criteria of marine diesel engines in this respect, so as to provide some essential guidance to attending surveyors. Reference to the DNV-legacy Instructions-to-Surveyors was provided [18]: "*(...) Metal coating, e.g. gas flame spraying, electric arc spraying, plasma spraying, electrolytic deposition and clad welding, is not an acceptable repair method for crankshafts, especially not in highly stressed zones such as fillets and bearing surfaces; (...) If, during the inspections, any indications of metal coating in high stressed zones are found, the shaft is to be rejected. Metal coating in other, lower stressed areas may be acceptable but should always be discussed with DNV HQ before acceptance is granted. (...) Guidance note: If, upon special evaluation, a crankshaft originally certified by another class society is being considered for acceptance, please note that some classification societies do accept metal coating of fillets and journals. This is normally stated on the certificate of repair report. In such cases and with reference to the above, the crankshaft is not to be accepted.*"

6. Development of the in-situ laser cladding prototype for marine diesel engine crankshaft crankpin journals

The prototype development began with obtaining a real ship crankshaft and building a mock crankshaft bed (see Fig.6). The Škoda/ČKD "6-27.5 A2L" type medium-sized marine diesel engine crankshaft was chosen for the trials. The project's aim was to try to place the laser cladding nozzle on the ship crankshaft housing and to develop the laser cladding process in situ. The final project result should be useable in-situ technology for crankshaft surface renovation.

Fig. 6. Crankshaft bed frame with gear and chain crankshaft transmission.

The initial data for the crankshaft cladding system development was defined by the laser cladding equipment parameters: cladding speed v = 200-3,000mm/min and clad width b = 2-16mm. It is important to note that b = 16mm could only be achieved if the rectangular nozzle type was used. This basic reference data was used for the initial calculation of the mechanical design, size and type of laser nozzle guidance device.

The first step was to calculate the circumference of the crankpin journal bearing surface:

$$L = \pi d = 3.141593 x 190 = 596.9 mm \tag{1}$$

Where d = crankshaft journal bearing diameter, mm

Hence the minimal and maximal crankshaft rotation speeds were calculated:

$$n_{max} = \frac{v_{max}}{L} = \frac{3000}{596.9} = 5.03\, rpm \tag{2}$$

$$n_{min} = \frac{v_{min}}{L} = \frac{200}{596.9} = 0.335\, rpm \tag{3}$$

After this step, the data for crankshaft rotation maximal and minimal speeds became available. Due to the relatively slow rotation speed, it was imperative to reduce transmission. The easiest way to achieve this low speed and variations was to reduce transmission. Consideration of the best solutions identified a 12 Pole AC engine, a worm gear speed reducer and frequency inverter. Furthermore the use of a frequency inverter facilitates rotation speed adjustment. In this case, the rotation speed reducer unit from the "*5107*" spur gear slotting machine was used. This unit is driven by the original 0.6kW 3-phase asynchronous engine with 1,410rpm at 50Hz and has two-stage transmission reduction in the gearbox with worm transmission i_w = 13 and spur gear transmission i_s = 4.4. The complete gearbox provided a transmission rate i_{box} = 57.2.

Additionally, for stable and reliable crankshaft rotation speed, a reduction transmission chain was built from our gearbox to the crankshaft (cf. Fig. 6). This was one of the most convenient ways to achieve transmission from the AC engine to the crankshaft. The chain transmission ratio was identified using optimal design and speed reduction considerations. The chain transmission ratio in the model was established as 4.77. Therefore together with the gearbox transmission rate i = 273 was obtained for this application.

Now at 50Hz, the chosen AC engine achieves:

$$n_{R50} = \frac{n_{50}}{i} = \frac{1410}{273} = 5.16 rpm \tag{4}$$

From here, the inverter unit frequencies for maximal and minimal crankshaft rotation can be calculated

$$f_{max} = \frac{n_{max} \times i \times 50}{n_{50}} = \frac{5.03 \times 273 \times 50}{1410} = 48.69 Hz \tag{5}$$

$$f_{min} = \frac{n_{min} \times i \times 50}{n_{50}} = \frac{0.335 \times 273 \times 50}{1410} = 3.24 Hz \tag{6}$$

After this, knowing the rotation speed, the axial movement speed of the laser head over the crankpin journal surface can be calculated:

$$v_{Amax} = n_{max} \times b_{max} = 5.03 \times 16 = 80.48\, mm/min \tag{7}$$

$$v_{Amin} = n_{min} \times b_{min} = 0.335 \times 2 = 0.67\, mm/min \tag{8}$$

The calculations provided above allow us to potentially opt for a smaller stepper motor (or *stepper*) capable of performing the calculated speed range whilst being small enough to fit into the mechanical composition. For the initial design, Nema 11 Geared Stepper Motors with 1:100 planetary gearboxes were chosen.

The chosen stepper can deliver a rated speed of 2rpm and rated max. torque of 4Nm. This data in turn allowed for selection of optimal size (smallest) rack and gear elements for the axial nozzle movement. The smallest possible spur gear, which maintains durability and could be fitted on the 6mm stepper axis is a spur gear with tooth module m=1 and the least possible number of teeth is 14. For that size spur gear and rack movement, the length on 1 rotation will be the same as the spur gear pitch circumference:

$$L_{SG} = d_p \times \pi = 14 \times 3.14 = 43.96mm \tag{9}$$

Where m = tooth module
z = number of teeth

Hence the minimal and maximal rotation speeds for the axial stepper drive were obtained:

$$n_{ASmax} = \frac{v_{Amax}}{L_{SG}} = \frac{80{,}48}{43{,}96} = 1.83rpm \tag{10}$$

$$n_{ASmax} = \frac{v_{Amin}}{L_{SG}} = \frac{0{,}67}{43{,}96} = 0.015rpm \tag{11}$$

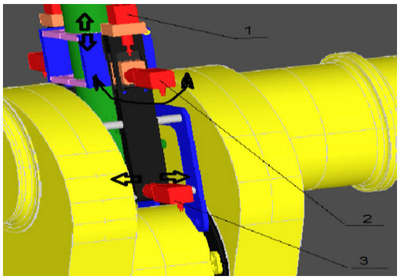


Fig. 7. Steppers on the nozzle positioning frame. 1 – focusing distance stepper; 2 – angular alignment stepper; 3 – axial movement stepper.

Similarly the rotation speeds were calculated for the laser nozzle focusing steppers and angle drive stepper.

In order to correctly position the nozzle angle, the use of two planetary geared NEMA 11 stepper drives was considered. These stepper drives work simultaneously from both sides of the nozzle frame. The angling mechanism was designed for maximum rotation angles of 5° on both axial directions of the crankshaft (cf. Fig. 7). Furthermore, the need arose for an angle stepper, in order to reach the corners of the journal bearing surface. As a result, the full travelling angle for the angling steppers is 10°.

For the laser nozzle focusing, two NEMA 11 Captive Linear Actuators with a travelling length 31.5mm were deployed. As with the angular alignment, it was suggested to use two linear actuators, one on each side, to provide more accurate and stable vertical movement of the laser nozzle. These linear steppers should provide the correct distance between the laser nozzle and processing surface. The NEMA 11 with lead screw gives 0.0032mm axial movement on 1.8° step, to ensure very precise nozzle focusing features.

It is important to note that the device described above is still under development and only the most relevant and certain calculations are provided in this article. Further conclusions will be available after a series of full-scale mechanical and guidance tests.

Conclusion

Ships engines' working conditions and intensive wear, accompanied by potential lubrication failures, may cause severe damage to crankshaft journal surfaces, such as ridges, cuts, grooves, tears, marks and the formation of a built-up edge. Consequently regular repairs of these surfaces are needed. Usually these repairs are performed in the workshop after dismantling the ships engine and moving crankshaft ashore. If needed various types of the build-up repairs are done on specialist machines. However, none of these provide for the possibility to renovate engine crankshafts on-board the ship, which would save time and money.

Assessment of previous studies in the field and current industrial practice confirmed that laser cladding can be successfully applied to crankshaft reconditioning. Inquiry revealed that laser cladding repairs of marine engine crankshafts are not yet accepted by the Classification Societies. At the same time, several ship repair enterprises are already offering laser cladding services. There are direct indications that ship repair, oil and gas and offshore industries are greatly interested by mobile laser cladding applications. Therefore, research was conducted on how to deploy laser cladding technology for in-situ repairs of the crankpin journals of crankshafts.

It has been confirmed that the coaxial nozzle is the optimal laser head solution for in-situ crankshaft repairs. For initial trials, commercially available laser components and equipment were used. Consideration should be given to both wire and powder based solutions.

As a result of the above considerations, an outline is provided in this paper for a full-scale prototype of the in-situ laser cladding apparatus designed for the renovation and repair of crankshaft journal surfaces. This apparatus ensures that damaged crankpin surfaces could be renovated by fitting the laser cladding nozzle positioning and guidance device directly onto the crankshaft journal fillets.

Relevant calculations and a comprehensive description are provided for the development of technological equipment for laboratory testing of marine diesel engine crankshaft renovation with the in-situ laser cladding device. This forms a solid basis for further research related to the developed prototype, and especially for eventual full-scale mechanical tests and guidance system alignments.

Acknowledgements

Support for this work was provided by the Riga Technical University through the Scientific Research Project Competition for Young Researchers No. ZP-2013/ 31

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