INFLUENCE OF HVOF SPRAYED COATINGS ON FATIGUE PROPERTIES OF COATING-SUBSTRATE SYSTEM

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Abstract

This research deals with the influence of thermally sprayed HVOF (High Velocity Oxygen Fuel) coatings on fatigue life of components. HVOF coatings are now a widespread technology commonly used for additional treatment of component surfaces. The advantages particularly consist in achieving of low coating porosity, high adhesion to the base material and residual compressive stress in the surface coating layer. The main application areas of HVOF coatings are applications requiring high surface hardness and wear resistance (pistons, rods, cylinder presses, etc.). Two coatings were evaluated in this study - carbide based coating (Cr_3C_2-NiCr) and alloy based coating (Stellite 6). The tests were carried out at room temperature and at 600 °C. The main contribution of this paper is to evaluate the coating influence on fatigue properties of coating-substrate system in comparison with the fatigue properties of the substrate itself. In particular, it was examined whether and how the increase or decrease of fatigue properties occurs in this system. The obtained results prove that both evaluated coatings reduce overall fatigue resistance; however, by Stellite 6 coating the reduction of fatigue properties is not so noticeable.

Keywords: Coatings, HVOF, fatigue, axial fatigue testing

1. INTRODUCTION

Thermal spraying of ceramic and other coatings are now widely used in highly stressed structural elements including equipment components designed for the aerospace industry, energy industry and space applications where it is necessary to ensure a high degree of abrasive, erosive, corrosive and thermal resistance. These coatings are widely used in many industrial applications as replacement of hard chrome plating. Proper application and selection of the coating, can increase component life and reduce risks of failure which also leads to reduction of maintenance expenses in the long term [1]. It is very important to clarify the fatigue behavior of components with coatings/substrate system because there is still little information concerning this problematic.

Speaking about the mechanisms of fatigue or fatigue breaking of coated system, we can say that it is still very little explored area. There are several studies [2], [3] which deal with comparing factors affecting fatigue behavior of coating as CoNiCrAlY, NiCrBSi and WC-Co. Majority of studies generally agree that application of thermal spray coatings leads to deterioration of fatigue resistance of the whole system, but there are also studies that point to a small percentage of coatings which can increase fatigue properties [4].

Recent research shows that the fatigue characteristics are very sensitive to changes in parameters of deposition process [5]. Understanding the mechanisms of crack formation is critical for optimization of the basic parameters and requirements for spray process. From earlier studies is known (e.g. [6]) that the formation of fatigue cracks is caused by four different mechanisms (abrasion, delamination failure of the base material, and peeling). These mechanisms are mutually combined during cyclic loading and the resulting fracture of the coating may be caused by single mechanism or combination of several of them. Factors like thickness of the coating, material of the substrate, spraying conditions and properties of the substrate before coating application have the most significant impact on the fatigue behavior of the resulting system. As already mentioned, the fatigue characteristics are affected by many parameters, whether the pre-spraying, spraying or after spraying-processing parameters. Evaluation of parameters of individual operations in relation to the resulting fatigue properties of the coted system is essential for a deeper understanding to mechanisms of fatigue fracture. Another factor influencing the fatigue properties is residual stress which is present in both the substrate and the thermally sprayed coatings [6].

The current problem is the lack of publicly available information comprehensively characterizing this issue [6]. However during the last few years the number of research studies aimed at determining the effect of different deposition parameters on the fatigue behavior of components using HVOF technology has increased considerably [7]. From the above information is clear that these failure mechanisms are interlinked and intensively interacting. The intensity of their occurrence depends on their joint variables, which makes impossible to completely optimize the spraying process for all kinds of limitations of fatigue mechanisms. The reason is that by change of one parameter and followed-up increase in resistance to one specific failure mechanism leads to a decrease of resistance against other failure mechanisms. For this reason it is important that the optimization of thermal spray process against fatigue fracture was performed with respect to all kinds of mechanisms of fracture and was sought as a compromise complying with required final properties [6].

Furthermore, the purpose of the study was to obtain new results that will be possible to compare with other studies. The requirement for increased operating temperature was based on future application of these coatings in the energy industry.

2. EXPERIMENT

Experimental samples were prepared using HVOF technology. Preparation of samples, and subsequent testing was performed in laboratories of Research and testing institute Plzen (VZU). W.Nr 1.4923 (X22CrMoV12) steel was selected as substrate material because it will be used in final parts in energy industry. Two materials ware selected as material for coating (namely Cr_3C_2-NiCr and Stellite 6). The selection was based on previous research and their good mechanical and corrosion characteristics. Standard optimized parameters were used for preparing the samples by HVOF technology. The substrate surface was degreased and grit blasted before spraying (brown corundum F22 grit 0.8 to 1.0mm was used as an abrasive medium).

2.1. Measurement conditions

High surface roughness of the coating is highly undesirable because they act as a large amount of stress initiators which result in decrease of fatigue life of the system. For this reason the surface of the samples was polished to gain roughness Ra 0.2.

Substrate/coating system was tested using a capillary nondestructive testing. Test was carried out on broken samples and also on samples which achieved the fatigue limit without breaking. The reason for this test was to determine whether the induced stress may cause formation of micro-cracks along entire length of the sample. This test was carried out using a contrast agent and the developer 280 Pfinder 870.

Optical evaluation of the coating was performed using a portable microscope Dino-Lite AM7013MZT. The samples were first cleaned and degreased. After that the surface and integrity of the coating was evaluated in terms of micro-cracks and other damage caused due to axial fatigue tests. This device was also used to document individual fatigue fractures. All captured images were captured at magnifications of 50 and 230.

2.2. Fatigue testing

Measurements were carried out at room temperature of 23 °C and 600 °C according to ASTM E466 - 07 [8]. Measurements at elevated temperatures were performed on equipment MTS 500kN in the VZU Plzen. Axial fatigue test at 20 ° C was performed on device Kraftaufnehmer Schneck 400M. The measurement conditions were as follows: frequency 50Hz, loading module R = 0.1. The samples were tested to full failure or 10^7 cycles.

The shape of the sample was chosen according to ASTM E466 - 07. Minimum of 8 samples was used for the preparation of SN curves from each set.

3. RESULTS AND DISCUSSION

3.1. Axial fatigue testing results

This section presents the results of axial fatigue testing. The results are presented as comparative chart of the measurements. **Table 1** presents numeric average values of fatigue life for each system and the substrate individually. For calculation of the fatigue life limit was used equation $N=\alpha\sigma^b$, which could be rewritten in form of $logN=a+blog\sigma$. Final S-N curves can be clearly seen in **Fig. 1**, which includes the results for the system of coating/substrate and for the substrate itself. All S-N curves are assembled in dependence on stress amplitude, not on the maximum stress.

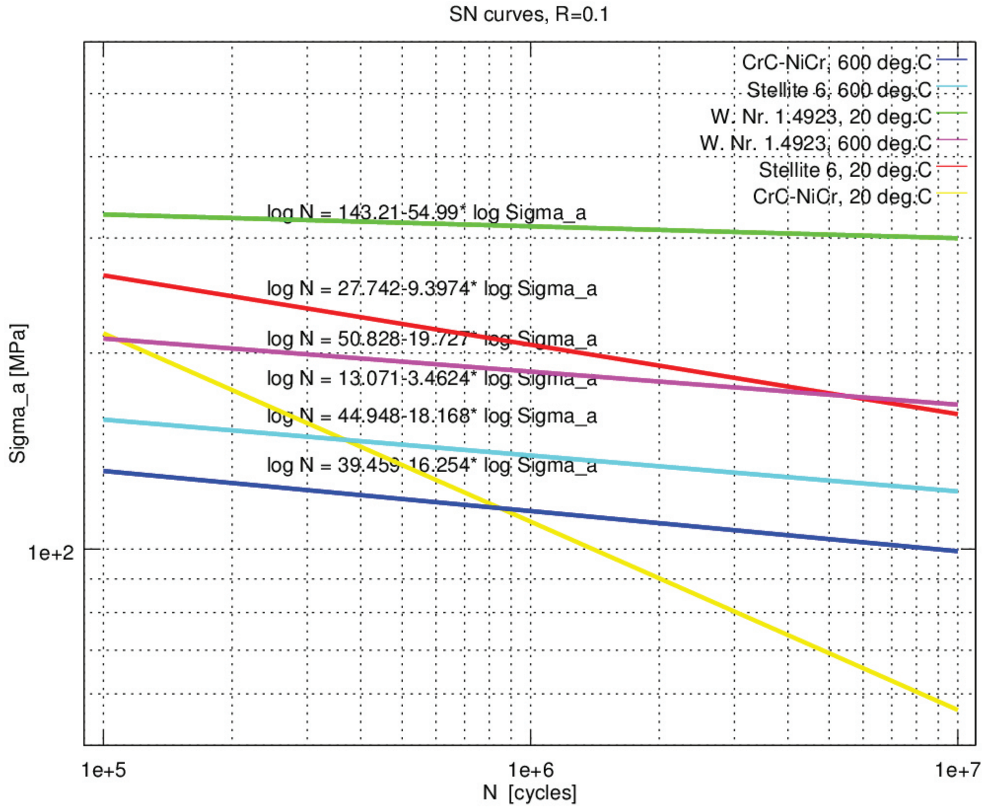

Fig. 1 S-N curves representing all tested sample sets

Table 1 Average numeric values of fatigue life

Coating and Substrate	Fatigue life limit 20 °C [MPa]	Fatigue life limit 600 °C [MPa]
Substrate	300	167
Stellite 6	161	123
Cr_3C_2-NiCr	56	99

3.2. Capillary test and optical evaluation

Specimens were evaluated by capillary testing in terms of micro-cracks formation in the coating structure due to exposure to axial fatigue test.

Stellite 6:

The first photograph (**Fig. 2**) displays a sample of Stellite 6. It is obvious that there was no formation of micro-cracks during axial fatigue tests. It was confirmed that near the fatigue limit there is no degradation of the coating and the system is able to operate safely under these conditions.

The sample coated with Stellite 6 and tested by stress above fatigue limit is shown in **Fig. 2**. During these loads the standard fatigue fracture occurs. Capillary test showed that even at such conditions, the system of coating/substrate is able to retain their mechanical properties and surface integrity. The surface of the sample (coating) does not degrade over its entire length during progression to fatigue crack, and can meet the protection requirements until a complete destruction of the component.

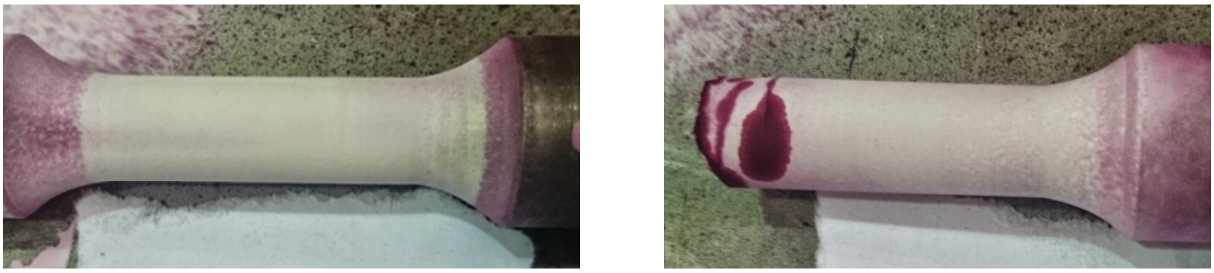

Fig. 2 Capillary testing of Stellite 6 coating at 20 °C (Left - sample with load under the fatigue life limit, right - sample above fatigue life limit)

From the result of capillary tests is apparent that destruction of the coating occurs only in the close vicinity of the fracture, where are localized strong plastic deformations. Capillary test of sample exposed to fatigue testing at 600 ° C showed that in case of load under fatigue life stress limit there is also no degradation present. These results prove that the coating of Stellite 6 is able to protect the component at elevated temperatures without loss of its protective properties. Test of Stellite 6 after axial fatigue test at elevated temperature stress above fatigue life limit confirms once again that in this case the Stellite 6 coating is able to protect the part until complete part failure. It is obvious that the coating retains its mechanical properties and adhesion to the substrate along the entire length. Mechanical damage of the coating is located only in fracture area.

Cr_3C_2-NiCr:

Below the stress of fatigue life limit the system coated by Cr_3C_2-NiCr powder at 20 °C showed that it can fully withstand fatigue damage and there is no formation of micro-cracks along whole length of the sample. Illustrative photograph of the sample is shown in **Fig. 3**. In the case of a stress above the fatigue life limit the system coated by Cr_3C_2-NiCr showed formation of micro-cracks along the entire length of the sample. Micro-cracks indicated by capillary test are shown on the following figure (**Fig. 3**). It has been shown that the coating Cr_3C_2-NiCr is not able to resist the stress conditions and relaxes in form of segmentation into annular shapes. It means that coating is not able to effectively protect the part above the fatigue life limit. Samples coated by Cr_3C_2-NiCr subjected to axial fatigue test at 600 °C shown that under these conditions the coating is capable of fully withstanding the conditions of the test and exhibits no micro-crack formation or other degradation. Samples coated by Cr_3C_2-NiCr at elevated temperature and at higher stress load revealed a surprising result. Unlike the same conditions at 20 °C samples at 600 °C withstand those conditions and capillary test demonstrated that the fatigue damage does not support formation of micro-cracks followed by segmentation of the coating. The results prove that Cr_3C_2-NiCr coating is better able to operate and protects the substrate at elevated temperatures up to a stress load 50% higher than the fatigue life limit.

Fig. 3 Capillary testing of Cr_3C_2-NiCr coating at 20 °C (Left - sample with load under the fatigue life limit, right - sample above fatigue life limit)

3.3. Fracture evaluation

Fracture of each sample exhibits normal fatigue characteristics. In most cases the fatigue fracture initiate from only one or two localized points, which are clearly visible in the following figure (**Fig. 4**). The probable cause of the localization of these initialization sites is pre-spray operation of grit blasting. This operation results in anchoring corundum grains on the substrate surface and subsequently act as stress concentrators and accelerates the fatigue damage [5]. Following figure (**Fig. 4**) also presents the segmentation of the coating due to stress relaxation.

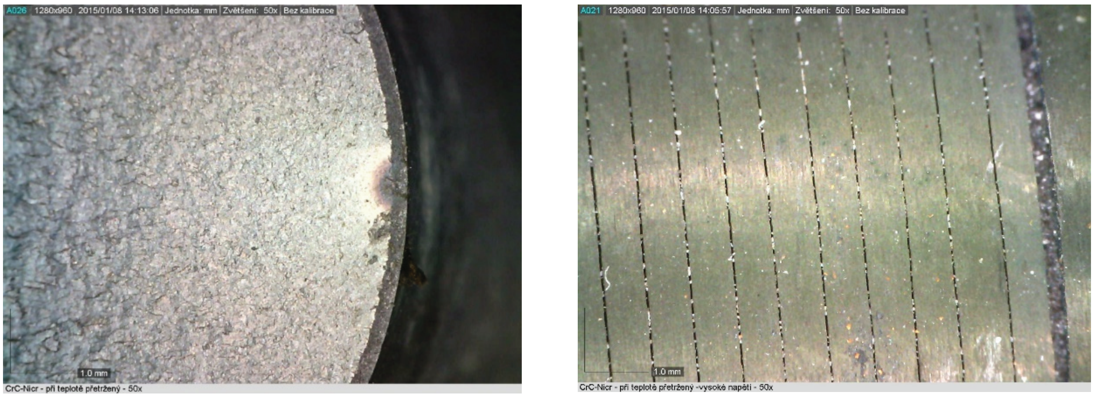

Fig. 4 Left side - example of fatigue cracking, right side - example of coating segmentation

4. CONCLUSION

We can state that conducted research corresponds with the trends mentioned in [2] and [9]. Based on the results of fatigue tests it is possible to say that coated systems exhibit decreased fatigue properties than substrate itself. This fact is very well confirmed by the image (**Fig. 1**), which compares the different systems at different temperatures along with the substrate material.

Looking on the fatigue life of the substrate itself, it is clear that at 600 °C there is a decrease of almost 50%. This effect is associated with the change of mechanical properties, which corresponds with change in the slope of S-N curve.

As it has already been confirmed greater reduction in fatigue properties occur particularly in a system with Cr_3C_2-NiCr coating. At higher temperature (600 °C) the fatigue strength was reduced by 37%, which corresponds with our assumptions and is consistent with the findings about carbide coatings (see [2]). An interesting fact is that this system showed a superior reduction in fatigue properties at 20 °C. This reduction in fatigue properties achieved 80% compared with the substrate material at the same temperature. This phenomenon is probably caused by following mechanisms. Cr_3C_2-NiCr coating exhibits relatively fragile properties. At 20 °C the delamination mechanism applies and begins cracking of the coating located near stress initiators presented as corundum grains anchored in the substrate. At this temperature, the coating does not have enough ability to absorb the stress and transform it in to the plastic deformation. This leads to rapid progress of delamination processes. There are new cracks forming in the coating, which further acts as new stress concentrators, and the coating thus quickly degrades [9]. On the contrary, this coating at elevated temperature is better able to absorb the induced stress because of reduction of its brittle-fracture characteristics.

System with Stellite 6 coating showed significantly better results than competing carbide coating. This is the expected result because the Stellite 6 is alloy coating which is capable of larger plastic deformations. At 20 °C, the coating showed 45% reduction in fatigue strength compared to the substrate itself. At the temperature of 600 °C the reduction of fatigue properties was only around 25% against the base material. This is a very positive result, which was not expected. Capillary test showed that this type of coating is capable of protecting a substrate and retain their functional mechanical properties together with cohesion to the substrate during all kinds of fatigue stress load. Furthermore, it was proven that in the case of this coating the formation of localized micro-cracks is only located in close vicinity of main fatigue breach.

Essential finding is that both coatings have demonstrated the ability to fulfill their function at stress load under the fatigue life limit at 20 °C and at 600 °C. This result is very positive finding as it demonstrates that under these conditions the coatings are capable to protect the substrate along the entire length of its fatigue life without causing micro-cracks formation, or other degradation of the coating, which could otherwise cause destruction of the system and thus the entire component.

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