CLADDING OF SUBMERGED PROPELLER SHAFTS: A COMPARISON BETWEEN CONVENTIONAL AND HIGH END TECHNIQUES AND MATERIALS

Плакирование приводных судовых валов: сравнение традиционных и новых технологий и материалов

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ABSTRACT

The performance of conventional cladding techniques, on the coating of submerged propeller shafts, is analysed and compared against a high end technique. A variety of criteria are used such as mechanical, metallographic and economic in order to obtain a more complete picture. The conventional technique under investigation is Gas Metal Arc Welding (GMAW/MIG) being one of the most established in the field, while the high end counterpart is an emerging technique referred to as Laser Cladding. The mechanical performance is judged in regard to tensile testing with classification society rules in mind. Furthermore, the economic aspects of the operation are examined considering capital investment, labour, welding consumable as well as post welding operation costs. A cladding material often used in such applications is compared, an austenitic stainless steel AISI 316L. In the case of the conventional technique, the filler material is in wire form while in the case of the laser technique, metal powder is used. Results indicate that the laser technique presents significant advantages in all respects as faster turnaround can be achieved with less material consumed and lower labour cost. While equivalent if not better mechanical and corrosion properties can be realised.

Краткий обзор.

Характеристики традиционной технологии восстановления погружных валов, проанализированы и сравнены с прогрессивной технологией. Различные критерии, такие как механические, металлографические, экономические использовались, чтобы получить более полную картину. Традиционная технология восстановления наваркой металлическим электродом в среде инертного газа (GMAW/MIG) является наиболее распространенной в данной области, в то время как наиболее прогрессивной альтернативой является лазерное плакирование. Механические характеристики оценивались по показателям прочности на растяжение, принимая во внимание требования Классификационного общества (учреждения, занимающиеся классификацией судов и надзором за ними при постройке и эксплуатации). Экономические аспекты процесса были исследованы, учитывая требуемые инвестиции в основной капитал, рабочую силу, расходные материалы, а также дополнительные операции после восстановления. Материал покрытия, часто используемый в данном применении - аустенитная нержавеющая сталь AISI 316L. При традиционной технологии восстановления используется материал покрытия в виде проволоки, в то время как при лазерной наплавке, используется металлический порошок. Результаты сравнения показывают, что лазерная технология имеет существенные преимущества во всех отношениях, снижение времени восстановления может быть достигнуто с меньшими затратами на материалы и оплату труда. Одновременно достигаются эквивалентные, если не лучшие механические и антикоррозийные свойства.

INTRODUCTION

Surfacing or otherwise cladding of components has been extensively used in the marine and petrochemical industry in order to increase the life cycle of components and reduce costs. Either during production or reconditioning, cladding provides huge gains through an intelligent utilisation of expensive materials and the capability of reusing components which would otherwise be scraped. The general term cladding covers a wide range of techniques where a thin coating with tailored properties is applied to working surfaces of components made of low cost materials. Thus the effects of corrosion, erosion and any other type of wear are minimised. In this way, the use of low cost low-alloy materials is retained, with the performance being equivalent to components constructed out of solid exotic materials.

Each cladding technique has its own merits. However, weld overlay cladding is considered as one of the most versatile due to the wide choice of welding techniques especially when a heavy duty, strongly adhered overlay is sought. It is utilised in most industries including mining, drilling, marine, petrochemical and automotive.

In the marine industry in particular, typical cladding applications include valve spindle hardfacing and/or coating, propeller blade repairs and propeller shaft cladding with corrosion resistant materials. Conventional surfacing techniques are based on arc welding in various forms such as gas metal arc welding (GMAW/MIG), submerged arc welding (SAW) and electroslag welding (ESW). These have been successfully used for the production and/or repair of a wide variety of components. However, due to a relatively poor spatial energy concentration, these often lead to a range of side effects which exclude weld overlay cladding from being applied to critical driveline components. In cases where cladding is the only option, such as in submerged propeller shafts, classification societies impose strict rules for the production and reconditioning procedures in order to minimise the risk of failure.

In this paper, a conventional (GMAW/MIG) and the advanced technique of Laser Cladding (LC) are compared in view of the production or reconditioning of submerged propeller shafts. Both technical and economic issues are taken into account in an effort to reveal the true potential of this new technique in the industry.

GMAW/MIG is a well established technique in the field with a very wide range of applications. It has been used successfully by the industry for many years and its impeccable level of industrialisation and development indicates its continuation in years to come. Laser cladding on the other hand, is relatively new in the industry with characteristics offering promise for enhanced quality and lower production costs. In an earlier paper (1) an example of the repair of a large propeller shaft was presented. Here laser cladding was successfully applied to recover the worn area in a technically sound and economically viable manner. Other publications also present the merits of this technique in similar applications and the efforts taken to standardise the technique for reconditioning of submarine propeller shafts (2). However, although the technique has been available for some years its industrial acceptance has been relatively slow especially in the marine sector (3) for various reasons. The main one has been the high capital cost of the equipment, followed by the low level of industrialisation of the technique, the low productivity and the limited number of vendors selling turnkey systems. With high power diode lasers, of the order of 10kW, currently available at rapidly declining prices and the emergence of laser-inductive hybrid technologies (4), an increasing interest is apparent in recent years with numerous ship repair industries investing in laser cladding. In order to comprehend the merits and drawbacks of these techniques a brief description is provided.

1. WELDING TECHNIQUES

In GMAW/MIG, the arc established between a continuously fed filler wire electrode and the base metal provides the necessary heat for the fusion of the coating to the substrate. Shielding gas is provided coaxially with the filler wire which protects the melt pool and the arc from the atmosphere. Although it is very frequently used manually, this technique has been developed significantly during recent decades and is now commonly integrated with robots. According to (5), fully automated, robotic cells have allowed for unmanned continuous cladding of components, this increases productivity dramatically. Furthermore, the level of refinement is such that the combination of pulsed currents and intermittent wire feeding are used in order to minimise the heat input and increase productivity. Finally, a wide variety of materials can be processed such as aluminium, steel, cobalt and nickel alloys.

Laser cladding on the other hand utilises a high power laser beam as a heat source for the melting and fusing of the substrate and filler materials. As the laser is a beam of electromagnetic radiation, all of the injected energy is confined within a small spot with no diffusion due to convection from hot gasses or electromagnetic forces taking place. As a result, the heat input to the part is minimised and higher welding quality and efficiency is attained. Filler metal is added in many ways with the most common being powder injection. The creation of a melt pool where a fine film of base material is melted and the filler material is injected, results in the formation of a welding bead which is strongly adhered to the substrate.

The high intensity of the laser beam and the associated low heat input results in minimised distortion, residual stresses and base metal degradation. Furthermore, the higher cooling rates attained result in finer microstructures and smaller heat affected zones leading to improved mechanical properties.

These facts allow the processing of critical parts which could not be repaired in the past with other fuse welding techniques. Thus opening new opportunities for performance enhancement and cost reduction through the salvaging of parts, which were previously scraped. Furthermore, the impeccable control of overlay thickness and low overlay roughness minimises the machining allowances and hence lowers the production or repair costs.

A comparison of the two techniques is shown in table 1.

Technique	GMAW/MIG	LC
Heat Input	~5 J/mm	~0.5 J/mm
Productivity	5-8 kg/hour (single torch)	4-10 kg/hour depending on laser power
Dilution	20-30%	<5%
Dendrite spacing	Coarse	Fine
Filler material form	Wire	Powder
Level of Development-Industrialisation	Very High	Moderate
Welding Bead Geometry Control	Good (+/-0.5-1mm)	Excellent (+/-0.1mm)
Machining Allowance	Large (3-4mm)	Small (1-2mm)
Spattering	Yes	Less
Investment Cost	~100-200 k€ (including robotic system)	~300-500 k€ (depending on laser source)
Operating Cost	Moderate (wire more expensive than powder)	Low (lower loss of material during machining and finer overlay thickness due to less dilution)

Table 1. *Characteristics of GMAW/MIG and laser cladding*

2. OBJECTIVES

The objectives of this paper are the understanding of the merits and shortfalls of laser cladding when applied in large scale applications such as propeller shaft cladding and the realisation of the potential of the technique in the field. Mechanical and metallographic testing were conducted in an effort to realise the technical advantages. Finally, the economic aspects were also considered such as the capital investment, labour cost and other operating expenses in order to compare the financial viability of the techniques.

3. EXPERIMENTAL

Laser cladding and GMAW/MIG were chosen as the methods for producing 20 mm thick welded coupons, on 100 x 80 mm x 25mm thickness low alloyed steel. The laser system used was a 4 kW direct diode laser with 808 nm wavelength together with an ABB 6 axis robot. The GMAW/MIG process was manual and performed by a skilled certified welder.

The parameters used in both processes are presented in table 2.

Technique	GMAW/MIG	Laser cladding
Heat input	180A /23V	4kW
Feed rate (kg/h)	4 kg/h	4 kg/h
Cladding speed	NA	8 mm/s
Shield gas	ENISO 14175-Z-Ar+NO-0,03 10 l/min	Argon 10 l/min
Feed gas	NA	Argon 3 l/min
Filler material	316L wire 0,8 mm diameter	316L powder

Table 2. *Welding parameters*

The dilution was measured after the first layer deposition in both cases, by using an XRF Niton XL2 gun. Tensile strength bars were machined from the 316L coupons according to ISO 2560-1973 standard, as shown in Figure 1.

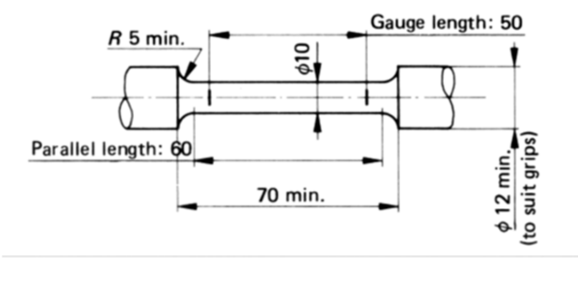

Figure 1. *Tensile test sample*

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

Metallographic test samples were prepared by cutting the laser clad and the GMAW/MIG samples perpendicular to the welding direction. These were placed in a mounting press which was filled to 1/3 with a glass fibre resin followed by 2/3 with bakelite resin. The samples were processed under high pressure during curing with standard heating and cooling cycles. Finally the samples were plane ground and polished with 9µmfollowed by 3µm and finally 1µm diamond polish, DP, suspension. The etching agent used was glyceregia which consists of 45 ml glycerol, 98% purum, 15 ml HNO_3 and 30 ml HCl.

4. RESULTS AND DISCUSSION

The physical properties generated are presented in table 2 and Figures 2a and 2b.

316L	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (HV_{300})
LC	582	418	36	257
MIG	518	264	57	226

Table 3. *Mechanical properties*

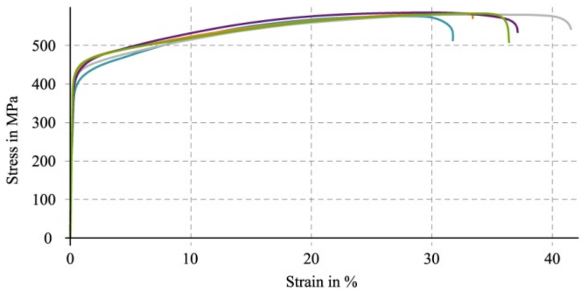

Figure 2a. *Tensile strength curves for 316L after laser cladding.*

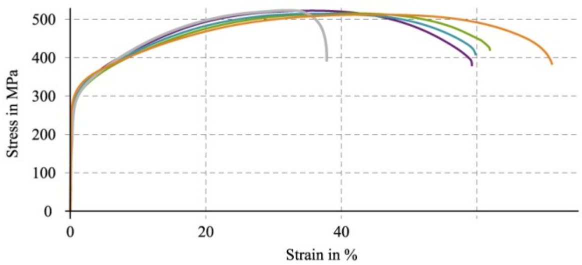

Figure 2b.*Tensile strength curves of 316L after GMAW/MIG.*

The mechanical testing shows higher tensile strength and yield strength for the laser welded samples compared to the GMAW/MIG welded samples, with lower elongation.

The micro hardness was also measured and the results show 257 HV_{300} for laser cladded material and 226 $HV_{300}$for the MIG welded samples.

The un-etched microstructure of both the laser cladded and GMAW/MIG depositions are shown in Figure 3a and 3b.

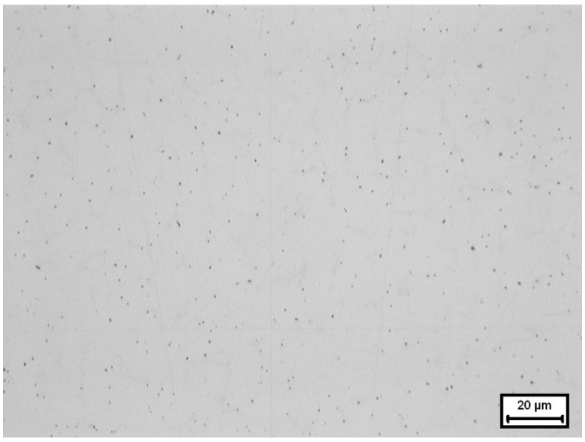

Figure 3a. *316L laser cladding*

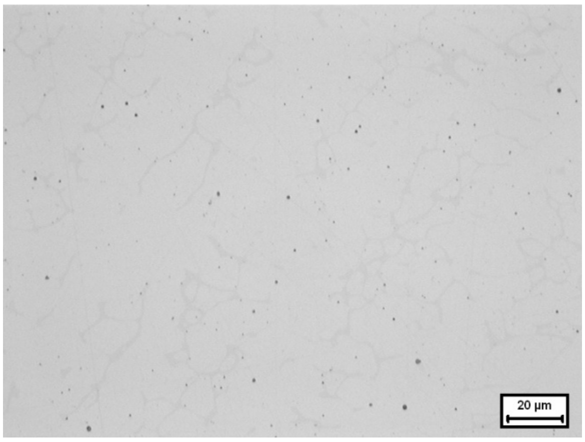

Figure 3b. *316L MIG*

The un-etched microstructure shows a pore and crack free weld cladding in both cases. A finer microstructure with a larger number of oxides of finer size is shown in figure 3a for the laser cladded sample compared to GMAW/MIG in figure 3b. The higher number of oxides can be explained by the different shielding gases used. The EN ISO 14175-Z-Ar+NO-0,03shielding gas used in the GMAW/MIG process is reducing, which limits oxides more so than the pure Ar used in the laser process. Moreover, the slower cooling rate during GMAW/MIG welding leads to fewer and larger oxides.

The higher number of oxides observed in the laser welded sample combined with the finer structure explains the higher microhardness and somewhat lower elongation.

The samples were etched in glyceregia and the micrographs are shown in Figure 4a and 4b for both laser cladding and GMAW/MIG at 10x and 50x magnification.

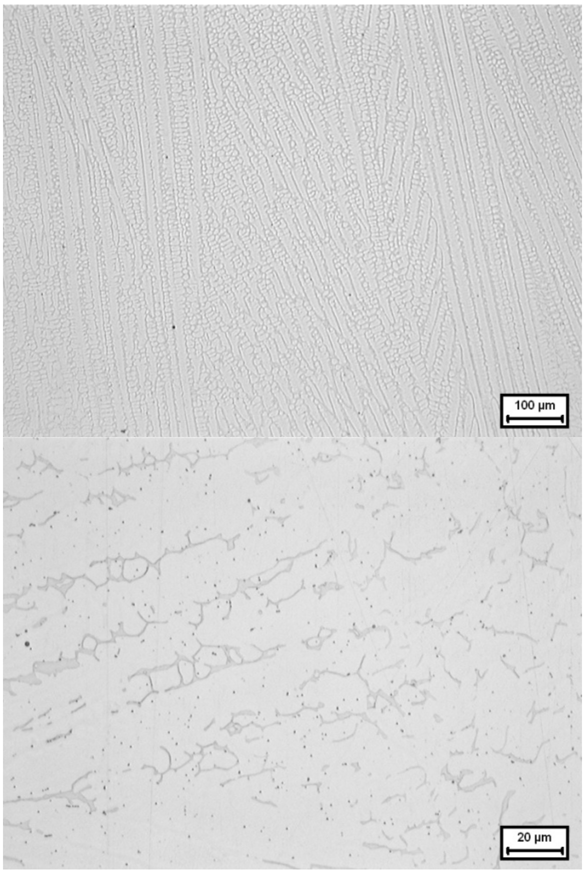

Figure 4a.*316L laser welded etched*

The value of microstructure as a tool is well established as an indicator of the physical properties that can be anticipated. The results generated here confirm some of these generally accepted theories. The etched photos show a coarser structure with larger dendrites in the GMAW/MIG welded part, which partially explains the lower tensile and yield strength values, table 2, obtained in this case. The microstructure of both samples consists of austenite, the lighter areas seen in Figures 4a and 4b, and delta ferrite phases, the darker areas,. The ferrite areas are more unevenly distributed in the GMAW/MIG sample in contrast to laser cladding.

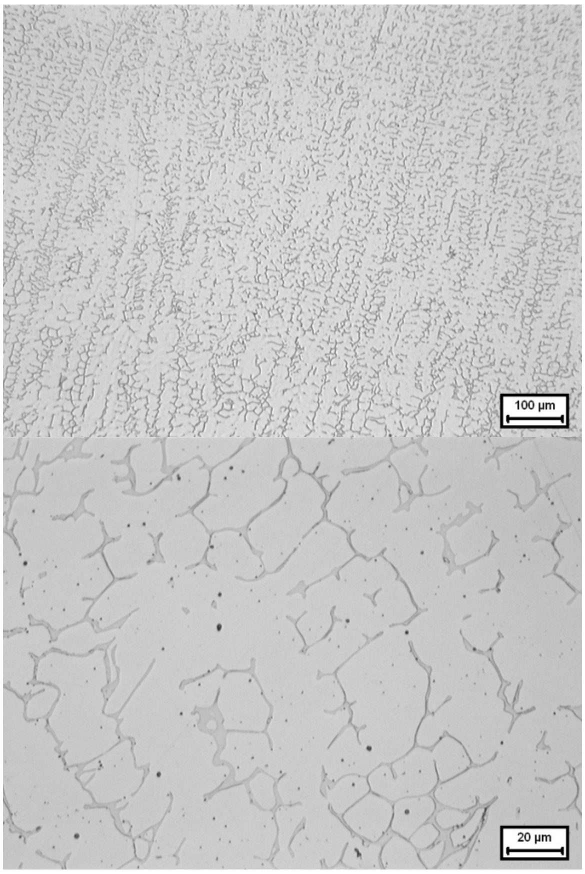

Figure 4b. *316L MIG welded etched*

The tensile strength was 11% higher for the laser cladded sample compared to the GMAW/MIG welded, while the yield strength was 37% higher. The difference in yield strength is considerably larger than that seen for tensile strength. It is generally accepted that defects, such as oxides. can play a key role in this. A partial explanation is the higher amount of oxides in the laser welded coating, due to the less reducing shielding gas used. This leads to precipitation hardening. The grain size is finer after laser cladding and this is a further contributor to this higher yield strength value.

Material 316L when laser welded shows excellent pitting corrosion, which was presented in an earlier paper (1). A finer structure indicates better corrosion resistance compared to a coarser one, (6), (7). This should be further investigated for more clarification in the future.

The dilution was also measured after the first layer deposition in both cases and the results were:

- 2% for the laser cladded sample
- 21% for the GMAW/MIG welded sample.

A comparison between laser and GMAW/MIG weld deposits on a low carbon steel substrate is illustrated in Figure 5. The alloy is applied to a low alloyed substrate with laser cladding and GMAW/MIG. The required surface hardness is 220 $HV_{300}$and this was achieved after deposition of 1mm with laser and 8mm with GMAW/MIG.

	Laser - powder	MIG - wire
Hardness HV_{300}	257	226
Weld thickness	1 mm	8 mm
Deposition filler volume	13%	100%

Table 4. *Deposition comparison*

As illustrated in table 4, 7 to 8 times more material must be deposited with the GMAW/MIG wire compared to laser powder.

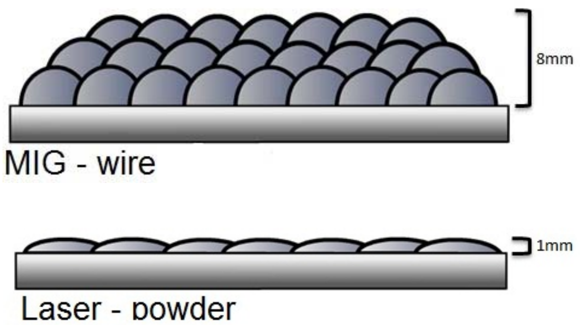

Figure. 5*Comparison of bead shape*

The surface finish of the laser welded sample is much smoother compared to the GMAW/MIG welded, which is also illustrated in figure 5. The smoothness is dependent on the bead form or shape and the overlap. This results in less machining required to reach the final dimensions after deposition when laser cladding is used.

5. COSTING

As previously discussed, both the mechanical and metallographic test results indicated the superiority of the laser cladding technique over GMAW/MIG on the technical side. Here a comparison of economic aspects will be made with the aid of a test case. A propeller shaft whose characteristics are given in table 5is to be cladded. These techniques are used in order to create a corrosion resistant layer throughout the submerged length of the shaft. For simplicity, only material and labour cost for welding and post welding operations will be considered. Other operations which are not affected by the welding technique are excluded.

As indicated in the results section, only 1mm layer thickness is necessary with the laser cladding case in order to achieve a low level of dilution and therefore adequate corrosion resistance. In contrast, in the case of GMAW/MIG 8mm was required in this example to achieve the same level of dilution. Some highly specialised units can reach this dilution level with as low as 4mm layer. Furthermore, considering the higher unevenness of the overlay as well as the distortions which may be encountered, due to higher heat input, greater machining allowances are necessary. As a result, the amount of filler material needed for the same job is considerably higher in the GMAW/MIG case.

It should be mentioned here that for this specific cladding material the price of powder and the lowest wire price are comparable, see table 6,.Wire price of 316L varies between 16 Euro to 22 Euro depending on the diameter. If more exotic Nickel based materials are used however, such as Inconel® 625, the price of the wire can be 3-5 times higher than that of the powder which can lead to considerable differences in the operating costs.

6. CASE STUDY FOR SUBMERGED PROPELLER SHAFT

The propeller shaft whose characteristics are diameter 500 mm and length 8 m, see table 5, is to be cladded.

The laser clad case has a 2.5mm cladding thickness, after machining, as specified. A 1mm machining allowance is needed. Thus 390kg of material will be used for this specific shaft considering a deposition efficiency of 90%[1].

In the GMAW/MIG case, when a highly specialised automated system is used, a4mm cladding thickness plus 2mm of machining allowance was specified. Thus 54% more material or a total of 600kg was used.

Assuming a deposition rate of 5kg/hour, for both techniques, this would lead to 78 hours of cladding for the laser cladding and 120 hours for the GMAW/MIG.

Considering machining, the Laser Cladded shaft will require only two passes on the lathe, one roughing and one finishing, and therefore 34.5 hours of machining. The net machining time, not considering setups etc. can be seen in table 6. On the other hand, the GMAW/MIG will necessitate 2 roughing passes and one finishing pass leading to a total of 48.1 hours of machining, see table 7.

Adding labour and material costs for both operations results in a cost of 11049€ (Euro) for the laser cladding and 19152€ (Euro) for the GMAW/MIG which is 73% higher. In the above calculation, labour costs for straightening the shaft were excluded. In the GMAW/MIG case, distortions due to residual stresses

[1]Deposition efficiency is the ratio of the amount of welded material to the amount of injected powder

can be expected, while this phenomenon is significantly reduced with the laser cladding technique. Therefore, the difference in costs may be even greater in reality.

Additionally, the production or repair of such a part can be achieved in 30% less time which translates to significant gains for the customer through reduced downtime.

	LC	MIG
Final Diameter	500mm	500 mm
Clad Length	8m	8 m
Deposition Thickness	2.5mm	4 mm
Machining Allowance	1mm (in thickness)	2 mm (in thickness)
Deposition rate	5kg/h	5 kg/h
Deposition Efficiency	90%	NA

Table 5. – *Test case propeller shaft characteristics*

Parameter	Value
Cutting Speed	40m/s
Depth of Cut	0.5-1mm
Roughing Feed Rate	0.4mm/rev
Roughing Speed	24rpm
Finishing Feed Rate	0.2mm/rev
Finishing Speed	32rpm
Roughing Time	13.67 hours/pass
Finishing Time	20.8 hours/pass

Table 6. – *Machining conditions*

	LC	MIG
Cladding material	AISI 316L	AISI 316L
Material Cost	12€/kg	16 €/kg
Gas Consumption	20 l/min	20 l/min
Shielding Gas Cost	4 €/m^3	4 €/m^3
Labour Cost	50€/hour	50 €/hour
Filler Quantity	390kg	600 kg
Welding Duration	78 hours	120 hours
Machining Time	34.5 hours	48.1 hours
Total Time	112.5hours	168.1hours
Filler Material Cost	4 680 €	9 600 €
Shielding Gas Cost	745 €	1145 €
Welding Labour Cost	3900 €	6000 €
Machining Labour Cost	1724 €	2407 €
Total Cost	11 049 €	19 152 €

Table 7 – *Laser Cladding vs. MIG costing comparison*

It is obvious therefore, that a high capacity laser cladding machine is certainly more economically viable for such operations than a conventional counterpart even when considering the higher capital cost.

The cost of a fully automated Laser Cladding system with a laser power of 6kW is in the order of 400 000 Euro, as seen in Table 1,.

The MIG equivalent automated system is in the order of 200 000 Euro.

Investment based on an assumption that 12 similar shaft parts are produced or repaired annually, is used to consider the return on capital. This corresponds to almost 50% of a normal shift period for a Laser Cladding system and 69% for the GMAW/MIG system. The laser cladding will give a return of 97 236 Euro higher profit annually which results in break-even after only 2 years. Furthermore, the laser cladding system being less occupied will have greater availability for other applications such as piston rods, turbocharger rotors, hydraulic pistons etc. returning even greater profit.

CONCLUSIONS

A direct comparison of the well established cladding technique GMAW/MIG and an emerging high end one such as laser cladding has been made both in technical and economic terms. Mechanical and metallographic testing was used to verify the theoretical advantages of the laser cladding on the technical side. Additionally, a case study was presented where the process of cladding a submerged propeller shaft was analysed from the economical perspective. In order to calculate the operating costs involved the filling material volume, repair time, gas consumables etc. were used. Finally an estimate of the investment break-even time was shown.

The results show that the laser cladded coating performed better from a mechanical testing point of view. Furthermore, the costing analysis indicated that the operating costs of the laser cladding system are considerably lower compared to those of the GMAW/MIG system and the turnaround is faster. The most important results are summarised in the following points:

- Higher tensile strength was attained with the laser cladded samples compared to the GMAW/MIG, 582 MPa vs 518 MPa.
- The yield strength of the laser cladded samples was significantly higher than the GMAW/MIG equivalents, 418 MPa vs. 264 MPa. This is attributed to the finer microstructure obtained due to the higher cooling rates of the laser cladding process.
- The elongation of the laser cladded samples was lower than that of the GMAW/MIG, 36% vs. 57%. This is attributed to the greater number of oxides in the coating due to the shielding gas used, which is less reducing in this case.

Furthermore, the higher cooling rates are also a significant factor.

- Significantly less dilution was obtained with the laser cladding process, 2% vs. 21%. Considerably less material is thus needed when laser is used as a welding method, which leads to lower material cost. Less machining is also needed for laser coating due to the smoother surface finish.
- 54% more material would be needed for cladding the same shaft with the MIG process compared to the laser cladding, in order to obtain a coating with an equivalent level of dilution at the surface
- 30% more time would be needed to clad the same shaft with a GMAW/MIG system compared to laser cladding.
- 73% higher operating costs are realised with a GMAW/MIG system compared to the laser cladding counterpart when cladding submerged propeller shafts.
- Even considering the higher capital investment costs the laser cladding system would be more profitable than the GMAW/MIG. In 2 years the former would reach break-even. The difference in the initial capital investment is countered by the higher profit and capacity.

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