INFLUENCE OF BALL MATERIAL ON THE RESULTING FATIGUE LIFE OF THERMAL SPRAYED HVOF COATINGS IN DYNAMIC IMPACT TESTING

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Abstract

Dynamic impact wear, i.e. contact between two components in the presence of high cyclic local loads, is a challenging failure mode that occurs in many mechanical applications. Many previous studies have confirmed that dynamic impact testing is suitable for evaluating the contact fatigue of thermal sprayed coatings. However, the effect of the test parameters on the resulting lifetime is unclear. The aim of this study describes the effect of the ball material used in the dynamic impact test on the resulting fatigue life of the HVOF thermal sprayed coating. Three test balls made of WC/Co alloy, Si_3N_4 silicon nitride and 440 C steel were chosen for this study. Dynamic impaction testing was carried out on the Cr_3C_2-NiCr coating, which was sprayed by HVOF on a 1.2376 high-speed steel substrate. The impact lifetime was described by the number of critical impacts, i.e. the number of impacts before coating fatigue occurs. Furthermore, the depth and volume of impact craters were measured. Using scanning electron microscopy (SEM), the surface of the impacts as well as the microstructure of the coating on the cross-section in the region of the impacts were observed. Furthermore, the mechanism of crack propagation in the coating and the microstructure of the indentor were investigated.

Keywords: Dynamic impact test, HVOF, Cr_3C_2-NiCr, fatigue

1. INTRODUCTION

Thermally sprayed coatings are a useful method for improving surface properties and increasing the lifespan of machine components. TS Coatings are often exposed to cyclic loading due to mechanical stress, aggressive environments, high-temperature work, or a combination of these factors. Studies have demonstrated that a dynamic impact test is an effective method for characterizing the behavior of thermally sprayed coatings under cyclic loading. This test can estimate not only the lifespan of the coating but also the mechanisms of impact wear. During dynamic impact testing, the surface of the coating is loaded with an indenter using a constant force and frequency. Many studies have focused on the impact resistance of different coating materials. For example, Bobzin et al. [1] or Li et al. [2] studied the impact resistance of Cr_3C_2-25%NiCr coating, Bolelli et al. [3] described the impact resistance of FeCrNiBC coating, and Barletta et al. [4] investigated the impact resistance of WC-CoCr coating. Osawa et al. [5] studied the effect of the substrate on the resulting impact resistance of the coating. Dynamic impact test can also be used to determine the adhesive and cohesive properties of coatings, as described by Bouzakis et al. [6] in their work. Therefore, dynamic impact testing has proven to be a useful tool for studying the fatigue behavior of thermally sprayed coatings. The impact of the test conditions themselves on the resulting lifespan has received significantly less investigation. In this article, the impact resistance of HVOF Cr_3C_2-25%NiCr coating was studied under the same conditions but using different ball materials. The balls were made of WC/Co, Si_3N_4, and 440C steel, which are commonly used in dynamic impact testing.

2. EXPERIMENTAL

Three samples of Cr_3C_2-25%NiCr (chromium carbide in a nickel-chromium matrix) HVOF coatings with a nominal composition of 70% Cr, 20% Ni, and 10% C (in wt%) were deposed to a 1.2376 high-speed steel substrate with dimensions of 15x20x14 mm [7]. The deposition was performed at the Research and Testing Institute Plzeň. Before the deposition, the substrate was roughened to a surface roughness of Ra = 0.8 by blasting with alumina particles of size 0.8 - 1 mm. After the deposition process, the surfaces of the samples were metallographically polished to a final thickness of 160 µm. Detailed information on the deposition parameters is provided in **Table 1**.

Table 1 Deposition parameters of the used Cr_3C_2-25%NiCr sprayed coatings

spraying device	feedstock	form	oxygen	fuel	barrel lenght	spray distance	feed rate
HP/HVOF TAFTA JP500	Amperit 588.074	Powder -45+15 µm	823 l/min	25.71 l/hour	100 mm	360 mm	70 g/min

Subsequently, a dynamic impact test was performed on each sample using an impact tester developed at the Institute of Instrumentation of the CAS in Brno [8]. The dynamic impact test was carried out at the same research center. A schematic description of the tester is shown in **Figure 1**. Three identical series of dynamic impact tests were performed on the samples using different indenter materials. Indenters with a diameter of 5 mm made of tungsten carbide (WC/Co), silicon nitride (Si_3N_4), and 440C steel were selected for the test (the mechanical properties are shown in **Table 2**). The indenters impacted the sample surface at velocities of 0.5 - 0.9 m/s with an impact frequency of 8 Hz. Impact tests were performed with impact loads of 600N and with the number of impacts ranging from 1 to 50,000. The surface of the impact craters was examined using a Keyence VK-X 1100 confocal microscope and a JEOL JSM 6490 LV scanning electron microscope. The results of the impact test were presented as a dependence of the number of impacts on the volume and depth of the impact crater. Moreover, cross-sectional structure of the impact craters and the indenter microstructure before and after the test were studied using the SEM JEOL JSM 6490 LV.

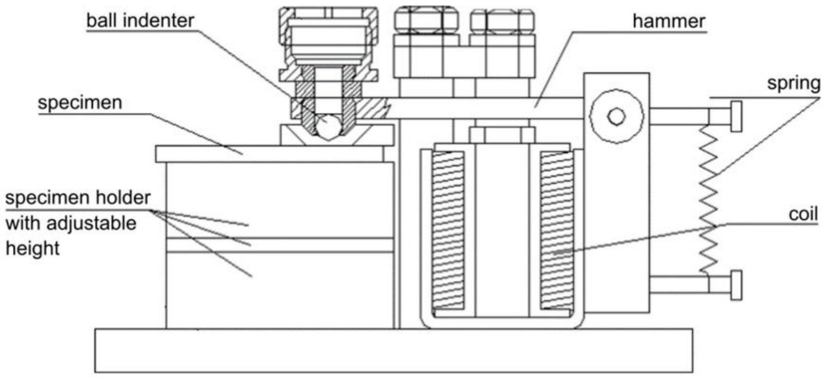

Figure 1 Scheme of the dynamic impact tester developed at ISI CAS [8]

Table 2 Mechanical properties of WC/Co, Si_3N_4 and 440C indenter materials

Material	Density (gcm^{-3})	E (GPa)	Hardness (HV)	Tensile strength (MPa)	K_{IC} ($MPam^{1/2}$)	References
Si_3N_4	3.2	96 - 220	1600	68 - 172	≥6	[9]
WC/Co	14.87	669 - 696	1622	344	9.2	[9,10]
440C Steel	7.8	220	510 - 760	760 - 1970	17.6 - 24.2	[11]

3. RESULTS AND DISCUSSION

After the dynamic impact test, the dimensions of the crater were measured. **Figure 2A** shows the dependence of the crater depth on the number of impacts. The highest crater depth was created using the WC/Co indenter and it was approximately 3.5 μm deeper than that of the 440C steel indenter. The same tendency was also observed in the crater impaction volume dependence (**Figure 2B**). When reaching 50.000 impacts, both the impact crater depth and the impact crater volume show a large measurement error. The cause of the sudden measurement error can be attributed to the depletion of coating plasticity and subsequent cracks initiation. When compared with the material properties of the used indenter, the size of the resulting impact crater seems to be mainly influenced by the hardness of the indenter. The tensile modulus of the indenter has a much smaller effect on the resulting crater size and therefore on the resulting fatigue life of thermal spray coatings.

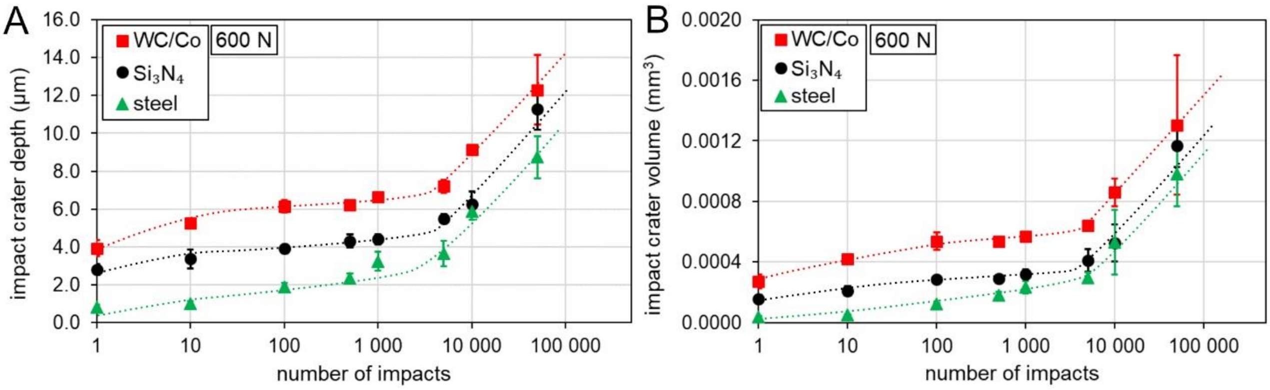

Figure 2 Comparison of impact crater depth (A) and impact crater volume (B) depending on the number of impacts

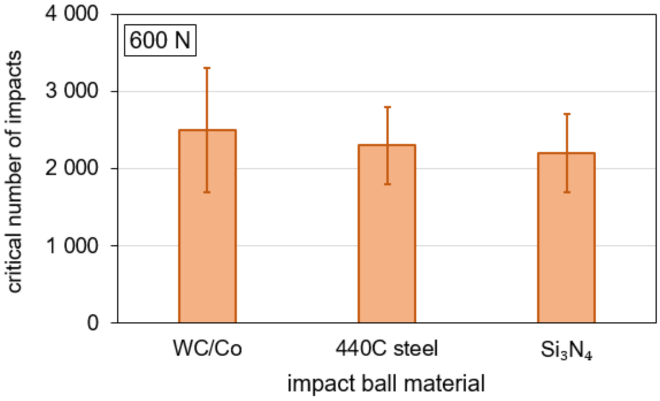

Figure 3 Comparison of critical number of impacts on the material of ball indentor

Figure 3 shows the critical number of impacts (i.e. the number of impacts before fatigue failure of the coating) depending on the indenter used. Although the measurement has a significant error, it can be concluded that the highest impact resistance and therefore the highest fatigue life was measured when using an indenter made of WC/Co material. In the case of the 440C steel indenter, the number of critical impacts was slightly higher than in the case of the Si_3N_4 indenter. This is interesting in the sense that the size of the crater is not related to the resulting impact resistance.

Observation of impact crater surfaces using SEM shows different characteristics of impact crater surfaces. In all cases, propagation of circumferential cracks around the indentation was observed. The circumferential crack propagated interlamellarly around the edges of the Cr_3C_2 carbides. The impact crater after using the Si_3N_4 indenter has the most noticeable circumferential cracks (**Figure 4C** and **Figure 4D**). However, in no case did the cracks propagate around the entire circumference of the impact crater. No radial cracks were observed on the surface. More interestingly, there was a difference in the amount of oxide tribofilm. In the case of the 440C steel indenter, more than half of the impact crater surface was covered with oxide tribofilm (**Figure 4E** and **Figure 4F**). In the case of the impact crater with the WC/Co indenter (**Figure 4A** and **Figure 4B**), oxide tribofilm was also observed but in much less amounts than in the previous case. The presence of oxide tribofilm may also affect the measured impact resistance, as its presence affects the surface properties of the coating and increases wear resistance [12].

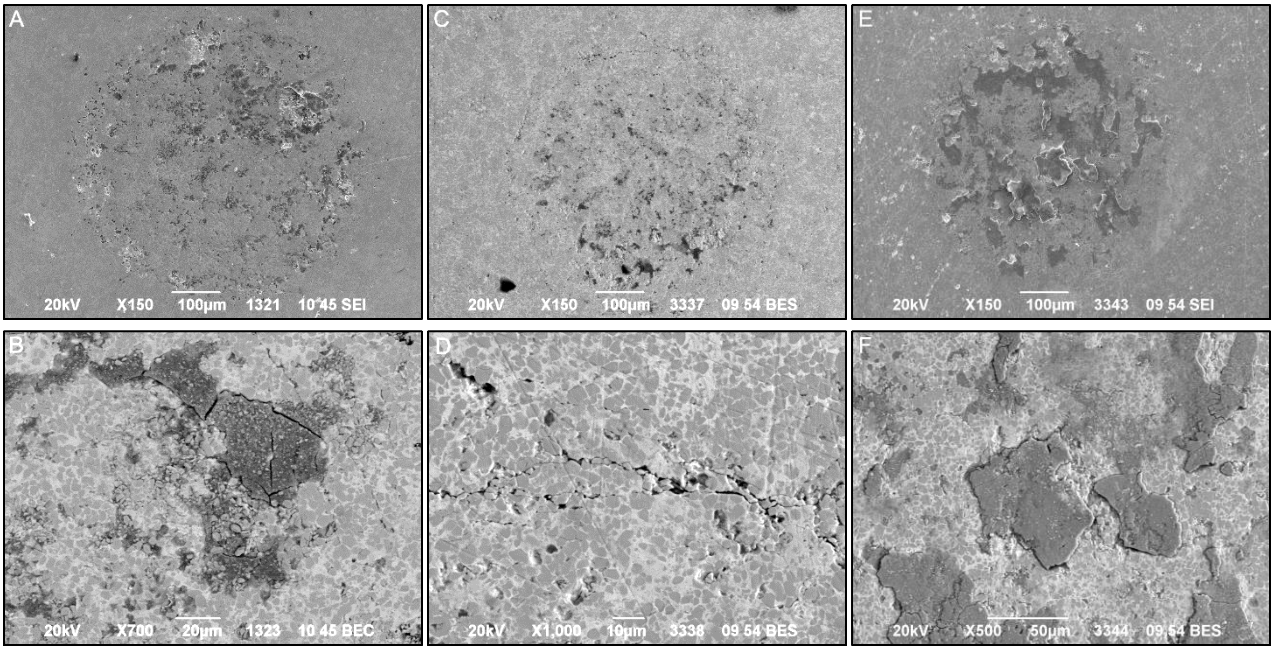

Figure 4 SEM micrographs of the surface of impact crater after dynamic impact test (Impact force 600N, 50 000 cycles) - A,B - WC/Co indenter, C,D - Si_3N_4 indenter and E,F - 440C Steel indenter

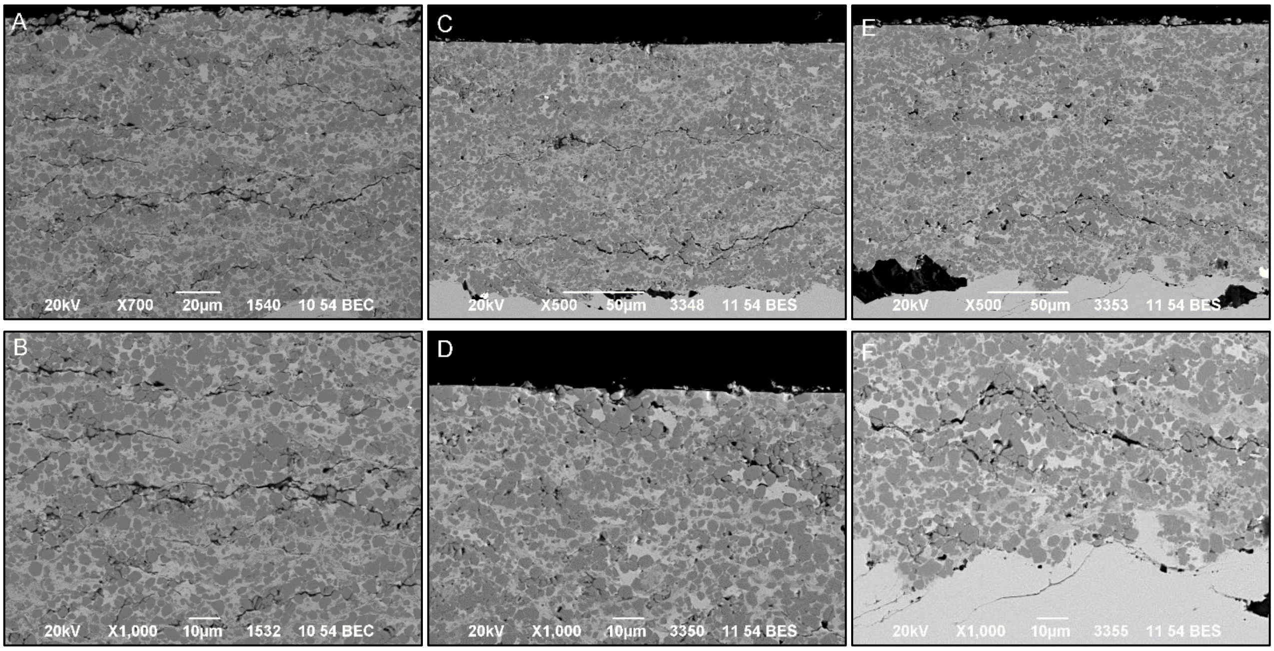

Figure 5 Backscattered electrons SEM micrographs of the polished cross-sections of impact crater after dynamic impact test (Impact force 600N, 50 000 cycles) - A,B - WC/Co indenter, C,D - Si_3N_4 indenter and E,F - 440C Steel indenter

Cross-sectional observation of the impact crater shows A cross-sectional view of the impact craters shows that in all cases the initiation of the major crack occurred at approximately 1/3 of the coating thickness. The crack propagated parallel to the surface of the coating. In the case of the impact crater created by the WC/Co indenter (**Figure 5A** and **Figure 5B**) and the Si_3N_4 indenter (**Figure 5C** and **Figure 5D**), a similar crack is seen in 2/3 of the coating thickness. The cracks in the cross-section propagate interlamellarly along the Cr_3C_2 carbide boundaries. Their direction of propagation is influenced by the presence of pores. The presence of cracks is least noticeable in the case of the impact crater created by the 440C steel indenter (**Figure 5E** and **Figure 5F**). However, this may be because the cross-sectional cut through the impact crater was not made precisely at its centre. In neither case was delamination of the coating observed, this indicates good adhesive properties of the coating.

SEM analysis of cross-sections of the spherical indenter showed that there was no deformation of the indenter during dynamic impact testing. For example**, Figure 6A** and **Figure 6B** show the microstructure on the cross-section of the AISI 440C steel indenter. Among the indenter materials used in this work, the 440C steel indenter has the lowest hardness, and therefore surface deformation should be the most noticeable in this case. The microstructure at the edge of the indenter is basically identical as the microstructure at the center of the indenter (**Figure 6C**). Practically no additional damages to the indenter were observed due to impact loading. Therefore, the indenter can be used repeatedly for dynamic impact testing.

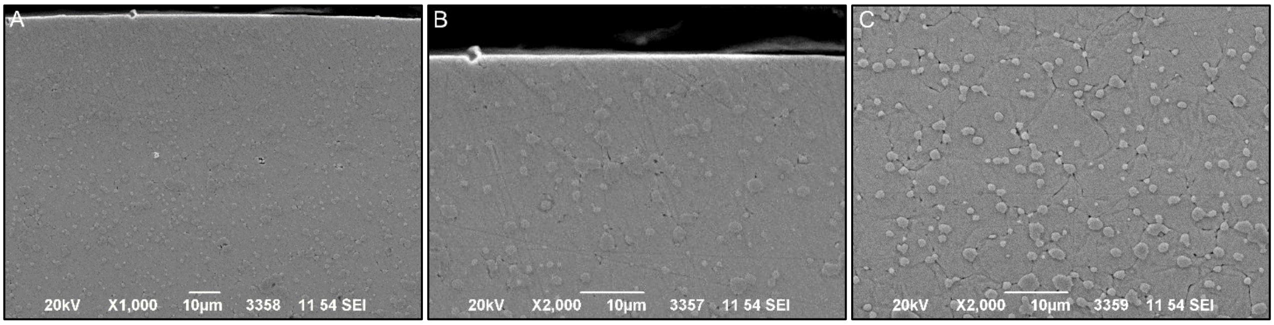

Figure 6 SEM micrographs of polished cross-sections of AISI 440C spherical indenter after dynamic impact test (impact force 600 N, 50 000 cycles) - A, B - microstructure on the edge of the indenter, C - microstructure in the center of the indenter

4. CONCLUSIONS

Using a dynamic impact test, the fatigue life of an HVOF Cr_3C_2-25NiCr coating was determined using three different indenter materials (WC/Co, Si_3N_4, and AISI 440C steel). The results demonstrated that the measured impact resistance and subsequent fatigue life were influenced by the material of the indenter. The highest fatigue life was obtained with a WC/Co indenter, while the lowest was observed with a Si_3N_4 indenter. The use of different indenter materials also resulted in varying depths and volumes of the indentation crater, with the AISI 440C steel indenter creating the smallest volume of the impact crater. Additionally, the surface of the crater differed depending on the indenter material used. An oxide tribofilm was observed on more than half of the surface of the impact crater when using an AISI 440C steel indenter. In the cross-section of the spherical indenter, no microstructure deformations or damage were observed that could be attributed to the dynamic impact test. Thus, the indenter is suitable for repeated dynamic impact testing.

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