PROPELLER SHAFT REPAIR FOR A LARGE FERRY WITH THE AID OF LASER CLADDING TECHNIQUE

N. Kampanis, Mechanical Engineer, PhD, MSc, DIC, BEng, Iroon Polytehniou 31 Piraeus 18532 Greece, Phone +30 693 6256759, email nicholaskampanis@gmail.com.
I. Hauer, Höganäs AB, SE-263 83 Höganäs, Sweden. Phone +46 42 338792, fax +46 42 338150, email ingrid.hauer@hoganas.com.

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SUMMARY

The process of reconditioning a propeller shaft from a large ferry boat with the aid of a robotic "Laser Cladding" system is described. The shaft was damaged following a failure of the aft sealing system and the loss of lubrication. This resulted in an accumulation of considerable wear and cold cracking to significant depths.

The propeller shaft, which measured 11.5 meters in length and weighted 26.2 tons, was transported to the workshop. The whole process, which was supervised by the classification society, was preceded by the conduction of a series of experiments such as tensile bar breaking test, Charpy impact testing, as well as metallographic imaging. Based on these results suitable filler materials were selected. The damaged section of the shaft was rebuilt utilizing a Laser Cladding system to weld 100 hours continuously and deposit 300 kg of material.

1 INTRODUCTION

It is a common occurrence that marine engine components reach the end of their service life due to wear on the working surfaces caused by a variety of mechanisms. Many of these parts represent a considerable monitory value. Therefore reconditioning is frequently employed to allow the reuse of these components. This significantly reduces the operational costs for ships.

Traditional reconditioning techniques are based on arc welding in various forms such as MIG/MAG, submerged arc and MMA. These have been successfully used for the repair of a wide variety of components. However, due to a relatively poor spatial energy concentration, they often result in considerable heat input to the component. This in turn may lead to distortions, significant dilution, large heat affected zones and in general the degradation of the base material. Furthermore, the quality and final outcome of the process is highly dependent upon the skill of the welder. This can lead to relatively poor repeatability. Thus critical and highly stressed engine components such as piston rods, crosshead pins, crankshafts, final shafts etc. are rarely reconditioned using these techniques.

Low temperature techniques are often used instead, such as hard chroming or thermal spraying. However, these techniques are characterised by low bonding strength, with the exception of HVOF, which is slightly higher. This can lead to premature failure due to flaking.

Considering these aspects, classification societies have been very reluctant to the use of any form of these reconditioning techniques. Instead, in cases where machining is possible parts are undersized up to certain limits and thereafter a replacement is required.

Laser cladding on the other hand, is an innovative welding technique originally developed for the aeronautical industry [1-3]. This utilises a high power laser beam as a heat source. The beam offers significantly higher power intensity (~10^5 W/cm^2) than any arc welding technique. It is capable of melting the substrate and the filler metal to form a strongly adhered defect free weld. The traversing of the cladding equipment is usually accomplished with the aid of a CNC machine or a robot. This guarantees absolute control of the welding parameters as well as the geometric characteristics of the overlay.

The main advantages of the laser cladding technique are summarised below:

- Reduced heat input to the substrate material leading to minimum distortion and residual stresses in the reconditioned part.
- Excellent bonding strength compared to some traditional reconditioning techniques as fusion occurs between the substrate and filler materials. This is a considerable advantage compared to thermal spray techniques where only mechanical bonding is present [4].
- Minimal dilution of the filler metal with the substrate. The properties of the overlay are very close to the specifications of the injected or powder feed material [1].
- Laser welded material attains very fine grain structure due to the high cooling rates [5]. This leads to improved mechanical and in some cases tribological properties.
- A wide range of filler metals are available. Nickel, Cobalt and Iron based materials are commercially produced.

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- Materials with otherwise poor weldability can be welded with excellent results [3,6]. This is due to the reduced heat input, modest inter-pass temperatures and minimum dilution.
- Machining is minimum due to excellent control of the geometric characteristics of the overlay. The height of the overlay is controlled within 0.1mm [7].
- The minimisation of the necessary filler metal can justify the use of higher alloyed materials without a considerable increase in cost. Thus improving the overall results.

Until now laser cladding has been utilised only in niche applications. These took advantage of the highly controlled deposits, could tolerate the high investment costs and relatively small deposition rates. The laser technique is now economically competitive to other reconditioning techniques due to the advent of fibre coupled diode laser sources, with power output in excess of 4 kW, wall plug efficiencies well above that of conventional laser sources and deposition rates in the order of 4-8 kg/hour. [8]. Therefore, Laser Cladding has become more attractive in applications requiring high quality as well as high deposition rates. According to [9,10], Laser Cladding was successfully utilised for the repair of marine components such as crosshead pins and torpedo shells. Therefore no reason exists for not extending the application of this technique to the repair of critical marine engine and hull components.

2 OBJECTIVES

The propeller shaft is a critical part for vessels where repair is traditionally a temporary solution while awaiting delivery of a replacement part. The laser cladding technique is an automated welding process with the precision and control required for critical parts. Laser cladding has been used for the repair of a propeller shaft with the aim to achieve a permanent classification society approved solution.

Considering the above, the repair of a damaged large ferry tail shaft was attempted with the aid of a custom built Laser Cladding machine within the premises of Roussakis S.A. workshop in Piraeus, Hellas. The 11.2m long and ø650mm shaft was heavily damaged on the stern tube region. The damaged area was approximately 2m in length. This was due to loss of lubrication (Figure 1).



Figure 1 – Tail shaft damage of the stern tube region as it arrived at workshop.

The failure of the aft seal caused a leak of oil to the sea and the intrusion of sea water in the bush region. Thereafter, the metal to metal contact between the shaft and the bush, resulted in a discarded bush and an extensively worn shaft. The shaft was worn to a depth of 17mm on the diameter. Also the heat generated by friction combined with the high cooling rates due to the presence of sea water, created subsurface fissuring. This extended locally to depths of up to 22.5mm. Under-sizing to such an extent was not an option due to the significant loss of strength and other practical issues. The shaft had to be either reconditioned or scraped.

The initial scenario investigated by the classification society (RINA) and the owner was a temporary repair of the shaft with traditional techniques. Immediate replacement with a new shaft would be required as soon as one could be manufactured. It is not difficult to realise the consequences of this option for the owner; both in terms of expense - a shaft of this size has a starting price in the order of 150,000 € - and loss of valuable time.

The technological advantages of the Laser Cladding technique convinced the classification society to supervise and approve a repair using this technique. This would offer equal or even enhanced properties to the shaft compared to a new one and render the replacement unnecessary.

3 CERTIFICATION

Research was swiftly initiated to realise the classification demands. The material properties demand, the availability of materials in the form of powder and the acquisition of experimental evidence that would prove the above claim.

The demands of the classification society are summarised in [11]. In brief these are:

- Submission of a welding procedure specification (WPS) for approval,
- Preparation of a welding coupon for the construction of specimens,

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- Mechanical testing,
- Non destructive testing (NDT) inspection of the shaft prior to and after the repair process
- Supervision of the complete effort with details of the welding specification and the specimen preparation.

The minimum mechanical testing requirement is tensile strength, Charpy impact test (3 specimen) and finally hardness testing of the substrate and deposition interface. The classification agency allowed welding to commence if the correct results for the required material tests are achieved if not alternative solutions would have to be sought.

The NDT inspection included subsurface artefact detection and surface crack detection throughout the weld region.

In order to commence the substrate material investigation, swarf was collected during machining and chemically analysed (Leco GDS500A atomic absorption spectrometer). The results shown in Table 1 indicate that the shaft was medium-carbon steel and specifically the Ck45 type whose properties are given in Table 2.

Material	Ck45	AISI 316L	AISI 410L
% C	0,42	0,03	0,03
% Mn	0,64	2,0	1,0
% Si	0,27	1,0	1,0
% P	0,011	0,045	0,04
% S	0,007	0,03	0,035
% Ni	0,07	12,0	
% Cr	0,09	17,0	12,0
% Mo	0,04	2,5	
% Fe	Bal.	Bal.	Bal

Table 1 – Tail shaft material chemical composition (material type Ck45)

The selection of the filler metal was not trivial as apart from having comparable properties to those of the base material it had to have:

- Proven low cracking susceptibility for both high and low temperature cracking.
- Offer smooth welding operation without sputtering for process stability.

- Have an acceptable cost and finally be available in large quantities at very short notice.

Among the large family of powders available for fusion welding, cobalt and nickel based materials were excluded. This was due to the higher cost. Thus iron based material from the stainless steel family was selected. An austenitic stainless steel and specifically AISI 316L was chosen as a candidate material to build up most of the accumulated wear. A martensitic stainless AISI 410L was chosen as a top layer to provide improved anti-scuffing properties. The composition and properties of these materials are also provided in Table 1 and Table 2. These are comparable if not better than those of the base material or substrate and provide a good starting point for experimentation.

As mentioned, apart from the wear accumulated throughout the bush region, subsurface cracks extending to considerable depths were found at various points. Grooves to various depths and widths were therefore created in order to eliminate these subsurface cracks completely. These would have to be welded up first to create a uniform diameter and then continue to rebuild the complete length of the stern bush region.

	Ck45	AISI316L	AISI410L (annealed)
Min.Yield Strength (MPa)	275	220	205
Tensile Strength (MPa)	490-570	515-690	450
Elongation at Brake (%)	20	40	20-34
Hardness	167-229 (Brinell)	155 (HV_5)	82-96 (HRB)

Table 2 – Base metal (Ck45) and filler material properties

In total it was calculated that 300 kg of material would have to be deposited. Considering the small dimensions of the laser cladding bead (~6mm in width) and a maximum overlay height being around 2mm, multiple layers were necessary. In some cases up to 10 were deposited in order to reclaim the worn material and leave a surplus of 2mm for final machining.

4 EXPERIMENTAL

4.1 LASER CLADDING SYSTEM

A custom built, fully computerized, robotic Laser Cladding system was used during the reconditioning process. It was based on a fibre coupled 6kW Diode laser source (Laserline LDF 1000-6000) with an emission wavelength range of 900-1030nm. The laser light was transmitted to the processing optics via an optical fibre. This had a core diameter of 1mm and heavy duty industrial standard coupling systems for increased robustness. The processing optics incorporated collimating and focussing optics as well as a two colour pyrometer optical system. This allowed for real time melt pool temperature monitoring. A range of spot sizes were available with the use of different combinations of collimating and focussing optics with the largest one (6.25mm) being chosen for this particular application for maximum productivity.

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The single step laser cladding process was favoured due to its versatility over the two step counterpart, with the metal powder being injected at the melt pool with the aid of a coaxial powder delivery system. A water cooled coaxial powder nozzle (COAX 8), specially designed for high laser intensities and maximum productivity, incorporated beryllium copper cladding cones. These parts are mirror finished for maximum light reflection and heat rejection to the cooling liquid. This allowed for the formation of a consistent powder cone just above the work piece and ensured repeatable of the welding bead geometry throughout the reconditioning process. On this account, an electronically controlled rotating disc powder feeder was also a significant contributor to the dimensional accuracy of the overlays.

An industrial six axis robot (Motoman UP50N) in combination with a heavy duty positioner were utilised for the accurate traversing of the optics and the handling and synchronised rotation of the heavy and bulky work-piece. Robot programming was performed offline with the aid of an in-house written software. In order to eliminate any misalignments and unwanted axial movement of the handled part, special care was taken to accurately align the rollers of the 11m long positioner to its headstock using a laser alignment system. Finally, stability of the rotational speed of the piece dictated tuning of the servo controller parameters in order to account for the inertia of this immense work-piece. An overview of the robotic system can be found in Figure 2.



a b

Figure 2 – Laser cladding robotic system (a) and tail shaft setup on positioner (b)

4.2 WELDING PROCESS PARAMETERS

Prior to the submission of the welding process specification (WPS) to the classification society, preliminary experimentation was conducted in order to optimise the welding parameters. Specimens were therefore prepared that were later sent for metallographic analysis (see following sections) for the validation of the soundness of the overlay. Following the successful outcome of these experiments, the final WPS was generated which is briefly described below.

4.3 SHAFT PREPARATION

The region of the shaft to be welded was machined on the lathe in order to eliminate defects by creating grooves with geometric characteristics that comply with the certification [12]. The total removal of such defects or damage was verified with the aid of NDT inspection. Subsequently all surfaces to be welded were thoroughly cleaned with solvents and wire brushing in order to be free of any organic compounds such as paint, grease etc as well as oxides (rust).

4.4 PRE-WELD HEAT TREATMENT

Pre-weld heat treatment was not necessary apart from minor preheating, as any heat affected material was removed during shaft preparation. Therefore, the complete region to be welded was mildly preheated uniformly using propane torches to a temperature of 150^{o}C. Torches were used throughout the reconditioning process as the heat input by the laser was not be adequate to conserve the above temperature.

4.5 WELDING

The welding parameters are summarised in Table 3.

Run	F_1-F_{n-2}	F_{n-1}-F_n
Process	Laser Cladding	Laser Cladding
Filler Material	AISI 316L	AISI 410L
Form	Powder	Powder
Power (W)	5300	5400
Powder Feed (Kg/h)	3.0	3.0
Travel Speed (mm/s)	15.0	15.0
Heat Input (J/mm)	350	360
Interpass Temperature (^{o}C)	250 max	250 max
Shielding Gas	Argon	Argon
Powder Carrier Gas	Argon	Argon

Table 3 – Welding parameters.

Stringer beads in the circumferential direction were created with the cladding head being positioned vertically above the piece. Finally, for the last layer the “temper bead technique” was used where possible.

4.6 POST WELDING HEAT TREATMENT (PWHT)

Following the completion of welding the shaft was insulated with blankets and left to cool down to room temperature. Subsequently, it was heat treated with heating blankets throughout the welded region (+20cm on either side of the region) according to ASME VIII and

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ASME 31.3. In brief the shaft, supported well to avoid distortions, was heated up to 580-620°C with 100°C/hour, dwell at this temperature for four hours and then cooled with 100°C/hour down to 300°C. Finally, it was left to cool in still air down to room temperature.

4.7 NDT INSPECTION

NDT methods were utilised before the reconditioning process, prior to and after PWHT. These techniques include the ultrasound method for subsurface flaw detections with angle beam transducers, the Magna Flux method for surface crack detection and hardness measurements.

4.8 WELDING COUPON PREPARATION

As mentioned, one of the classification society requirements was the preparation of a welding coupon which was used for the construction of specimens for mechanical testing. The coupon which was constructed according to [11] was built on a 30mm thick plate of the same material as that of the shaft (Ck45). The filler metal used was AISI 316L as this was the material intended for reclaiming most of the wear on the shaft. Additionally coupons were prepared with 410L deposited on 316L in order to versify the metallographic structure. The welding parameters used were those as stated in the welding procedure specifications. In total seven layers were deposited in order to have enough material for specimen preparation and to adequately simulate the regions of the shaft where at least 10 layers were necessary. As also stated in the welding procedure, the coupon was heat treated according to the same PWHT schedule as the shaft.

4.9 MATERIALS

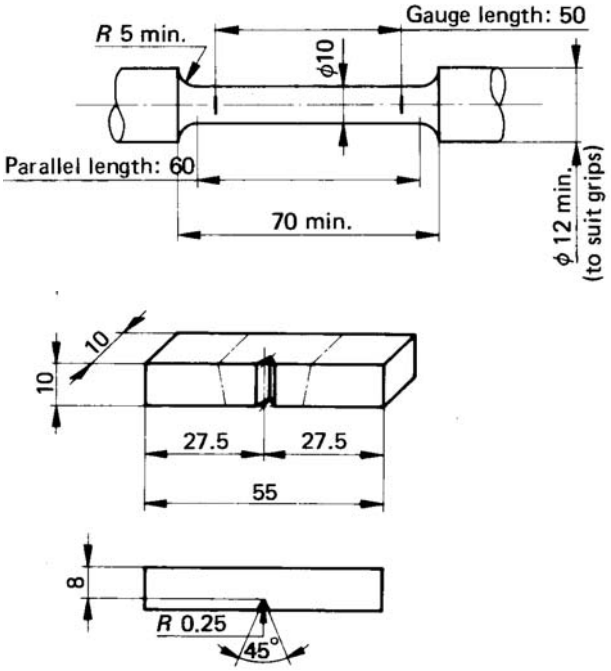


Figure 3 Tensile and Impact energy test sample

Tensile strength and impact energy samples were machined from the 316L part of the laser coating according to ISO 2560-1973 standard, as shown in Figure 3.

Tensile and impact tests were performed according to ISO 2560-1973 standard.

Metallographic test samples were prepared by cutting the laser clad coating perpendicular to the cladding direction. These were placed in a mounting press which was filled to 1/3 with a glass fibre resin followed by 2/3 with a bakelite resin. The sample was processed under high pressure during both the heating and cooling cycles. Finally the sample was plane ground and polished with 9μm followed by 3μm and finally 1μm DP (diamond polish) suspension. The etching agent used was 3.3 which consists of 100 ml 95% Ethyl alcohol, 2 g Picric acid and 1 ml concentrated HCl.

Electrochemical (cyclic polarization) tests were performed in order to evaluate the pitting corrosion of this material. Cyclic polarization is a corrosion technique that utilizes a two step voltage scan or ramp. This is programmed from an initial potential to a vertex potential and from the vertex to a final potential, at a defined step height per step time. The vertex potential may also be defined by a specific current (threshold current) that limits the forward scan to the potential at which that current is reached.

Using this technique the metal sample is polarized, which means that the potential of the sample is forced away from open circuit potential or equivalent open circuit (E,O,C.). This is the equilibrium potential of the metal sample. The response current of the metal sample is measured as it is polarized. This response is then used to develop a model of the corrosion behaviour of the sample.

Cyclic Polarization (CP) technique can also be referred to as “pitting scan”, as it is used to determine the tendency of a material to undergo surface pitting or crevice corrosion.

A comparison of the test results for laser cladded 316L, Co based 2528-00 and Ni based 1540-00 was generated. The composition of these materials is shown in table 4.

Material	Co	Ni	Fe	Mo	Others
1540	-	Bal.	2.5	-	Al=1.0
2528	Bal.	2.8	1.5	5.5	-
316L	-	12.0	Bal.	2.5	Mn=1.5

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Material	Cr	C	Si	B	S
1540	7. 7,5	0. 25	3.5	1.6	-
2528	2 27.0	0 0.25	1.0	-	- -
316L	17.0	<0.03	0.8	-	-

Table 4 chemical composition of materials 1540, 2528 and 316L.

5 RESULTS AND DISCUSSION

5.1 MATERIAL RESULTS

A point of high importance is the bond between the metallic deposition layers. The interface between the 316L laser clad layer and the substrate is shown in figure 4. There it can be seen that a good bonding was achieved with no pores or cracks and low dilution. The micro-hardness of the 316L layer was measured and also the heat affected zone of the substrate with values of 180 $HV_{0,5}$ and 150 $HV_{0,5}$ respectively.

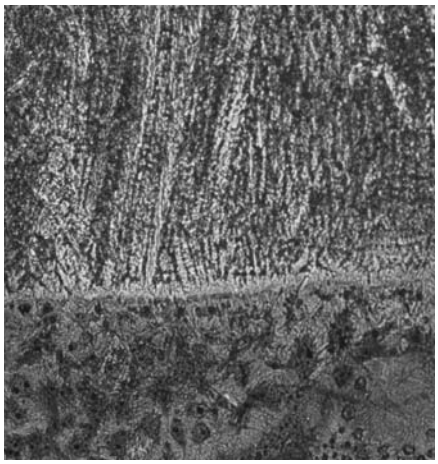


Figure 4 Interface between 316L and the substrate.

Two microstructure photos of the 316L coating are presented in Figure 5.,

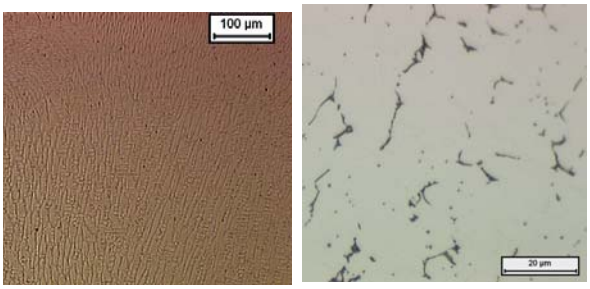


Figure 5. Laser cladded 316L etched in glyceregia

Figure 5 shows the fine dendritic structure obtained after the fast cooling rate achieved under the laser welding process. The microstructure consists of austenite and delta ferrite. Fully austenitic stainless steels are known to be prone to hot cracking during welding. In order to prevent the occurrence of hot cracking, in the order of 5-10% ferrite should be present in the finished weld. This has been achieved with the laser cladding process.

The interface between the two layers: 316L and 410L can be observed in Figure 6., where excellent bonding between the two materials can be seen with no cracks or other defects.

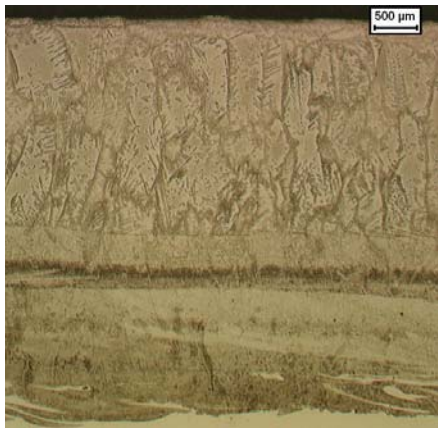


Figure 6. Interface between 316L and 410L layers etched with 3,3 agent.

The microstructure of the 410L, Figure x, consists of a mixture of martensite and ferrite. The martensite content is higher closest to the bonding area, which is confirmed by the micro-hardness values. Close to the interface area between 410L and 316L a microhardness of 340 $HV_{0,5}$ was measured. This hardness level remained constant up to the area near the surface. A hardness of 220 $HV_{0,5}$ was observed closer to the surface. This confirms the lower content of martensite in this area.

In order to better understand this behaviour, the composition of the 410L layer from the bonding to the surface was analysed by EDS (energy dispersive analysis system) and the results are presented in table5:

Element	Surface	Center	Bonding
Si (%)	0,4	0,4	0,5
Cr (%)	12,5	13,1	13,2
Mn (%)	0,7	0,8	0,7
Fe (%)	86,1	84,5	84,1
Ni (%)	0,4	1,2	1,6

Table 5. Composition of 410L laser clad at the surface, center and bonding zone of the deposition.

As can be seen in Table x. the 410L layer contains Ni also, as some dilution occurs in the zone between 316L and 410L. The Ni builds austenite that transforms to martensite during cooling. The presence of Ni could be one reason for the higher martensite content in the first bonding layers.

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The properties of the 316L layer were evaluated in regard to mechanical properties. The tensile strength and the yield strength of the 316l laser coating was measured to be 546 MPa and 330 MPa respectively. This combined with a high elongation of 35% gives a very good trade-off between high strength and ductility. The impact energy of the laser weld coating was 98 J.

The mechanical properties exceed those of the original shaft substrate material CK45. The tensile and yield strength values are higher than all material requirements in Table 2. This is due to the fact that the structure of the laser welded material is finer compared to the structure of wrought material. The elongation is slightly lower compared to 316L wrought, due to the fact that in laser welded structures, some defects may be present such as oxides.

In this particular application the corrosion resistance is not a requirement; as this region of the tail shaft is oil lubricated and normally does not come into contact with sea water. In many other cases where parts come in contact with sea water corrosion tests may be required. So for full approval corrosion tests are included and presented here.

The material 316L is considered to have excellent corrosion resistance. The pitting corrosion of this material after laser cladding was evaluated. If the laser clad layer was porous, contained defects or cracks pitting corrosion can occur.

The laser cladded 316L was tested and compared to Co-based material, 2528, and a Ni-based material, 1540, The composition of these materials is presented in table 4.
In order to compare the different powder grades after laser cladding, anodic polarization curves (first scan of Cyclic Polarization study) of Ni-, Fe-and Co- based alloys are presented in the same graph.

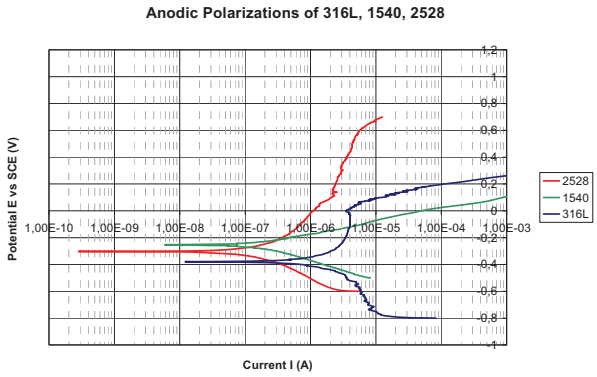


Figure **7**. Corrosion data comparison for 316L, 1540 and 2528 laser cladded depositions.

This gives a clear view of the difference in terms of corrosion potential, passivity and passive current pitting potential and transpassive region (Figure 7).

The behaviour of 316L during the experiment was as expected, the typical behaviour of a passive material. The passive region was well defined with a stable period and also a clear passivation current and pitting potential. The high slope corresponding to the passive region confirms a stable passive layer.

In the case of the Cobalt-based alloy, 2528, the pitting potential is difficult to estimate since the stable period (passive region) is less clear than that of 316L. It is expected to be around 0,6V for each grade but, the main point is that the increase of current is lower after 0,6V. The diagram shows that this material is in the passive state, with quite high pitting potential (0,6V compared to 0V for 316L) so higher resistance to pitting corrosion is expected. However the slope of the respective curves in the "passive region" is not very high, which suggests that passive layers are not very stable and that a type of uniform corrosion is initiated.

The Nickel-based 1540 contains 7,5% of Chromium, which is low for the formation of a stable passive layer as the curve shows; therefore no stair showing passivation can be seen.

It can be concluded that choosing a cost effective material can be combined with excellent corrosion resistance properties. The Chromium content is key to the passive layer formation.

5.2 SHAFT REPAIR EXPERIENCE

Following the successful outcome of these experiments, the classification society gave approval for the repair and welding on the shaft could begin. The Laser Cladding system was programmed off-line and could then be left to operate, almost unmanned, for intervals of up to 8 hours. After which the 25kg powder feeder canister had to be refilled. The exceptional process stability, dimensional control of the overlays and the use of gas as a shielding medium instead of flux reduced the need for monitoring. Furthermore significantly improved reconditioning without the presence of voids and inclusions found in traditional techniques was achieved.

As a result, the system was operated 24 hours a day with one operator per shift and continual shifts allowing the completion of the process in only 4.5 days and 100 hours of cladding. Subsequently, the shaft was insulated, left to cool down to room temperature and then positioned on the lathe for pre-machining and NDT inspection. It is interesting to note that straightness measurements taken before reconditioning and after the reconditioning showed that the shaft was not distorted at all during the process. Following the successful outcome of the NDT tests where no flaws whatsoever were identified, PWHT was initiated. The shaft was instrumented with thermocouples and covered with heating blankets for the PWHT. This procedure lasted another 3 days after which it was positioned on the lathe one more time for NDT inspection

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and final machining. The NDT tests revealed no flaws once again and hence the part was finally machined according to the manufacturers' drawings.

6 CONCLUSIONS

The investigation revealed that the laser cladding weldments of the selected filler materials, outperformed the mechanical properties of the base material and provided adequate strength. With the submission of these experimental results the classification society accepted the repair of this critical part of the vessel as a permanent refurbishment with no replacement being necessary.

This together with the fact that the item was delivered in ten days deems the laser cladding technique a valuable tool for reclaiming critical marine components.

The shaft was dispatched 10 days after it arrived at the workshop and was swiftly installed on the ship together with new bushes and sealing systems. It has now been in operation since December 2009 and no problems have been reported. High power Laser Cladding has proved to be a valuable tool for reclaiming marine components in a fast, efficient and safe manner. A precedent has therefore been created and an opportunity for the marine industry to further consider looking into the recondition of critical parts with high technology laser welding techniques.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] Sexton L.et al, Laser Cladding of Aerospace materials, Journal of Materials Processing Technology Vol. 122 (2002) 63–68

[2] Nowotny S.et al, Laser Beam Build-Up Welding Precision in Repair, Surface Cladding, and Direct 3D Metal Deposition, Journal of Thermal Spray Technology Vol. 16(3) (2007) 344-348

[3] Richter K., Orban S., Nowotny S., Laser Cladding of the Titanium Alloy TI6242 to Restore Damaged Blades, Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics, 2004

[4] Hjornhede A., Nylund A., Adhesion testing of thermally sprayed and laser deposited coatings, Surface and Coatings Technology Vol. 184 (2004) 208–218

[5] Lin W.C., Chen C., Characteristics of Thin Surface Layers of Cobalt-Based Alloys Deposited by Laser Cladding, Surface & Coatings Technology Vol. 200 (2006) 4557-4563

[6] Ocelik V. et al, Thick Co-based coating on cast iron by side laser cladding: Analysis of processing conditions and coating properties, Surface & Coatings Technology Vol. 201 (2007) 5875–5883

[7] Nowotny S. et al, Integrated Laser Milling Center for Complete Machining, Assembly Automation, Vol. 30 (2010), 36 – 38

[8] Tuominen J. et al, Deposition of Thick Wear and Corrosion Resistant Coatings by High Power Diode Laser, Proceedings of the 2006 International Thermal Spray Conference, May 2006 p 1189-1191

[9] Bludszuweit S. et al, Approval for Laser Beam Cladding of Marine Components, United Thermal Spray Conference, 1999 p 418-421

[10] Bergan P. Implementation of Laser Repair Process for Navy Aluminum Components, DoD Laser Applications Conference, 2003

[11] ISO Standard 15614-7:2007, Specification and Qualification of Welding Procedures for Metallic Materials – Welding Procedure Test

[12] ABS Rools Part 7 Section 11, Guide for Repair and Cladding of Shafts

9. AUTHORS BIOGRAPHY

Ingrid Hauer holds the position "application development eng." at Höganäs AB (Publ). She is responsible for laser cladding applications. Previous experience includes material development, characterization, and stainless steel components.

Nicholas Kampanis is a Mech. Eng. and provides Laser Cladding consultancy services. He has extensive experience on laser applications including fluid flow measurement techniques and material processing. He was responsible for integrating and developing the laser cladding system for the project described in this paper.

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