MICROSTRUCTURE AND TRIBOLOGICAL BEHAVIOUR OF HVOF SPRAYED AND LASER REMELTED HASTELLOY C-276 COATING

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Abstract

Hastelloy C-276 is commercially used representative of Ni-based superalloys family which is widely applied due to good corrosion and wear resistance. In this work the HVOF sprayed and post heat treated coatings of Hastelloy C-276 are studied. Heat treatment for 116 h at 600 °C in furnace and laser remelting with different parameters was carried out in order to reach different thickness of laser remelted coatings. Erosion test and linearly oscillating ball on flat test were applied to evaluate tribological behavior of HVOF sprayed Hastelloy C-276 coating. Microstructure of as-sprayed and heat treated coatings were also studied. XRD and SEM analyses of wear tracks were applied to reveal the dominant wear mechanism. The evaluation of erosion test revealed the positive effect of laser remelting on the other hand was observed increased wear coefficient for all heat treated coatings.

Keywords: Hastelloy C-276, HVOF, laser remelting, wear

1. INTRODUCTION

Materials with high corrosion and wear resistance have been at the forefront of the interest of wide spectrum of industry applications such as power generation, chemical industry or aerospace. Only materials with excellent properties can withstand such high demands like a highly corrosion environment and mechanical load often both in combination with elevated temperatures. Thermal spray technologies represent really good possibility how to combine contradictory requirements, low manufacturing costs and excellent material properties. One of commonly used thermal spraying variant is HVOF (High Velocity Oxygen Fuel Spraying) which can provide coatings with high adhesion to the substrate and low oxidation during the spraying process. Laser surface remelting (LSR) is a method of heat treatment. It is a technology that modifies the surface properties of materials to improve them. Laser remelting of thermal sprayed coatings has an impact on the elimination of porosity and oxides at the splat boundaries, which lead to increase of internal coating cohesion and consequently to secondary effect on improving of the corrosion and wear resistance [1]. The typical wear resistant material is composed of hard carbides (especially chromium carbides Cr_3C_2 and tungsten carbides WC) which are distributed in Ni, Cr, Co-based metallic matrix or a combination of these metals [2]. Numerous family of Co-based alloys is called Stellites typically represented by Stellite 6 alloy which is CoCrWC alloy [3]. The Cr-based alloys with high content of chromium carbides Cr_3C_2 belong to cermets and can withstand high temperatures, they are represented by Cr_3C_2-25NiCr and Cr_3C_2-25CoNiCrAlY [4] [5] [6]. And last but not least there are Ni-based alloys which are generally based on the Ni-Cr solid solution. Well known and wide-spread Ni-based alloy for thermal spraying is NiCrBSi [7] [8]. Hastelloy C-276 or just Hastelloy or C-276 alloy is also Ni-based superalloy with Ni-Cr metallic matrix. It is distinguished by its excellent oxidation resistance in wide range of temperatures and different corrosion environments. The high content of Mo (15.5 %) is responsible for high pitting corrosion resistance in reducing environments, on the other hand Cr (15.5 %) causes Hastelloy C-276 resistant in oxidizing media. Surface treatment of Hastelloy C-276 by laser was carried out in [9] at different process parameters of laser in order to improve wear resistance by microstructure changes without undesirable precipitation. On the other hand, the precipitation was used for strengthening of the Ni-based coatings with composition similar to Hastelloy C-276. In [10] was Hastelloy C-276 coating deposited by magnetron sputtering. The aim of this study is to evaluate the effect of laser remelting applied on the HVOF sprayed coatings of Hastelloy C-276 especially on the microstructure, mechanical properties and tribological behavior of the coatings. Laser remelting with two different laser parameters were applied to carry out coatings with different thickness or remelted layers. Moreover furnace annealing was applied to coatings (age hardening at 600 °C for 116 h) to compare principles of different heat treatment methods.

2. EXERIMENTAL

2.1. Coatings preparation

The Hastelloy C-276 coatings were sprayed in VZÚ Plzeň s.r.o. by HP/HVOF TAFA JP5000 spraying equipment. As a substrate was used grit blasted steel 11 523 with the dimensions 200 mm × 100 mm × 10 mm, the dimensions were chosen to ensure sufficient cooling rates during laser remelting process. For grit blasting of substrates was used Al_2O_3 powder F22 with a grain size 0.8-1 mm. For spraying was used commercially available powder FST 341.33 with nominal chemical composition of 15.5 % Cr, 15.5 % Mo, 4 % W, 3 % Fe and the rest of Ni. The maximal content of C in Hastelloy C-276 is expected to not exceed 0.01 %. The HPDD 4 kW laser Coherent HighLight ISL-4000L with wave length 808 ± 10 nm was used for laser remelting. Two different laser parameters (named LR1 and LR2) were applied, for LR1 it was the specific energy 8.9 J/mm^2, traverse speed 10 mm/s and spot size 12 mm x 6 mm. For parameters LR2 it was the specific energy 17.8 J/mm^2, traverse speed 5 mm/s and spot size 12 mm x 6 mm. To prevent samples from high thermal gradient which may cause cracks in the coating, the preheating of the substrate to the 350 °C was applied. Samples were cooled after laser remelting in air atmosphere. The heat treatment of Hastelloy C-276 coating was carried out in air atmosphere in muffle furnace LM 212 at 600 °C for 116 hours. The annealed samples were then cooled also in air atmosphere. Parts of specimens without coating were protected against oxidation by oxidation protective paint CONDURSAL Z 1100.

2.2. Coatings analyses

On all four prepared Hastelloy C-276 specimens (as-sprayed, laser remelted with parameters LR1 and LR2 and annealed at 600 °C for 116 h) were applied same experimental procedures. The cross sections specimens were ground and polished by automated LECO grinding and polishing equipment and their quality was continuously checked by optical microscope Nikon Epiphot 200. The microstructure was evaluated on cross sections by digital optical 3D microscope Hirox KH7700 and for SEM images was used microscope EVO MA25 from Zeiss with LaB6 thermal filament and equipped by EDX detector SDD X-Max 20 Oxford Instruments. The microhardness was evaluated by HV0.1 measurement for all samples, the indents were made in 50 μm distant steps and started 50 μm below the coatings surface. It results in 6 × 6 indentation matrix, the mean values are plotted in the graph in **Figure 3**. The wear coefficient (K) and coefficient of friction (COF) were evaluated at room temperatures by linearly oscillating Ball-on-Flat wear test (ASTM G-133), the parameters were as follows: 25 N normal force, steel 100Cr6 counterpart (6 mm diameter ball), 5 Hz oscillating frequency; 10 mm stroke length, 1000 s testing time, 100 m total sliding distance. For each specimen were performed three different measurements, depth profile of each wear track was measured by profilometer KLA-Tencor P-6 Profiler at three different places, then the total volume loss was calculated. Surfaces of specimens for Ball-on-Flat wear test were at first ground and polished to ca. 0.04 ± 0.02 Ra value. The wear tracks were observed by SEM to identify wear mechanism. The erosion test (**Figure 1**) was carried out at VZÚ Plzeň s.r.o. with their own testing equipment. This device provides a given constant amount of abrasive media (white corundum F70) from the reservoir at the top of the device. The abrasive particles enter between two rigidly connected rotating discs with four accelerating channel and there the abrasive particles are accelerated by centrifugal force and at the outlet of the channels the particles stream interferes with specimens. At the end of the test the weight of specimens is evaluated. Because the density of tested material is known the weight loss can be converted to the volume loss of material.

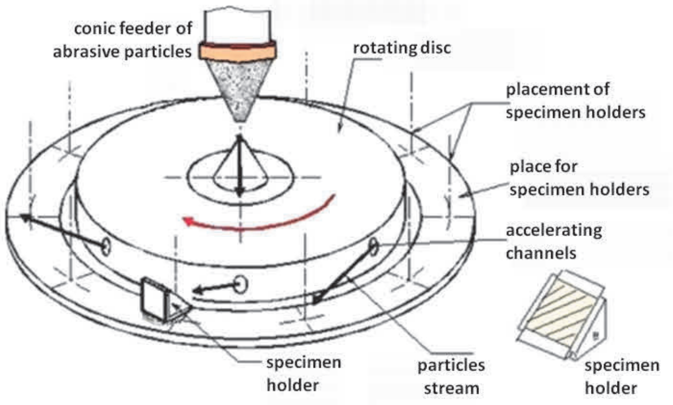

Figure 1 Schematic drawing of erosion test at VZÚ Plzeň s.r.o.

3. RESULTS AND DISCUSSION

This study follows the results which were reported in [11] and adds new experimental procedures in order to evaluate especially tribological behavior of HVOF sprayed and laser remelted Hastelloy C-276 coatings.

3.1. Microstructure and microhardness

Microstructure of HVOF as-sprayed coatings of Hastelloy C-276 (**Figure 2a**) is characterized by dense web of splats, partial decohesion between individual splats could be also seen and certain amount of porosity typical for HVOF coatings is present. Specimen after furnace annealing (600 °C for 116 h) (**Figure 2b**) is also characterized by certain amount of porosity which is comparable to as-sprayed coating. On the other hand in both laser remelted coatings (**Figures 2c, 2d**) the final porosity rapidly decreased and final coatings are denser and more compact. Another consequence of laser remelting is that the coating surface is much smoother than as-sprayed and furnace annealed coatings.

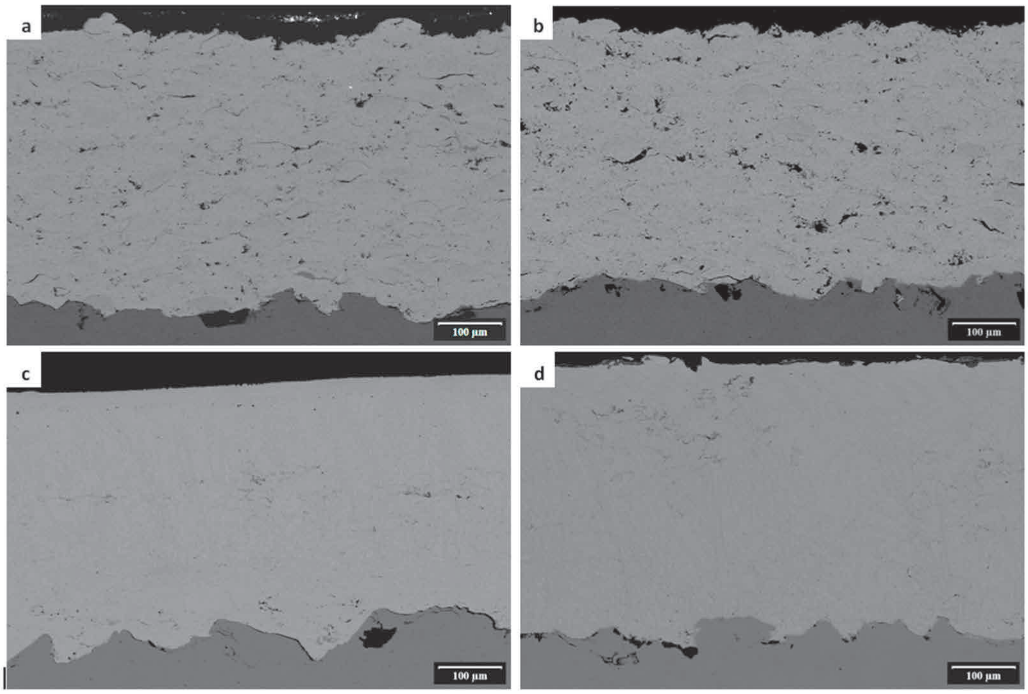

Figure 2 SEM of microstructure for HVOF Hastelloy C-276 coatings: (a) as-sprayed, (b) furnace annealed, (c) laser remelted LR1, (d) laser remelted LR2

Laser parameters LR1 (specific energy 8.9 J/mm^2) led to remelting of ca. half of coating thickness whereas LR2 (specific energy 17.8 J/mm^2) resulted in remelting of almost complete coating thickness because substrate-coating boundary was occasionally remelted. More detailed explanation of microstructure changes for all samples was reported in [11].

Results of microhardness measurement are shown in the graph in **Figure 3**. For both laser remelted coatings (LR1 and LR2) there is a significant decrease of microhardness which is most probably caused by size of dendrites. Fine dendritic microstructure contributes to high microhardness of as-sprayed coating whereas in laser remelted coatings the coarser dendrites are present closer to coating surface and that resulted in negative influencing of microhardness. The furnace annealed coating shows slight microhardness improvement as a consequence mainly of oxidation of intersplat boundaries and partly of precipitation hardening of Co-based solid solution inside individual splats [11].

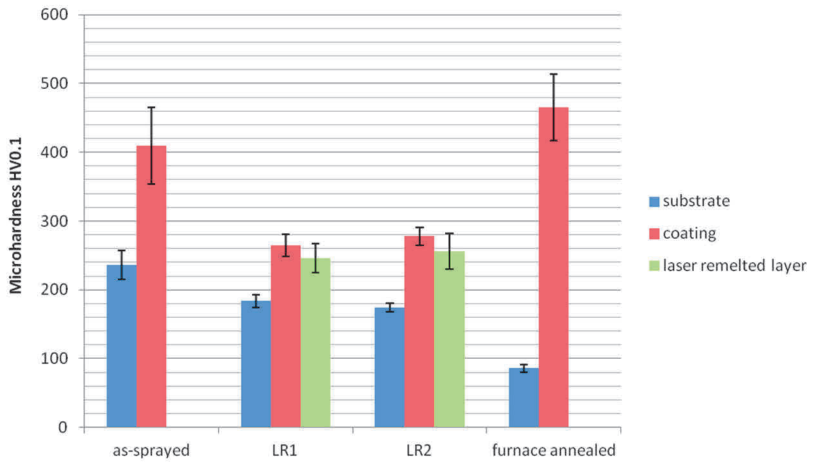

Figure 3 Measurement of microhardness HV0.1

3.2. Wear behavior

Evaluation of linearly oscillating Ball-on-Flat wear test (ASTM G-133) is shown in graphs in **Figure 4**. These results don't reveal any changes in coefficient of friction (COF) depending on the heat treatment method on the other hand there is an evident trend in increasing of wear coefficient with increasing of laser remelted coating thickness. The higher wear coefficient for both laser remelted coatings (LR1 and LR2) could be explained by reduction of microhardness which makes coatings more prone to plastic deformation. SEM images of wear tracks after Ball-on-Flat test are shown in **Figure 5**. Despite increment in microhardness, the furnace annealing has a negative effect on sliding wear resistance. The precipitation in Hastelloy C-276 as a result of heat treatment could cause brittle cracking during wear tests [11]. Main wear mechanism of all tested coatings is abrasion, additionally for as-sprayed coating (**Figure 5a**) was also observed partial delamination of individual splats that is a consequence of present intersplat decohesion (**Figure 2a**).

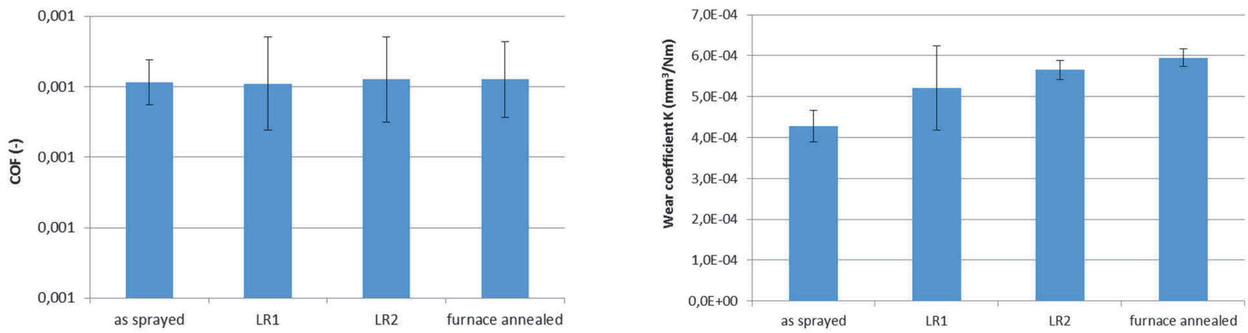

Figure 4 Coefficient of friction (COF) and wear coefficient K

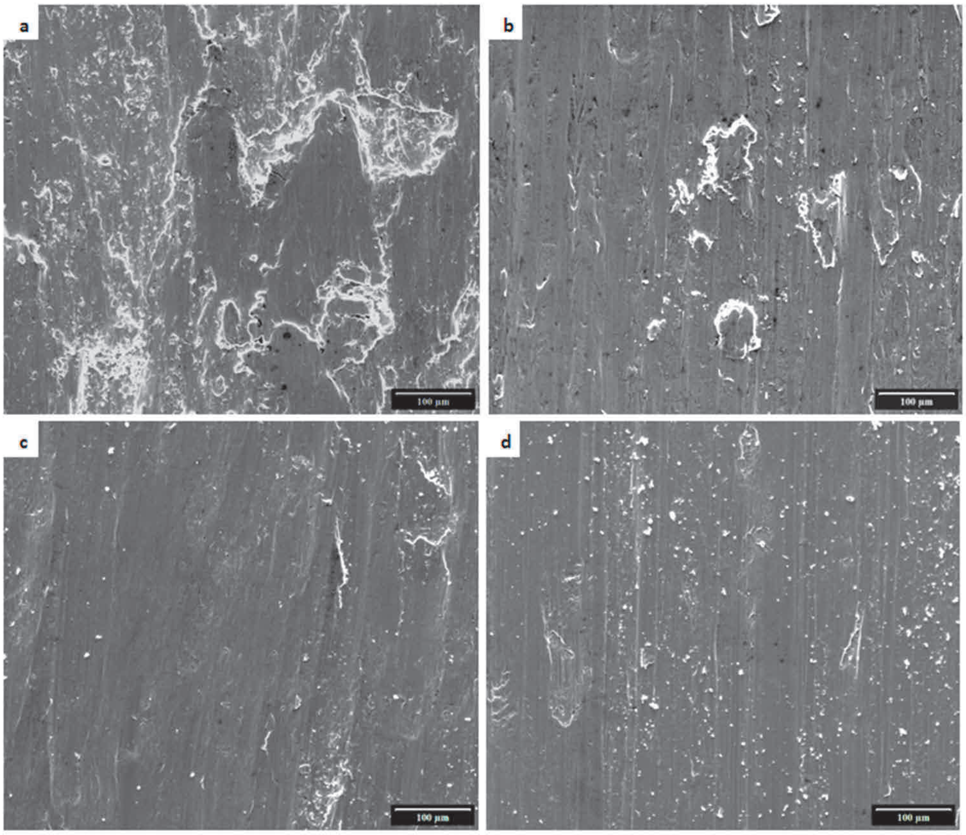

Figure 5 SEM of wear tracks for HVOF Hastelloy C-276 coatings: (a) as-sprayed, (b) furnace annealed, (c) laser remelted LR1, (d) laser remelted LR2

3.3. Erosion resistance

Evolution of volume losses with dependency to impact angle of erosion media and heat treatment method is reported in graph in **Figure 6**. The positive effect of both laser remelted coatings is obvious and more visible for completely remelted coating thickness (LR2) and additionally the volume loss is decreasing with decreasing of impact angle. It is a consequence of enhanced internal coating cohesion and elimination of porosity after laser treatment. It is also accompanied by increased elasticity which allows more erosion particles to not affect the coating at all. The coating brittleness together with still present porosity for furnace annealed coating is causing high volume losses especially for lower impact angles.

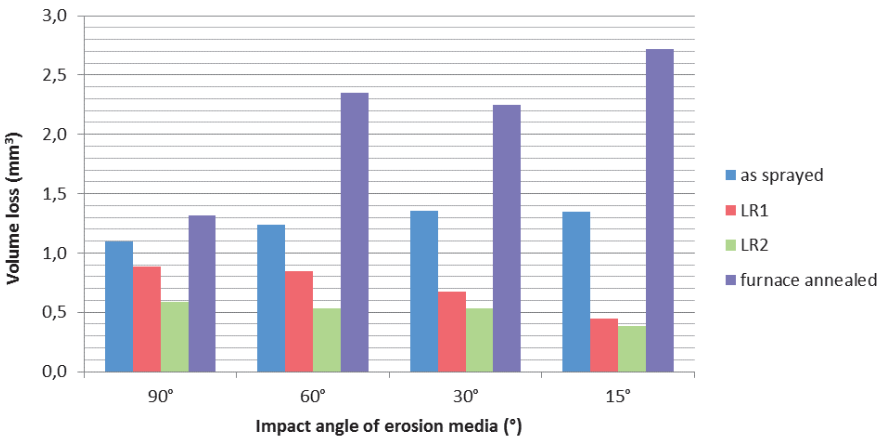

Figure 6 Volume losses with dependency to impact angle of erosion media

4. CONCLUSION

This study is focused on evaluation of laser remelting in application on the HVOF sprayed coatings of Hastelloy C-276 especially on the microstructure, mechanical properties and tribological behavior. All used heat treatment methods (twice laser remelting and furnace annealing) proved negative effects on sliding wear resistance despite different changes in microstructure and microhardness. On the other side the erosion test reveal beneficial influence of enhanced internal coating cohesion and elimination of porosity within laser remelted coatings which resulted in reduction of volume loss for both laser parameters and all impact angles of erosion media. Further wear test should be applied to reveal the true wear behavior of Hastelloy C-276 HVOF coatings.

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