Investigations on the Characteristics of Thermally Sprayed NiCrBSi Coatings Fused by Flame and Inductive Processing

P C Vălean¹,², N Kazamer¹,²,*, R Muntean¹, D T Pascal¹, Y Kilic¹, G Mărginean¹ and V A Șerban²

¹Westphalian University of Applied Sciences, Neidenburger Str. 43, 45897 Gelsenkirchen, Germany
²Politehnica University Timisoara, Piața Victoriei 2, Timișoara 300006, România

*Corresponding author: norbert.kazamer@yahoo.com

Abstract. Ni-based materials are some of the most used hardfacing alloys to improve wear and corrosion resistance for parts functioning under severe conditions. For the current study, a NiCrBSi self-fluxing alloy powder with particle size in range of 45-106 μm was employed as feedstock material and deposited onto a steel substrate material using the oxyacetylene thermal spraying process. The as-sprayed components have been subsequently subjected to thermal post-processing in order to increase the adhesion to the substrate and to reduce the inherent porosity of the coatings. Consequently, two types of heating sources were chosen. One of them was the neutral oxyacetylene flame and the second one was based on high frequency currents. The aim of this work was to study the influence of the heat source type of the post treatment on the final characteristics of the coatings. Evaluation of the morphology and microstructure of the developed coatings was performed after the remelting process by means of scanning electron microscopy. Hardness tests were carried out in cross-section complying with the ASTM E384 standard. In both cases, after fusing, the microstructure was refined, with a drastic decrease in porosity. Evaluation of the hardness distribution along the coating cross-section revealed similar values of microhardness.

1. Introduction

In order to compensate the rising personal and raw material costs, machines and technical installations, which are working in high-technology industrialised countries necessitate a constant rise in productivity and performance [1]. Recently, the requirements on components of machines that are utilised in offshore environments have become so stringent that the demands cannot be any more satisfied by the base material alone [2]. Thermally sprayed coatings are a practical and economical solution for the protection of parts against wear and corrosion. These processes are divided according to the type of heating source (laser, combustion gas, electric arc, plasma) and the feedstock material used for the deposition (powder, rod, wire) [3, 4, 5]. In this work a low velocity oxygen fuel (LVOF) process, known in the industry as the combustion process with oxygen-acetylene flame was used. This spraying method has been well-known in industry for many years being currently used for repairing damaged parts as well as for depositing new protective coatings, which can provide good resistance to wear and corrosion. In the process of repairing or depositing new coatings with oxyacetylene flame, the particles are accelerated and also partially melted inside of a turbulent flame and are deposited on a surface prepared in advance, having high roughness, thus forming a coating with a lamellar and
heterogeneous structure [6]. In the thermal spraying process, the most important mechanism of adhesion of the coating to the substrate is mechanical interlocking; the process creates a mechanical bonding between the particles and the asperities resulted after the sand blasting process. Following this deposition process, the adhesion of the coating is very low, due to this fact further treatment is necessary [7].

In the current work, to solve the initial problems regarding the increased porosity of the as-sprayed coatings and to minimise the induced micro-cracks, two types of post treatment processes are applied. The first one is the flame remelting process, where, typically NiCrBSi coatings are remelted by oxyacetylene flame during or after the deposition process. Due to the difficulty of maintaining a constant temperature during the fusion process and also interfering with the operator's experience and skills, this remelting process is not reproducible and also difficult to control [8]. The second post-treatment was performed using high frequency currents for heating and remelting the coating, increasing in this way, for the both applied processes, the adhesion of the coating to the substrate and significantly reducing the porosity.

2. Experimental procedure

2.1. Materials

The feedstock powder used in this study (480-FS6, LSN Diffusion, England) obtained through water atomisation, is a nickel-based alloy with a chemical composition shown in Table 1, and a particle size between 106-45µm.

| Powder NiCrBSi | Base | 13 | 2.5 | 3.5 | 3.4 | 0.5 | - | - | - | - |
| Substrate 42CrMo4 | - | 1.13 | - | 0.26 | Base | 0.42 | 0.73 | 0.012 | 0.023 | 0.21 | 0.027 |

The high amount of chromium in the powder composition, increases the wear resistance of the coating, and the presence of Si and B favours the wettability and deoxidation during the remelting process [9].

2.2. Samples preparations

The geometry of substrate was cylindrical with a diameter of 160 mm and a length of 200 mm. Prior to deposition the samples were cleaned with alcohol, sandblasted with cast iron particles having a nominal size between 0.8 and 1.25 mm in order to reach a surface roughness higher than 75 µm. An increased roughness is strongly necessary because after the LVOF process the coatings adhere only mechanically to the substrate [1]. The coating procedure was performed by Karl-Schumacher GmbH, Germany using a flame spraying gun produced by Metatherm, Germany.

After the deposition, the coatings exhibit very high porosity and require a subsequent thermal treatment in order to close the pore and to achieve an increased adhesion to the substrate. Considering these essential aspects, two types of thermal treatments using different heat sources to reach the necessary remelting energy for the system were applied. First sample was remelted by flame using an oxyacetylene gas process with a neutral stoichiometry. The results for this type of process are directly connected and depend on the experience of the worker. The sample is slowly heated to the melting temperature, the heat dissipates inside the material and therefore it is no risk for crack initiation after the remelting process. The main disadvantage of this method is that it is not suitable for large parts.
The second sample was remelted using an induction heater (EKOHEAT 200/30, Ambrell, The Netherlands) This induction heating unit requires 15 kHz to 40 kHz frequency range. According to a similar research made by Hemmati and the team [4], the remelting process consisted of a preheating step, comprising several passes at a lower power and a relatively faster velocity of the inductor in comparison with than the one used for the remelting procedure. For further analysis, metallographic samples were prepared according to the standard guide for metallographic preparation of thermal sprayed coatings [10].

3. Results and discussions

3.1. Porosity of the NiCrBSi coatings

The micrographs were acquired with a Leica DM-RME light microscope and further processed. Figure 1 exhibits a considerably reduction of the porosity from 15% in the case of as sprayed coatings to a mean value of 3% after the flame remelting and to 1% after electromagnetic remelting treatment respectively. It is already known that heat treatment of NiCrBSi coatings will reduce their volume up to 20%. [1, 3]

The porosity degree was calculated with the aid of ImageJ processing Software from metallographic specimens in as-polished cross-section, presented in figure 1.

![SEM micrograph of the a) inductive remelted and b) flame remelted NiCrBSi coatings](image)

Previous works of the authors as well as the experimental results of this work showed that a complete densification cannot be achieved. In the case of flame remelting process, one may not assure an homogeneous temperature distribution in the coating material, fact which will induce some difference concerning the degree of porosity.

The flame remelted coating was more compact at the surface than at the interface (coating/base material), phenomenon which in the case of electromagnetic induction remelting was not observed. The induction fused coating revealed a very compact structure due to the influence of frequency on the penetration depth, which assured a constant temperature distribution maintained during the whole process.

3.2. Microhardness and adhesive properties of the NiCrBSi coatings

Microhardness investigations were carried out on a Zwick Microhardness tester according to ISO 6507 / ASTM E 384. The indentation were performed in different spots along the cross-section of the NiCrBSi coating, the load used for determining the Vickers microhardness was 3 N applied for 15 seconds on each indentation and the distance between measurements was minimum 0.15 mm. The investigations, revealed for the inductively remelted samples an average value of around 600 HV 0.3, and for flame-remelted ones, the hardness mean value was around 490 HV 0.3. This difference can be very good associated with the degree of coating porosity.
Another very important property for the thermal sprayed coatings is their adhesion to the substrate. In order to determine if the coating has a good adhesion to the substrate, the samples were investigated concerning their adhesive properties.

![Figure 2. HBW2,5/187,5 indentation for a) inductive remelted and b) flame remelted NiCrBSi coatings](image)

The test was carried out with a Hardness Testing Instrument equipped with a tungsten carbide Brinel type indentation ball with 2.5 mm nominal diameter and an applied force of 187.5 kgf. The indentations were made in different points along the coating/substrate interface (in cross-section). The results (figure 2) have shown that both remelting processes offer a good adhesion of the coating and do not present delamination at the interface.

### 3.3. Corrosion behavior

The corrosion behavior of the NiCrBSi coatings was investigated by electrochemical testing in 3.5% NaCl aqueous solution. A saturated calomel electrode (SCE) was used as reference electrode, a platinum disk as auxiliary electrode and the NiCrBSi samples represented the working electrode. The samples were polarized in a potential interval from -1000 mV to +1000 mV, with a scan rate of 0.16 mVs⁻¹.

![Figure 3. Polarisation curves of the flame and inductively fused NiCrBSi coatings tested in 3.5% NaCl aqueous solution.](image)

The polarisation curves illustrated in figure 3 reveal no differences concerning the values for the corrosion potential of the tested coatings. As can be noticed, the corrosion current density $i_{corr}$ is 20 times lower in the case of the inductive remelted sample compared to the flame remelted one. This
observation indicates a better corrosion resistance of the inductive fused coatings exposed to a 3.5 % NaCl aqueous solution.

4. Conclusions
In the preliminary state, flame sprayed NiCrBSi coatings present high porosity, low cohesion between particles and poor adhesion to the substrate, as well as an irregular surface geometry. Therefore, the as sprayed coatings do not fulfil the technical requirements to be used in the industry and necessitate a remelting post-treatment. Two different types of remelting methods were applied and analyzed, namely manual oxyacetylene flame remelting and inductive remelting process. The obtained samples were further analysed regarding the microstructure and mechanical properties. The inductive remelted coatings are more compact (lower porosity), the structures are much finer and better dispersed compared to the oxyacetylene flame remelted ones. After the remelting process, porosity decreased from 15% as in the case of the as-sprayed samples to 3.2% for flame remelted samples and as low as 1% for inductive remelted ones. The microhardness investigations revealed a higher value (up to 100 Vickers units) for the inductive remelted coatings in comparison that remelted with oxyacetylene flame. This aspect was attributed to the more compact microstructure respectively lower porosity. The electrochemical corrosion tests showed that inductive remelted specimens exhibit better corrosion resistance than the flame remelted one.

In conclusion, inductively remelting process can be successfully applied for thermal sprayed coatings in order to improve the mechanical characteristics and the corrosion resistance, since the inductive remelted specimen exhibit a higher hardness, and an improved corrosion resistance, in comparison to the samples remelted with oxyacetylene flame, these aspects making them suitable for of shore applications.

5. References
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