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Cavitation erosion of CrN/CrCN multilayer coating

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ABSTRACT

Results of investigations of multilayer CrN/CrCN coating – X6CrNiTi18-10 stainless steel substrate system exposed to cavitation degradation are presented. CrN/CrCN coating with six CrN + CrCN bilayers was deposited using cathodic arc evaporation PVD method. Cavitation erosion tests showed that deposition of CrN/CrCN coating increased incubation period, but cumulative mass loss of the CrN/CrCN – X6CrNiTi18-10 system was higher than that of the steel substrate one. Microscopic study revealed that the degradation process was dominated by fatigue. Austenitic steel fractured in a mixed mode with domination of a ductile mode, while the CrN/CrCN coating fractured mainly in a brittle mode. Degradation of the CrN/CrCN coating was accelerated by delamination that decreased coating toughness. A highly eroded zone of the coated specimen was of similar size to the steel specimen one, but the whole eroded area was much smaller. Performed investigation indicated that the CrN/CrCN coating is not resistant to high-velocity impacts of micro-jets. Other impacts caused coating undulation and removal of micro-droplets formed during coating deposition. The main reason of brittle fracture was high stiffness of the coating and high-velocity impacts of cavitation pulses.

1. Introduction

PVD coatings due to their high hardness and low coefficient of friction are widespread in industry. The most popular are monolayer TiN and CrN coatings. Recently multilayer coatings have been widely investigated [1–5]. Multilayer coatings, in general, provide better fracture and wear resistance than monolayer coatings [6,7]. However, not all properties of multilayer coatings are better from the monolayer ones. According to Ref. [4], wear resistance of Ti/TiN multilayer coating in a tribological test (ball-on-disk tests) was lower than that of TiN coating. It was caused by plastic deformation mismatch between Ti and TiN layers. On the other side, cavitation erosion resistance of Ti/TiN coating [7] was better than that of TiN coating [8]. The investigation of properties of CrN/Cr multilayer coatings [9] showed that hardness increases with increasing number of bilayers or with a decrease of bilayer thickness. Similar results of investigations of multilayer coatings were obtained by Cheng et al. [4], Holleck and Schier [10], Duck et al. [11] and Zhao et al. [12]. Investigation of wear resistance of Cr/CrN multilayer coatings in a pin-on-disk test showed that the best resistance had 3-bilayer coating [9]. Authors attributed a decrease of wear resistance with an increase of number of bilayers to poor adhesion of Cr layer to CrN layer [9]. On the other side, tension-tension fatigue test (R = 0.05) has shown that deposition of Cr/CrN multilayer coating increases fatigue resistance in comparison to CrN monolayer coating. Fatigue test [9] showed that increasing the number of bi-layers to more than 3-bilayers in Cr/CrN multilayer coating does not affect fatigue resistance.

Another important group of multilayer coatings are ceramic/ceramic coatings, e.g. CrN/CrCN coatings. Addition of carbon to Cr-N coatings results in residual stress, hardness, elastic modulus and friction coefficient [13,14]. With an increase of carbon content to 20 at% residual stresses decreased, but further increase in carbon content caused an opposite effect – an increase of residual stresses. Similarly, the maximum hardness of Cr-C-N coatings is achieved for coating with carbon content of 20 at% [14]. Friction coefficient and wear depth in tribological test of Cr(CN) coatings are lower than those of CrN coatings [13,14]. Multilayer CrN/CrCN coatings show better adherence to substrate than CrN or CrCN coating and better wear resistance in a ball-on-disc test [15]. Among many CrN/CrCN multilayer coatings with various number of bilayers and the layers thickness ratio in a bilayer, the best wear resistance had the coating with 6 bilayers and the ratio t_{CrCN}/t_{CrN} = 1:1 [15].

Besides tribological properties (friction coefficient and wear resistance), resistance against dynamic loading has been determined as an important property. In the cavitation erosion phenomenon, surface of a material is subjected to many dynamic local loads that impact the surface with velocity in the range from few m/s to hundreds m/s. Investigations of cavitation erosion resistance of PVD coating – steel

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Table 1
Chemical composition (%) of X6CrNiTi18-10 steel.

C	Mn	Si	Ni	Ti	Cr	P	S
0,01	1,79	0,53	9,56	0,15	17,05	0,025	0,027

substrate systems [16] showed that deposition of thin monolayer TiN and CrN coatings improves resistance against dynamic load in comparison to that of a substrate material. Moreover, investigations of a Ti/TiN multilayer coating – steel substrate system [7] showed that this system had better cavitation erosion resistance than the systems with TiN coating [8]. The aim of this paper is to present the results of cavitation erosion tests of CrN/CrCN multilayer coating deposited on austenitic stainless steel. The CrN/CrCN multilayer coating with 6 bilayers and the CrCN to CrN thickness ratio of 1:1 (in bilayer), has been chosen as an object of investigation, due to its very good wear resistance in a tribological test [15].

2. Experimental techniques

2.1. Specimen preparation

Specimens (45 × 26 × 14 mm) are made from X6CrNiTi18-10 steel. Chemical composition of the steel is shown in Table 1. The density of X6CrNiTi18-10 steel is 8.00 g/cm^3. In order to remove residual of manufacturing effects, dissolve TiC particles and gain the homogeneous structure of the solid solution (austenite), all specimens have been subjected to quenching at 1050 °C. However, another effect of steel quenching is an improvement of ductility and a slight decrease of hardness. Mechanical properties of X6CrNiTi18-10 steel after quenching are shown in Table 2. Next, the surface of specimens was mirror polished with diamond paste (Ra = 0.02 μm). Polishing was performed up to high standard with consideration to minimize strain in the surface layer. Finally, PVD coating has been deposited on the specimens. Some of the specimens have been left uncoated, and later used as the reference ones.

2.2. Coating deposition

CrN/CrCN multilayer coating was deposited by cathodic arc evaporation (CAE) method in the conventional multi-arc PVD system in the Koszalin University of Technology. Substrate preparation for the deposition process included ultrasonic-aided cleaning with alkaline detergents, rinsing twice in deionized water and drying with compressed air. Next, substrates were placed on a rotating substrate holder situated 180 mm from each source. The chamber was evacuated to a pressure of 1×10^{-3} Pa and substrates were heated up to 300 °C. Then, substrates were etched in the atmosphere of argon at a pressure of 0.5 Pa by Ar and Cr ions at a voltage of −600 V during period of 20 min, in order to remove the surface oxide layer. A pure (99.98%) chromium disc was used as a target material. Reaction gases, nitrogen and acetylene (in the case of CrCN layer), were introduced by the pipe placed near the cathode in order to increase the density of plasma. The pressure of nitrogen for the CrN phase deposition was 1.8 Pa. An experimentally matched flow rate of acetylene allowed to obtain CrCN with 10 at % of carbon content. The substrate was initially coated with thin chromium sub-layer (~0.1 μm) in the argon atmosphere, in order to ensure proper adherence of the coating to the substrate. The CrN layers were deposited alternately with the CrCN layers starting with the CrN layer, and therefore CrCN layer was a top layer coating. The CrN/CrCN coating consists of six CrN + CrCN bilayers of the total thickness of 4 μm. The precise coating thickness was determined using ball cratering test (Calotest) method. Density of the coating is taken as 6.18 g/cm^3 [17].

Table 2
Mechanical properties of X6CrNiTi18-10 steel after quenching.

Hardness [GPa]	Young's modulus [GPa]	Ultimate tensile strength [MPa]	Yield strength [MPa]	Elongation [%]
1,7 (25 HRC)	~ 200	662	307	36

The phase compositions of coatings have been tested on a DRON2 X-ray diffractometer using Co Kα radiation. Hardness and Young modulus have been measured with a Hardness Tester Fischerscope HM2000 equipped with Berkovich indenter. The maximum indentation depth of 300 nm have been applied. In order to investigate coatings adhesion, a scratch tester Revetest produced by CSEM has been used. A diamond indenter with radius of 0.2 mm has been used and measurements have been carried out at standard conditions: normal loading rate of 100 N/min, scratch speed of 10 mm/min and scratch length of 10 mm. For each specimen at least three scratches have been done. The adhesion has been determined by observations from optical microscope. The critical load L_{C1} is associated to the first cracks of the coating, whereas the critical load L_{C2} is related to the first delamination of the coating from the substrate.

2.3. Cavitation erosion test

The experimental cavitation erosion tests have been performed in the Institute of Fluid Flow Machinery Polish Academy of Science using a cavitation tunnel with a system of barricade / counter-barricade. The scheme and description of the cavitation chamber and the test device has been presented in Ref. [8]. Specimens (uncoated and coated) were subjected to cavitation loading at inlet pressure p_1 = 700 kPa, outlet pressure p_2 = 128 kPa, a slot width of 5 mm and using a 4 mm thick distance washer. The temperature of working liquid (tap water) was 20 ± 2 °C. At the beginning of the cavitation test, exposure intervals lasted 15 min in order to estimate the incubation period and to observe the development of degradation of the tested specimens. After 30 min of the test, the duration of exposure intervals increased gradually to 30, 60 and 120 min. The total cavitation test lasted 600 min. Before the test and after each test interval, specimens were cleaned, dried and weighed using a first class analytical balance with sensitivity of 0.1 mg. Based on mass measurements, the cavitation curves were achieved. Cavitation curves were defined as an increase of mass loss vs. exposure time. In the case of materials with different density, it would be recommended to present erosion curves in form of an increase of volumetric loss vs. time. However, in the case of coated specimens, there is a problem with accurate calculation of the removed volume from a coating-steel substrate system. Due to the risk of significant error of calculated volumetric loss, erosion curves have been presented in form of an increase of mass loss vs. exposure time.

After each particular exposure time, degradation of tested material was analysed with specimen surface observation using a scanning electron microscope (SEM). Additionally whole specimens were scanned and the eroded surface was calculated based on the scanned images with use of AutoCad® software. Before and after coating deposition, and after the whole cavitation test, roughness of the specimen surface was measured with the SJ-301 Mitutoyo Surface Roughness Tester. Because surface of steel substrate specimens was flat and mirror polished, only a few roughness measurements were performed before the cavitation test. After the cavitation erosion test, due to essential variations in surface roughness depending on the distance from water inlet, roughness measurements have been performed along the network shown in Fig. 1. The sampling length was 0.8 mm, evaluation length was 4 mm. Due to high sensitivity of the roughness measurement, all measurements were performed three times.