Applications of Laser Cladded WC-Based Wear Resistant Coatings

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Abstract

Laser cladding is an additive process wherein a laser source is used to melt metal-based powder or wire on to a metal substrate. The technique is frequently used to produce wear resistant coatings consisting of a metal matrix and a ceramic strengthening phase. In this study mixtures of nickel based powders and various amounts of tungsten carbides have been used as feedstock for laser cladding on a range of steel substrates and for different applications. Crack-free low porosity coatings with a thickness of about 1 mm and carbide concentrations up to 50 vol% have been produced. The evaluation of the wear resistance of the different coatings is performed on lab scale or in the application itself.

Keywords: laser cladding; tungsten carbide; wear resistance

1. Motivation / State of the Art

Laser cladding is an additive process wherein a laser source is used to melt metal-based powder or wire on to a metal substrate [1,2]. A laser beam melts the additive material and a thin layer of the substrate (Figure 1). In this way metal or metal matrix composite (MMC) coatings with typically a thickness of the order of 1 mm are formed. Thanks to the superficial melting of the substrate, a strong metallurgical bond is formed between substrate and coating. With a low and local heat input, laser cladding is very well suited for the treatment of heat sensitive materials and components. Deformation of the component is limited and the heat affected zone is small. The high cooling rate during laser treatment results in coatings with a fine microstructure and minimal reaction between the ceramic and metallic phase in case of MMC coatings. After deposition, machining of the component to its final dimensions is mostly required. As laser source, different types of lasers can be used: CO₂, Nd:YAG, diode, disk or fiber laser. The former two lasers are the most commonly used lasers in materials processing by laser welding and laser cutting. However, there is currently a strong development in new, more compact and more efficient lasers: the diode, disk and fiber laser. The results presented in this paper are obtained using a diode laser as heat source.

As mentioned earlier, the laser cladding process enables the treatment of heat sensitive materials and deformation sensitive components, which cannot be processed by other techniques like conventional welding. The technique is increasingly being used in industry as a pro-active technology for corrosion and wear protection and as a reactive
technology for repair of worn components. In both aspects, laser cladding is a technology contributing to cost-effective maintenance.

![Principle of laser cladding using powder](image)

Carbide metal matrix composite materials are known for their high resistance to wear thanks to the combination of properties given by hard phase particles included in a tough matrix. For laser cladding mostly nickel or cobalt based materials are used as matrix phase.

In the present investigation, coatings of tungsten carbide particles in a nickel based matrix are produced on different steel grades and for different applications. Three different types of steel are cladded with tungsten carbide powder in order to improve the wear resistance of the cladded parts. The different applications for which a tungsten carbide containing coating was applied are: a plunger used in a glass forming machine, a knife for cutting asphalt and finally a pressing tool.

2. Experimental

The Figure 2 shows the experimental setup used for laser cladding in this study. It uses a 3 kW fiber-coupled diode laser (Laserline), which uses specific optics to create a circular spot with a diameter of about 3.7 mm at the substrate. A powder feed unit of Medicoat, which is commonly used for thermal spraying applications, is used. The powder is supplied in an argon gas flow to the coaxial cladding head. A CCD camera through a semi-transparent mirror coaxial with the laser beam, enables the alignment of the cladding head to the area to be treated.

![Laser cladding setup](image)
2.1. Feedstock powder

The matrix of the applied laser cladded coatings consists of a nickel based alloy with following chemical composition: Ni (bal.) – 7.5Cr – 1.6B – 3.5Si – 0.3C – 2.6Fe. The nickel alloy has self fluxing properties, which is favourable for thermal coating processes. The particle size is between 45 μm and 125 μm. Various amounts of tungsten carbide powder are mixed with the nickel based powder with ratio’s ranging from 0-50 vol%.

2.2. Substrate material

The types of steel chosen for the different cases depend on the final application. In Table 1 an overview of the steel substrates used is given. As can be seen from this table, the substrates used are very diverse.

Table 1: Overview of the different steel substrates used in this study

| Application | Steel type    | Standard Number | Carbon equivalent |
|-------------|---------------|-----------------|-------------------|
| Plunger     | SAE8620       | 1.6523          | 0.51              |
| Knife       | AISI316L      | 1.4404          |                   |
| Pressing tool | H11 steel   | 1.2343          | 1.59              |

2.3. Coatings

Depending on the chemical composition/carbon equivalent of the substrates, there will be a large difference in pre-treatment and cladding parameters in order to obtain a crack free coating for each application. For each application a maximal amount of WC in the cladded layer is targeted, since for each application a reduction in wear is essential. Depending on the application one or more carbide layers are needed. For the asphalt roofing cutter knife a multi layer coating with a thickness of 2.5 mm is applied. Both the plunger and press tool need only one layer with a high WC content (max. 50 vol%).

3. Results and Discussion

The laser cladding for each application will be described in detail. Depending on the type of steel substrate the laser cladding parameters were adjusted in order to obtain a crack free coating. A higher carbon equivalent of the steel substrate requires a higher preheat temperature. The austenitic stainless steel was not preheated, the press tool was preheated above 400°C. All the laser cladding parameters will be discussed in detail. For each application the wear resistance will be compared with the standard solution used. The plunger currently has a HVOF coating, the knife is made from hardened steel, the press tool uses a nitrided surface.

3.1. Knife

The knife, to cut asphalt into shingles, is very liable to wear. For this reason a coating containing a high amount of WC is applied. The standard knifes used on the cutting machine are hardened steel, without any coating. The service life of a standard knife is limited to one day (24 hours) and the aim of the study is to increase the service life significantly.

The cutting edges of the knife were laser cladded on an austenitic stainless steel sheet with relatively small dimensions: 100x20x2. A gradient coating is applied on the small side of the stainless sheet (2 mm). In the first step 2 layers of 80% Ni based alloy and 20 vol% WC are applied. In the consecutive step 2 layers of 60% Ni based alloy and 40 vol% WC are build to finish with 3 layers of 40% Ni based alloy and 60 vol% WC. The total thickness of the coating is 2.5 mm. The knife is cladded on both sides, enabling a double use of the knife. A cross section of the
cladded coating is shown in Figure 3. The machining of the cladded coating to its final shape is performed by grinding off the excess material.

![Image of cladded coating with final shape indicated](image_url)

Figure 3: cross section of the cladded coating, the final knife shape is indicated

As can be seen from Figure 3 the coating is crack and pore free. In the next figure, 4 knives are shown:

- Up right: standard hardened steel knife
- Up left: laser cladded knife
- Down left: machined laser cladded knife
- Down right: worn-out hardened steel knife

For the final application it is important to keep the deformation of the knife limited. If deformation is too large, grinding of the knifes will result in an excessive loss of Ni/WC coating which is to be prevented.

![Image of four different conditions of asphalt cutting knifes](image_url)

Figure 4: 4 different conditions of the asphalt cutting knifes

To test the wear reduction of the laser cladded knifes, the knifes were tested under real production conditions. The knifes are mounted on the asphalt shingle cutter and the service life of the knifes is monitored. After testing 5 cladded samples, the average service life of the cladded knifes is 75 hours, this means an improved service life with a factor 3 (standard lifetime = 24 hours). This factor can be improved using a thicker laser coating. Since the coating thickness applied on the knifes is limited up to 2.5 mm and the height of the cutting edge on standard knifes is 5 mm, the volume of the coating can be increased with a factor 4 if the total cutting edge of the knife was cladded. This will certainly lead to another significant increase in service life for the knifes. Knifes will be cladded with a 5 mm thick laser coating to demonstrate the increase in service life with the thicker laser coating.

### 3.2. Plunger

A plunger is a tool used in the production of glass containers during the first stage of shape forming. The task of the plunger is to help give the glass container its final shape inside the blank mould. During forming a periodic lubrication of the mould is performed in order to reduce the dynamic friction, to minimize corrosion and to prevent
sticking and adhesion of the glass during the forming step. The surfaces of the plunger are subjected to high cycling temperatures (550-750°C), thermal, corrosive and abrasive wear. Worn surfaces dramatically affect the quality of the glass product in terms of surface finish and impact strength. Reduced wear would result in high energy and material savings. To reduce wearing of the standard plunger has a fused HVOF Ni alloy + WCCo coating with a hardness between 60 and 65 HRC. In the laser cladding experiments, the HVOF coating was replaced by a Ni alloy + WC clad layer. In the next figure the laser cladding procedure of plungers and cladded plungers are shown. Four different laser coating are applied: Ni alloy, Ni alloy + 20 wt% WC, Ni alloy + 40 wt% WC and Ni alloy + 60 wt% WC.

Figure 5: Plungers completely laser cladded for wear testing in the glass machine.

In the next figure a cross section of a HVOF Ni alloy + WCCo (left) and a laser cladded Ni alloy + 60 wt%WC coating. The laser cladded coating, obtained without preheating is pore and crack free.

Figure 6: cross sections of applied coatings. Left: HVOF coating, right laser cladded coating
To compare the wear resistance of the laser cladded coating with the HVOF coating, tribological tests are performed using a Wazau TRM 1000 under rotating sliding conditions. The effect of spherical tungsten carbide size and volume fraction on sliding and abrasive wear of laser cladded Ni based tungsten MMC coatings was studied by Van Acker et al. [3]. Tests have been performed at varying speeds and loads. For both coatings at least two samples have been tested. The laser coating samples are tested in grinded and polished condition, the resulting test conditions are as follows:

- Spherical Al₂O₃ counterbody with diameter of 6 mm
- Load = 150 N
- Temperature = 430°C
- Air atmosphere
- Speed: 240 rpm
- Radius of wear track = 16-18 mm
- Duration = 0.5 or 1 hour

To evaluate the wear resistance, profilometry of the wear track along its circumference is performed. The average wear volume is used to calculate the wear coefficient, which expresses the wear volume per unit load and unit traversed distance. Scanning electron microscopy of the wear track is performed to analyse the wear mechanism. The results of the tribological tests are shown in Figure 7, showing the wear coefficient as a function of the applied coating.

![Figure 7: wear coefficient of the different applied coatings](image-url)

From Figure 7 it can be seen that laser coatings containing at least 20 wt% WC have a higher wear resistance compared with the standard HVOF coating. Unfortunately, at this time no data of the behaviour of laser cladded plungers under real glass machine conditions are available. This test will show the potential of laser cladded layers for plungers in glass industry.

3.3. Pressing tool

Nitriding hot work tool steel in a gaseous environment is by far the most common surface treatment for this application. It increases the service life substantially by protecting the surface against wear. Nitriding of steel involves diffusion of nitrogen into the surface at temperature ranges from 450 – 580 °C [4]. The treatment generates a 50 – 300 μm thick nitrogen enriched diffusion zone and a 2 – 10 μm thick iron nitride compound layer on top which attains a hardness of 1000 – 1200 HV. This compound layer is relatively brittle and it is not clear that its
The presence is advantageous for wear resistance. For this reason an alternative solution using a laser cladded coating was studied.

The steel substrate for this application is a H11 hot work tool steel with a carbon equivalent = 1.59. A single clad layer of 1 mm thickness will be sufficient for the application if the amount of carbides is high. The aim is to achieve a crack and pore free Ni alloy + 50 vol% WC coating on soft H11 tool steel. All tests performed on hardened H11 steel resulted in cracks in either the coating or the heat affected zone of the cladded area. For this reason it was decided to perform laser cladding on soft H11 steel and harden the tool after cladding. After hardening, the tool is machined to its final dimensions. To obtain a crack free coating containing 50 vol% WC, a preheat temperature of 450°C was needed. A cross section of a laser coating applied on H11 steel is shown in the next figure.

![Cross section of H11 hot work tool steel with Ni alloy + 50 vol% WC coating](image)

To compare the wear resistance of the laser cladded coating with the nitrided surface, tribological tests are performed using a Wazau TRM 1000 under rotating sliding conditions. Tests have been performed at varying loads (100 and 200 N). For both coatings and loads, at least two samples were tested. The laser coating samples were tested in grinded and polished condition. All other conditions are comparable with those used to test the coatings of the plunger application.

| Coating          | Load [N] | Temperature [°C] | Wear coefficient [mm³/Nm] |
|------------------|----------|------------------|---------------------------|
| Nitrided steel   | 100      | 400              | 48.98                     |
| Ni alloy + 50% WC| 100      | 400              | 6.18                      |
| Nitrided steel   | 200      | 400              | 78.7                      |
| Ni alloy + 50% WC| 200      | 400              | 6.46                      |

From these results it can be seen that laser coatings have a significantly higher wear resistance compared to nitrided hot work tool steel surfaces. To test the wear reduction of the press tool, it is tested under real conditions. The service life of the nitrided hot work steel press tool was compared with a laser cladded press tool. The service life of the laser cladded tool was over 6 times higher than the service life of a nitrided tool. The nitrided steel had to be re-nitrided 5 times and even then the service life of the laser coated tool could not be reached. Knowing the service life under real conditions, laser cladding of press tools will surely be introduced into this market.
4. Conclusions

- Crack-free nickel based tungsten carbide coatings with a carbide concentration up to 50vol% are produced by laser cladding on different steel substrates.
- In the case of a hot work tool steel, the substrate was preheated up to 450°C in order to obtain a crack free coating.
- For all applications, an increased wear resistance by at least a factor 3, is observed.
- The wear coefficient during sliding contact with an Al₂O₃ counterbody at elevated temperature is significantly lower for the applied laser coatings compared with the standard coating used.

Acknowledgements

Some of the results were obtained in the frame of the Matera project MOTRICOT - Model based tribologically optimised thick multimaterial coated surfaces. The financial support of The Institute for the Promotion of Innovation by Science and Technology of Flanders (IWT) is gratefully acknowledged.

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