DEVELOPMENT OF LASER CLADDING MCrAlY COATINGS: HIGH TEMPERATURE FRICTION AND WEAR BEHAVIOUR

J.C. Pereira Falcón[1,2(*)], J.C. Zambrano Carrullo[3], M.J. Tobar Vidal[4], V. Amigó Borrás[1]
[1] Instituto de Tecnología de Materiales ITM, Universidad Politécnica de Valencia, Spain
[2] Centro de Investigaciones en Mecánica CIMEC, Universidad de Carabobo, Venezuela
[3] Centro de Investigación en Materiales CIM, Universidad de Carabobo, Venezuela
[4] Departamento de Ingeniería Industrial II, Universidade da Coruña, Campus Ferrol, Spain
[*] Corresponding author: jpereira@uc.edu.ve

ABSTRACT

Temperature can have a significant effect on the extent of wear damage of metallic components. Thermal barrier coatings with MCrAlY (where M=Ni, Co, Fe or combinations) alloys can improve the high temperature tribological and friction wear behaviour. In this work the dry friction and wear behaviour at room temperature and high temperature of new developed NiCoCrAlY and CoNiCrAlY laser cladding coatings were evaluated. Dense coatings, with good metallurgical bonding to the AISI 304 substrate was obtained by coaxial laser cladding tracks (40% overlapping), with previously optimized laser parameters. Tribological tests were performed by sliding wear at room temperature and 500 ºC, with an Al_2O_3 counterpart in ball on disk configuration tribometer. The wear scar surface was evaluated by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) microanalysis. The 3D wear track topography was measured by inductive contact profilometer which enabled the wear rate calculation. The microstructure of the coatings consists of γ-Ni/β-NiAl or γ-Co/β-(Co,Ni)Al phases depending on the chemical composition of the alloy, as confirmed by X-ray diffraction (XRD) analysis. The wear test results show a reduction in wear rate at high temperature for all materials tested. For the NiCoCrAlY coating, the high temperature also reduces the friction coefficient, while it significantly increases the friction coefficient of CoNiCrAlY coating. The main damage mode is abrasion and adhesion, caused by oxides and partially-oxidized particles in the contact surface. The coatings and substrate results were compared, resulting in improved wear behaviour.

KEY WORDS: friction; wear; MCrAlY; laser cladding; coating.

1.- INTRODUCTION

Components in aircraft and power-generation turbines are protected by barrier layers of MCrAlY alloys. Nickel and Cobalt based superalloys are widely used as coating or bonding layer between the substrate and a top layer of ceramic material in thermal barrier coatings (TBCs) [1], due to its good adhesion, high modulus, high strength and its good resistance to oxidation at high temperature, so that, are widely used in mechanical engine components and modern gas turbines [2]. The NiCoCrAlY and CoNiCrAlY alloys containing large amounts of Cr with small additions of Y, which produce solid solution strengthening. These effects are quite stable, and act as a brake on the progress of dislocations in grain boundaries, resulting in the typical yield strength of these alloys [3]. An aluminum content of 8-15% by weight enables the formation of a thermally stable, adherent, continuous layer of alumina (α-Al_2O_3) of slow growth at high temperature [4,5], the adhesion of the oxide layer to substrate is influenced by the distribution of Y in the alloy before deposition [4].

Laser cladding process (LC) can be used to produce dense coatings free of pores and cracks that improve their oxidation resistance, and this technique can be applied in small parts with complex geometry [6-8]. The laser processing parameters and the shielding gas can be controlled to obtain a minimum chemical dilution with the substrate and reduce defects such as cracks and pores.

At high temperature, most metals inevitably oxidized with a wide range of conditions, and various interactions between the substrate materials and the atmosphere can be expected, such as diffusion, inter-diffusion, decomposition, volatilization and thermal growth of the layer oxide [5]. The wear rate and friction coefficient are important parameters in the performance of the coated components and subjected to contact with other parts at high temperature. The oxidation of metals may influence the process of wear and damage mechanisms [9]. The wear behavior of MCrAlY alloys has been studied by several authors, seeking to improve the high temperature performance with the inclusion of ceramic particles [10-12]. In this paper we evaluated the friction and wear behavior at high temperature (500 °C) and room temperature, in static air, of two laser cladding coatings made with NiCoCrAlY and CoNiCrAlY superalloys and optimized laser cladding parameters as a novel alternative to thermal spray coating process. The evaluation of the wear scar surfaces was made by SEM and EDS microanalysis. The profile of wear scars was measured and the wear rate was calculated for both coatings and the substrate.

2.- EXPERIMENTAL PROCEDURE

2.1.- Material and laser cladding processing

Gas atomized prealloyed MCrAlY powders supplied by Sulzer Metco (Amdry 365-2 and 995C) were used. NiCoCrAlY alloy was composed mainly of Ni with 23% Co, 17% Cr, 12% Al and 0.42% Y. CoNiCrAlY alloy was composed of Co with 32% Ni, 21% Cr, 8% Al and 0.45% Y. The substrate was a cold rolled stainless steel AISI 304 of 10 mm in thickness. Extensive coatings (30x30 mm^2) were obtained using a Nd:YAG solid state laser (Rofin-Sinar DY 022) in continuous mode with a maximum power of 2.2 kW and a wavelength of 1064 nm; a power (P) of 2.2 kW was used in this study. The diameter of the beam focus (D) on the part was 4 mm. The XYZ movement was achieved by a robot with 6 degrees of freedom (ABB IRB 2400 unit), velocity (V) of 15 mm/s and overlapping ratio in laser scan of 40%. Powder was supplied per unit length of 25 mg/mm and provided with a coaxial annular nozzle (Precitec YC50) and Sulzer Metco Twin 10-C powder feeder. Helium (20 l/min) was used as a shielding gas and Argon (15 l/min) as a powder carrier gas.

2.2.- Powder characterization and coatings microstructure

For powder characterization, a laser beam was diffracted through particles suspended in distilled water using a Mastersizer 2000 laser diffractometer to obtain the variations in particle size diameter. The powder morphology and chemical composition was obtained by SEM and EDS microanalysis. The measurements of X-ray diffraction were carried out on a Philips X'pert using monochromatic Cu Kα radiation (λ=0.15406 nm). The patterns of X-ray diffraction were in the range of 2θ from 20°to 90° and were analyzed using X'Pert Plus software (PANalytical). Microstructural characterization of the coating was carried out on a cross section, which was previously cut and metallographically prepared for analysis, using backscattered electron images (BSE) of the microstructure at different magnifications in a Jeol JSM6300 scanning electron microscope. Microanalysis to quantify the chemical composition was performed by EDS using an X-Max Oxford Instruments microanalysis system with an X-ray detector of 20 µm².

2.3.- Dry sliding wear test

The sliding wear tests were performed with a high-temperature tribometer with a ball on disc configuration, manufactured by MICROTEST MT2/60/SCM/T, according to ASTM G99-03 and DIN 50324 standards. Four wear tests were made for each material/condition. Before the tests, the coating surface was ground to a finish of 500 grit SiC paper (Ra=0.17 ± 0.05 µm), and were cut into samples of 15x15 mm. Al_2O_3 grade 25 balls (5 mm diameter, 0.05 microns Ra and hardness of 2400 HV) manufactured by Precision Ball & Gauge Co. were used as counterpart material, due to the stability of this material at high temperature. The test parameters were: contact load of 10 N, speed 0.1 m/s, sliding distance of 500 m, temperatures of 24 °C (RT) and 500 °C (HT) in static air (65% RH), the heat rate for HT wear tests was 20 ºC/min. A radius of wear track of 5 mm was used for all tests.

The temperature near the ball-sample contact area was measured with a contact type ‘K’ thermocouple with grounded hot junction of Inconel alloy, and recorded during the test. Wear profiles were measured with an inductive contact profilometer (range 2.5 mm) Taylor Hobson Talysurf 50 to obtain the 3D topography of the surface wear track. The average wear area was determined through the measurement of four different profiles of the wear track. The measurements were done on four wear tested samples for each material. The wear rate (Wr) was calculated using the following formula:

$$W_r = \frac{P.A}{F.L} \tag{1}$$

Where W_r is the rate of wear in $mm^3/(N\cdot m)$; P is the mean scar circumference in mm; A is the average wear area in mm^2; F is the applied normal load in N; and L is the sliding distance in m.

3.- RESULTS AND DISCUSSIONS

3.1.- Powder characterization and coatings microstructure

Two pre-alloyed MCrAlY alloys powders were used in this study. Both powders have a spherical morphology as shown in figures 1a and 1b, typical of the gas atomization process, and particle size analysis of the powder revealed a mean particle size of 55.3 µm for NiCoCrAlY powder and 64.7 µm for CoNiCrAlY powder. The morphology and size of the powder is very important for the coaxial laser cladding processing because the flowability of the powder influences the quality of the coating. Two phases can be distinguished in each powder’s feedstock according to XRD analysis, consisting of γ-Ni(Cr)/Co(Ni,Cr) and β-NiAl/(Co,Ni)Al depending on the base element of the superalloy.

Many variables are involved in the laser cladding process, which requires studying the geometry and chemical dilution of single clad tracks before creating extensive overlapping coatings. In previous work [13-15], laser cladding parameters were studied on a NiCoCrAlYTa alloy to obtain an adequate aspect ratio, homogeneity, low dilution and a good metallurgical bond with the substrate. In this study, high velocity, high powder feed rate and high laser power were combined to build overlapping coatings. The specific laser energy (36.67 J/mm^2) was combined with a laser with a 4 mm diameter allowed us to obtain adequate coatings. This provided a dense coating with a homogeneous structure, and minimum dilution with the substrate.

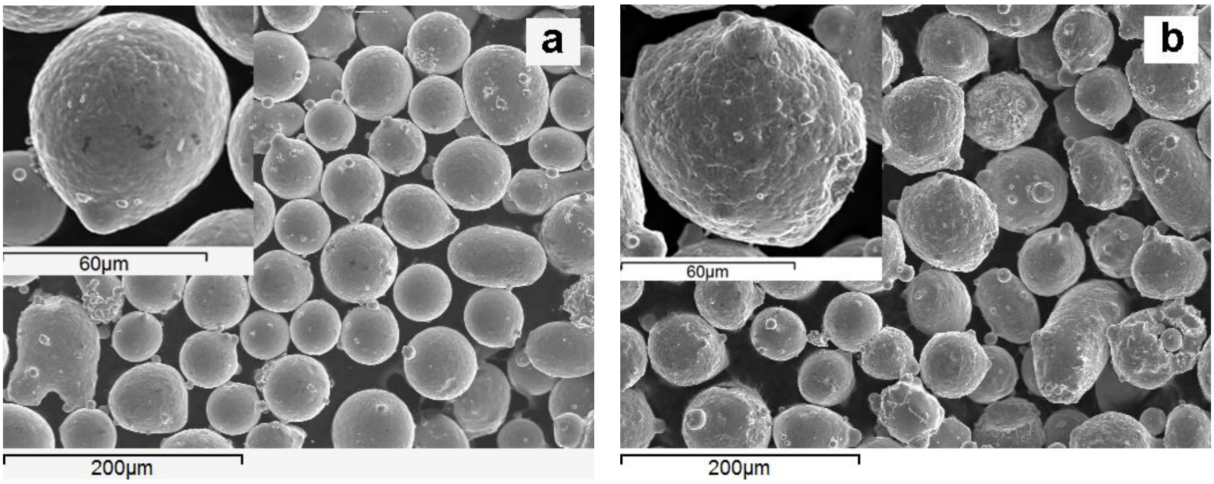

Figure 1. Powders morphology detail in SEM micrograph (20 kV SE mode) a) NiCoCrAlY and b) CoNiCrAlY

The thickness of the CoNiCrAlY alloy coating was 715±32 μm (Figure 2b), with a dendritic columnar structure and small pores, while the initial coating thickness for the NiCoCrAlY alloy was 832±45 μm (Figure 2a).

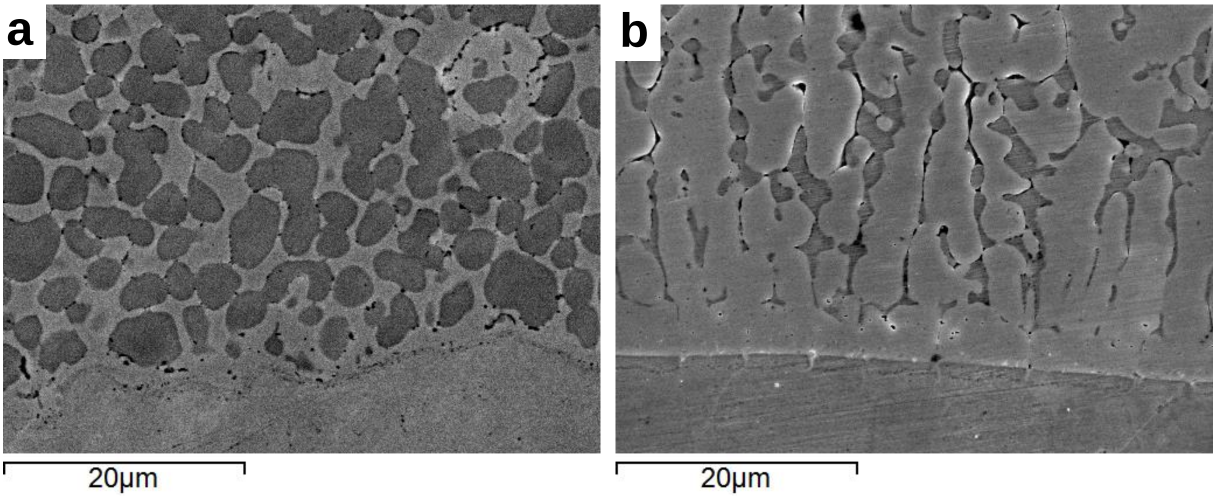

Figure 2. SEM micrographs of the interface coating/substrate (20 kV BSE mode) a) NiCoCrAlY laser cladding coating and b) CoNiCrAlY laser cladding coating

The coatings' microstructures are composed of two principal phases, a γ matrix phase and β phase. The NiCoCrAlY coating has a cellular dendritic structure (Figure 2a), and EDS microanalysis revealed a dendritic γ–Ni matrix phase with Cr and Co elements in solid solution and an interdendritic β-NiAl phase (dark) rich in Al with Co in solid solution. Ni-Y rich zones are present in some γ/β grain boundaries. In the CoNiCrAlY coating, a columnar dendritic structure with planar solidification front was observed (Figure 2b). In this case, the content of interdendritic phase (dark) is less due to the lower content of Al in this alloy. EDS analysis also suggests a hypoeutectic solidification with γ-Co(Ni,Cr) and β-(Co,Ni)Al interdendritic phase. The γ/βcoatings' microstructures are confirmed by XRD analysis.

3.2.- High temperature friction behavior

The friction coefficients were obtained from dry sliding wear tests. Figure 3 shows the behaviour of the friction coefficient, for both alloys, in function of the sliding distance, obtained at room temperature and high temperature (500 °C) in static air. During testing, a slight instability in the initial friction coefficient can be attributed to the removal or redistribution of the particles on the contact surface. The NiCoCrAlY friction coefficient decreases slightly at high temperatures going from 0.49±0.08 (RT) to 0.45±0.01 (HT), possibly due to the formation of oxides and other intermetallic compounds which reduce the adhesion phenomenon and plowing on the coating. While for the CoNiCrAlY coating the plowing phenomenon and adhesion are increased on the surface coating at high temperature, greatly increasing the friction coefficient going from 0.46±0.03 (RT) to 1.00±0.30 (HT). Both coatings have similar frictional behaviours at room temperature but radically different at high temperature.

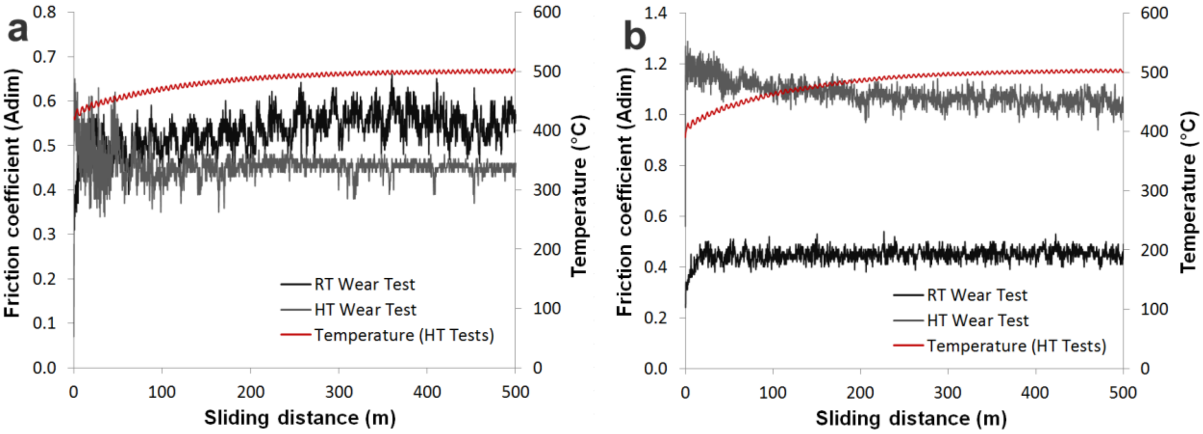

Figure 3. Friction coefficient evolution with sliding distance at room and high temperature (10N, 0.1 m/s, Al_2O_3 ball) a) NiCoCrAlY laser cladding coating and b) CoNiCrAlY laser cladding coating

The cobalt-based super alloy has a higher content of cobalt and chromium with aluminium content lower than the nickel-base alloy, which affects the kinetics of oxidation of the contact surface and the frictional behaviour, increasing the resistance to plowing at high temperature. At room temperature, the main damage mode for the NiCoCrAlY coating is abrasion (Figure 4a); at the edges of the track the material is plastically deformed in CoNiCrAlY coating, this behaviour at room temperatures is common in metallic materials [16]. At high temperature, it appears that the primary mode of damage is abrasion for the NiCoCrAlY coating. Wear debris induced the formation and removal of oxides during the wear process (Figure 4a) with a higher accumulation and adhesion of oxides (Al_2O_3, Cr_2O_3, NiO) for both coatings as see in Figure 4b and 4d, possible material delamination can also be seen in certain areas of the track. The coatings suffered plastic deformation due the increased ductility at high temperature. The continuous formation and destruction of the transfer layer influences the fluctuation of friction coefficient (Figure 3). Material removed in HT tests is lower due to the formation of oxides and partly oxidized alloy particles at high temperatures which reduce metal-metal contact and thus reduces the wear rate [11].

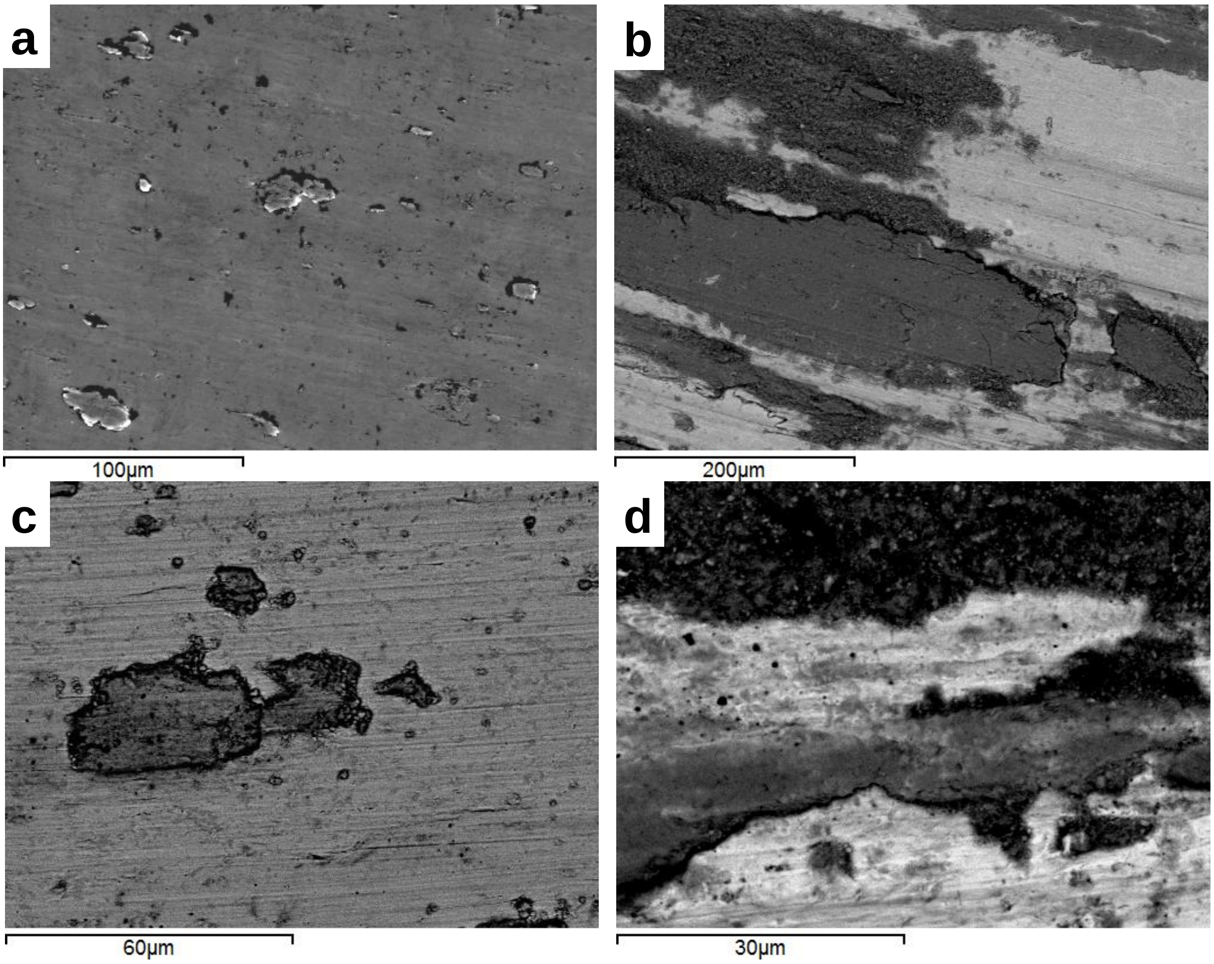

Figure 4. SEM micrographs of wear tracks surface (20kV) a) NiCoCrAlY RT test (SE mode) b) NiCoCrAlY HT test (BSE mode) c) CoNiCrAlY RT test (BSE mode) and d) CoNiCrAlY HT test (BSE)

3.3.- High temperature wear behavior

3D profiles of the wear track of the coatings are shown in Figure 5. Differences were observed in the width and roughness of the wear tracks obtained at high temperature. For each sample the 2D profile of the wear scar was obtained and the volume of material removed was calculated from these profiles. The results of the wear test indicate that the RT removed volume is higher than the HT volume removed, so that the wear rate is reduced by 39% for the NiCoCrAlY coating and 60% CoNiCrAlY coating at high temperature. In the substrate the trend is similar; the wear rate is reduced by 84.6% at high temperature. In wear scar surface the plastic deformation at the track edge are observed for CoNiCrAlY (Figure 5d) coating and AISI 304 substrate samples tested at high temperature. The counterbody analysis after HT tests reveal that in ball surface small abrasion marks (maybe microplowing) and dark colour is observed (with flat and undeformed surface), with small residues of coating oxides (3-body-abrasion). Summarized results of the friction coefficient and wear volume are shown in Table 1. At high temperature the laser cladding coatings and substrate have better frictional wear behaviour due to the formation of compacted layers of oxide and partially-oxidized alloy particles on the sliding surface that reduce the wear [9]. At room temperature the NiCoCrAlY laser cladding coating wear rate is similar to reported by previous work [12,17] and lower than wear rate reported for thermal spray TBCs [18].

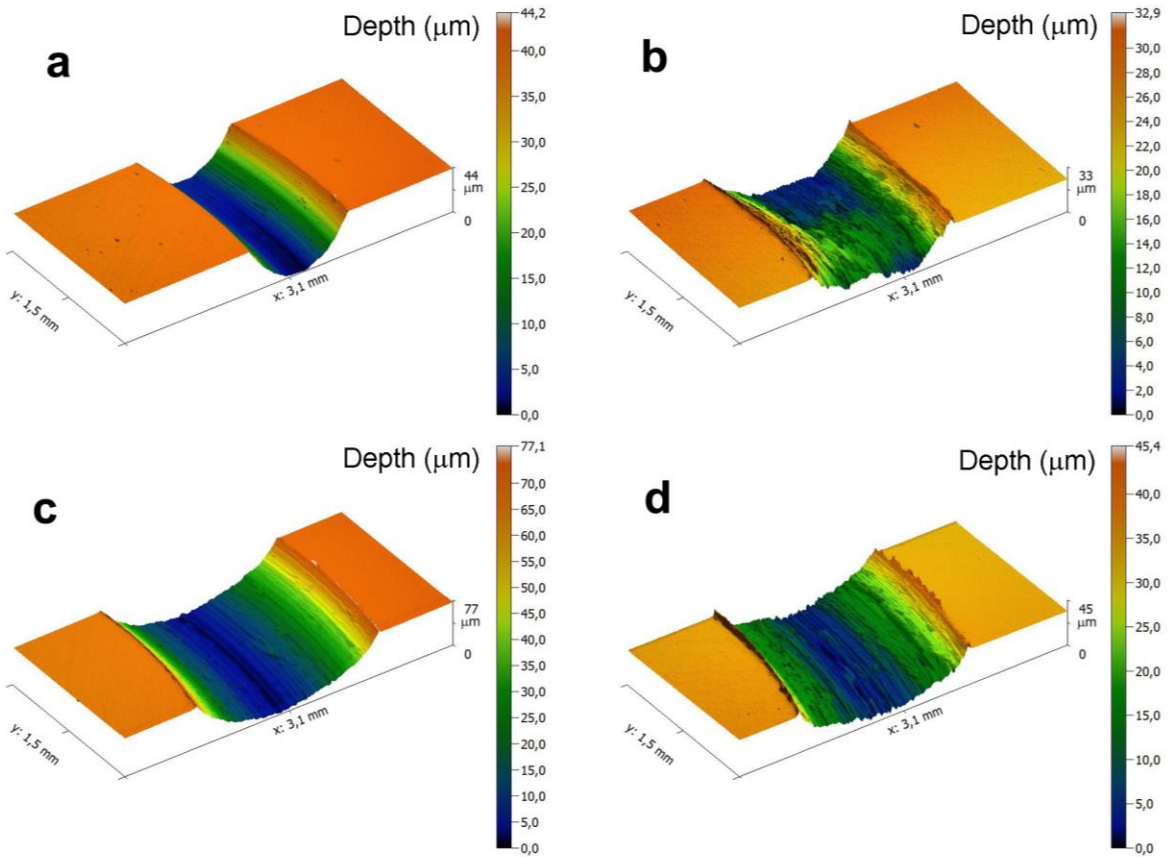

Figure 5. 3D topography of the wear tracks a) NiCoCrAlY LC coating in RT test b) NiCoCrAlY LC coating in HT test c) CoNiCrAlY RT test and d) CoNiCrAlY HT test

At high temperature the nickel-based laser cladding coating has lower wear rate than the substrate, but the cobalt-based coating has a higher wear rate. This is due primarily to a combination of wear mechanisms at high temperature: abrasion, adhesion by the oxide particles (as see in Figure 5b and 5d), maybe surface fatigue and plastic deformation due to the high ductility showing both the substrate and the NiCoCrAlY coating at temperature test (500 °C), also the difference in the aluminium content and solid solution matrix phase between coatings alloys can affect the wear behaviour and hence a lower wear rate is obtained.

Table 1. Summarized results for RT and HT sliding wear tests

Laser cladding coating	**Temperature test (°C)**	**Friction coefficient**	**Removed volume (mm^3)**	**Wear rate, W_r (10^{-4} $mm^3/(N\cdot m)$)**
NiCoCrAlY	24 (RT)	*0.49 ± 0.08*	*0.82 ± 0.09*	*1.63 ± 0.18*
	500 (HT)	*0.45 ± 0.01*	*0.50 ± 0.18*	*0.99 ± 0.36*
CoNiCrAlY	24 (RT)	*0.46 ± 0.03*	*2.36 ± 0.24*	*4.73 ± 0.47*
	500 (HT)	*1.00 ± 0.30*	*0.94 ± 0.23*	*1.89 ± 0.46*

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CONCLUSIONS

1. The results confirmed that the coaxial laser cladding is a good alternative to the thermal spray coating process and that the MCrAlY coatings can improve the friction and wear behaviour of austenitic stainless steels. The friction coefficient decrease in NiCoCrAlY coating at high temperature, while it increases significantly in the CoNiCrAlY coating.
2. The primary mechanism for material removal at high temperature is abrasion due to the contribution of the action of oxidized particles or residues formed at high temperature, although oxide adhesion, surface fatigue and material plastic deformation due the ductility is displayed during the tests. At low temperature the dominant wear mechanism is abrasion with some adhesion and delamination of the coating material. At high temperature the NiCoCrAlY laser cladding coatings obtained have better frictional wear behaviour, reducing the wear rate and friction coefficient obtained on the substrate.

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