Alicja KRELLA
The Szewalski Institute of Fluid-Flow Machinery Polish Academy of Sciences, Gdańsk
Andrzej CZYŻNIEWSKI
Technical University of Koszalin, Koszalin

THE INFLUENCE OF NANOSTRUCTURE COATINGS DEPOSITION ON CAVITATION RESISTANCE OF X6CrNiTi 18-10 STAINLESS STEEL

Key words

Cavitation, cavitation erosion, nanostructure coatings, fracture.

Summary

The results of the cavitation erosion resistance of nanostructure TiN, CrN and WC/a:C-H coatings deposited on X6CrNiTi18-10 stainless steel by means of PVD method are shown. The tests of cavitation resistance were performed in a cavitation tunnel with a barricade system. It was noticed that the deposition of TiN and CrN nanocrystalline coatings has improved the cavitation resistance of X6CrNiTi18-10 stainless steel while the deposition of WC/a:C-H nanocomposite coating has decreased the cavitation resistance. The high adhesion and good plastic deformation abilities of coatings are very important to assure the high cavitation resistance of the austenitic steel-hard coating system.

Introduction

Cavitation degradation is a dynamic phenomenon. The load rate ranges from 0.3 to 2 MPa/μs, and it acts on 10^{-10} m^2 area, so the degradation has an impact character. Because of a high load rate and a high load amplitude range, the material durability properties, material structure and the load history are very important. The load history has an impact on the plastic deformation of the exposed material and of the microcracking progress. In the case of coated materials, it also has the influence on delamination. Several research studies [1–4] have shown that the cavitation resistance of a solid material depends on fatigue resistance, yield stress, hardness and Young modulus. It is also influenced by structural features, such as the grain size, the phase composition and roughness.

In the case of coated materials, the relationships among the mechanical properties of the solid material and of the hard coating and the cavitation erosion resistances of coated materials are more complicated due to the interaction between the substrate and the coating. An accurate determination of the factors on which the cavitation resistance is depended is very complicated. Erosion investigations [5, 6] proved that coating adhesion has an effect on coating durability. Leyland and Matthews [7] showed that the "the plasticity index" which is the ratio of the hardness and the Young modulus is the essential parameter of coating durability in tribological behaviour. They emphasised the significance of a low value of the elastic modulus for the improvement of the wear resistance of ceramic coatings.

The hard nanocrystalline coatings, like TiN, TiAlN, CrN, WC, WC/a:C-H, made by the PVD method are recently widely used to protect cutting tools.

The aim of this work was the assessment of the influence of the nanostructure coatings on the protection of stainless steel X6CrNiTi18-10 in cavitation erosion.

1. The test rig

The experimental tests were performed in a cavitation tunnel with a system of barricades at the laboratory of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences [8]. Cavitation intensity is controlled by varying the slot width and the boost pump speed. Flow conditions are defined by the p_1 and p_2 absolute pressures measured at the chamber inlet and outlet, respectively.

The specimens (45 x 26 x 14 mm) made of X6CrNiTi18-10 stainless steel and quenched at 1050°C were subjected to cavitation impingement in the cavitation chamber operated with inlet pressure p_1 = 1000 kPa, outlet pressure p_2 = 130 kPa and a slot width of 5 mm. In order to obtain the erosion curves the mass loss measurement was performed after each exposure interval. Before the test and after each test interval the specimens were cleaned, dried and reweighed. At the beginning of the cavitation test the measurements were conducted after every 30 min of exposure (for the first 180 min of test) to estimate the incubation period. The duration of exposure intervals was then gradually increased. The total cavitation test duration was 600 min.

2. Deposition, structure and properties the coatings

The nanocrystalline TiN and CrN coatings were deposited by the cathodic arc evaporation method (ARC), whereas the nanocomposed WC/a:C-H coating by pulsed reactive magnetron sputtering. The deposition was performed at Engineering Materials Department of Technical University of Koszalin in a high vacuum chamber equipped with arc-magnetron sources [9]. The depositions technology of the TiN and CrN coatings are described in [10], while the deposition technology of WC/a:C-H coating is decribed in [11]. The properties of the deposited coatings are presented in Table 1.

The phase compositions of coatings were tested on a DRON2 X-ray diffractometer using CuK_{α} radiation. The grain size was determined by means of the Scherrer method with reflex parameters (location and FWHM) using Gaussian analysis. The coating morphology was examined with JEOL JSM 5500 LV scanning electron microscope (SEM). The hardness and Young modulus were measured with a NanoHardness Tester (CSEM) using the method of Oliver and Pharr [12]. A scratch tester Revetest® produced by CSEM was used to investigate the coating adhesion.

Table 1. Properties of coatings

Coating	TiN	CrN	WC/a:C-H
Chemical composition [% at]	Ti – 48.9 N – 49 O – 2.1	Cr ~ 65.6 N ~ 32.7 O – 1.7	W – 52 C – 46 O ~2, N, Ar
Phase composition	δ-TiN, regular	$CrN + Cr_2N$	β-WC_{1-x} + a-C:H
Mean crystalline size [nm]	16	6	2 – 3
Hardness [GPa]	25.4	21.2	32.2
Young modulus [GPa]	295	285	311
H/E coefficient	0.086	0.074	0.104
Coating thickness [μm]	3.7	3.7	3.5
Coating adhesion (scratch test) [N] L_{C1} – cohesion failure L_{C2} –adhesion failure	 10 23	 10 18	 7 7

3. Results

The mass losses of the coatings deposited on X6CrNiTi18-10 stainless steel and of the uncoated X6CrNiTi18-10 steel during cavitation tests are shown in Fig. 1. The deposition of nanocrystalline TiN coating has extended the incubation period by approximately 100% and has decreased the mass loss by approximately 50% in comparison to the uncoated austenitic steel. The CrN coating has also decreased the mass loss in comparison to uncoated stainless steel, but the incubation period was similar to that of stainless steel. The steel coated with WC/a:C-H coating has shown the lowest cavitation resistance.

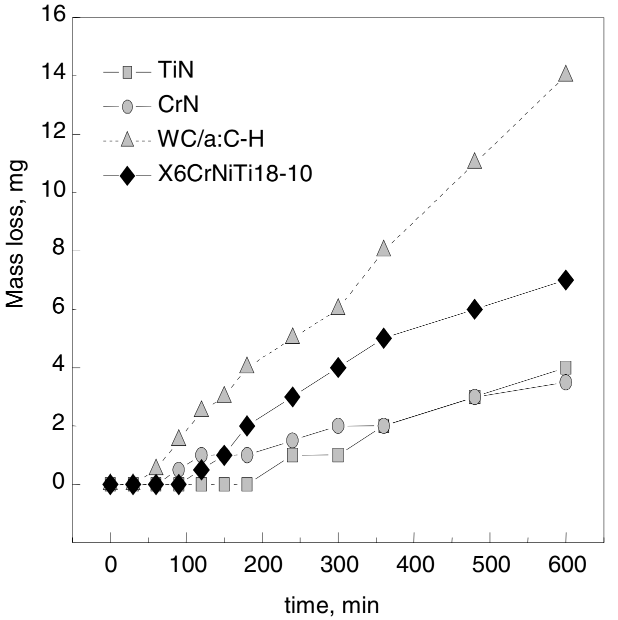
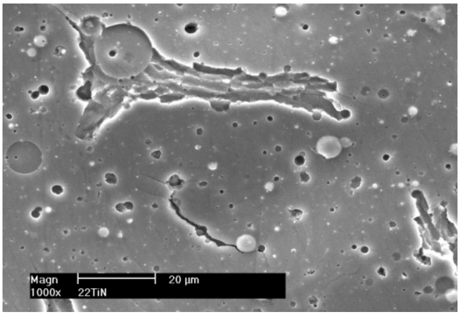


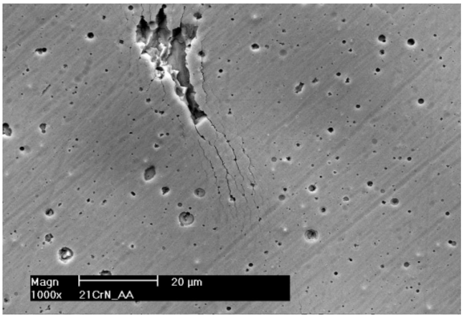
Fig. 1. Erosion curves

The microscopic observations have revealed the coatings' damage (Fig. 2). All coatings have formed micro-folding in the initial degradation stage as the result of the substrate deformation. The substrate, the X6CrNiTi18-10 stainless steel, has undergone a micro-folding and some slip systems and twins have arisen. The slip planes are seen as intrusions and extrusions. They have a typical fatigue character. Fatigue cracks have started from the surface of a component, where fatigue damage begins as shear cracks on crystallographic slip planes (Fig. 2d, arrows).

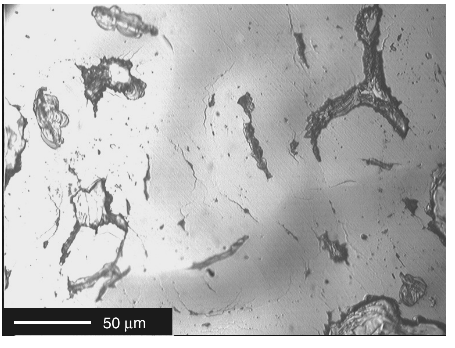
The first cracks of all coatings have started at the top of the foldings. They have developed mostly along the tops, where the highest tensile stress might be expected. In case of TiN and CrN coatings, the cracks have developed by migrating through concave traces of post-microdroplets (Fig. 2a and 2b). At the sides of micro-folds some microcracks are also observed. Microscopic observations suggest that delamination occurred there. At the delamination areas microcracks occur faster especially if coating defects exist. In case of the nano-composed WC/a:C-H coating (Fig. 2c), the net of the cracks has appeared very quickly and large parts of the coating have been removed quite easily.



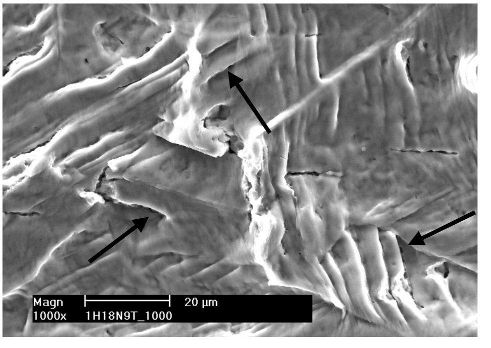
a) TiN



b) CrN



c) WC/a:C-H



d) stal X6CrNiTi18-10

Fig. 2. Cavitation damages on exposed specimens with a) TiN coating; b) CrN coating; c) WC/a:C-H coating; d) on X6CrNiTi18-10 stainless steel

4. Discussion

The above test results indicate that the deposition of nanostructure coatings on stainless steel changed the steel cavitation resistance. The nanocrystalline TiN coating has the best cavitation erosion protection properties due to its the longest incubation period among all coatings (approximately 100% longer than the uncoated steel's). The incubation period of others coatings were shorter than the uncoated steel's. The deposition of TiN coating decreased approximately 50% the mass loss during the whole cavitation test. The TiN coating also has good adhesion (scratch test) and good plastic properties. The TiN coating was deformed by imploding bubbles causing micro-folding and fitted to the deformed substrate. The CrN coating also has good cavitation resistance, which was confirmed by the Iow mass loss. However, the incubation period of the CrN coating was a little shorter than the incubation period of the uncoated X6CrNiTil8-10 stainless steel. Good plasticity and good adhesion of the nanocn stalline CrN coating to the "soft" steel was confirmed by the micro-folding of the coating. A slightly worse adhesion of the CrN coating in comparison to the adhesion of the TiN coating was confirmed by the reduced incubation period.

Most of the cracks appeared at the tops of the micro-foldings. probably because of higher tensile stresses than the tensile strength of the coating. The nanocomposed WC/a:C-H coating has high stiffness (high H/E coefficient) and Iow adhesion, which have produced very Iow cavitation durability (łąck of the incubation period and very high mass loss after the whole test).

The presented investigations show that the coating ductility and the adhesion have an influence on the cavitation resistance. The microscopic observations reveal the micro-folding on all coated specimens, which is evidence for the coating adjustment to the plastically deformed substrate due to imploding load. Taking into account the fact that the coating's Young modulus (E = 285-311 GPa) are approximately 50% higher than the substrate's (E = 199 GPa) and the coating's hardness (21–32 GPa) is over 10 times higher than the substrate hardness (~ 2 GPa). It can be affirmed that, during coating deformation, a significant amount of degradation energy is absorbed by the coating. In this aspect, the increase of the coating plastic deformation properties will be conducive to the increase of the cavitation resistance.

The next important endurance factor for the coating is adhesion. Low adhesion leads to rapid micro-crack occurrence and to the rapid removal of coating particles at a low impact force. This is an important problem during the cavitation degradation, where the cavitation pulse amplitude ranges from kPa to MPa [12]. It means that even low amplitude cavitation pulses can cause microcracks initiating coating delamination during plastic deformation. This can cause rapid removal of cavitation particles, especially when the coating has high stiffness (high H/E coefficient). This degradation process was seen during the erosion of WC/a:C-H coating.

The increase of adhesion means that greater force is needed to cause the cracks or the coating failure. In case of the cavitation degradation, it means the increase in the cavitation pulse amplitude needed to initiate the coating piercing. If the increase of adhesion is accompanied by the increase of the plasticity index (TiN and CrN coatings), the delamination process and the initiation of the crack development could be delayed. This could lead to a cavitation resistance improvement.

Presented investigation results show that the increase of the cavitation resistance of the soft substrate – hard coating system (X6CrNiTi18-10 coated TiN) depends mainly on the good adhesion and good plasticity of the coating.

Acknowledgements

Results presented in this paper were funded by budget resources allocated to scientific research in 2005–2007 as a research project no. 4 T07B 015 28.

References

1. Bogachev I.N., Mints R.I.: Cavitational erosion and means for its prevention, Jerusalem 1966.
2. Heathcock C.J., Protheroe B.E., Ball A.: Cavitation erosion of stainless steels, Wear 81 (1982) 311–327.
3. Wade E.H.R., Preece C.M.: Cavitation erosion of iron and steel, Metallurgical Transactions A 9A(1978) 1299–1309.
4. Thiruvengadam A.: A unified theory of cavitation damage, Transactions of the ASME, Journal of basic Engineering (1963) 365–376.
5. Iwai Y., Honda T., Yamaa H., Matsumura T., Larsson M., Hogmark S.: Evaluation of wear resistance of thin hard coatings by a new solid particle impact test, Wear (2001) 861–867.
6. Han S., Lin J.H., Kuo J.J., He J.L., Shih H.C.: The cavitation-erosion phenomenon of chromium nitride coatings deposited using cathodic arc plasma deposition on steel, Surface and Coating Technology 161 (2002) 20–25.
7. Leyland A., Matthews A.: On the significance of the H/E ratio in wear control: a nanocomposite coating approach to optimized tribological behaviour, Wear 246 (2000) 1–11.
8. Krella A.: Badanie wpływu zmian parametrów ruchowych w tunelu kawitacyjnym z komorą typu Erdmanna-Jesnitzera na gęstość strumienia energii doprowadzonej do materiału. IMP PAN prace wew. 533/99, Gdańsk 1999.
9. Czyżniewski A. Precht W.: Wytwarzanie i właściwości warstw Me-C:H na stopach aluminium, Elektronika 5 (1998) 15–19.
10. Czyżniewski A., Krella A.: Wytwarzanie i właściwości powłok TiN i CrN w zastosowaniu do ograniczenia zużycia elementów maszyn przez kawitację, Inżynieria Materiałowa XXVII (06) nr 3, s. 360–363.
11. Czyżniewski A.: Deposition and some properties of nanocrystalline WC and nanocomposite WC/a-C:H coatings, Thin Solid Films 433 1–2 (2003) 180–185.
12. Oliver WC, Pharr GM.: An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. J Mater Res 1992;7:1564–1583.
13. Krella A., Steller J.: Badania doświadczalne erozji wybranych materiałów w zależności od obciążenia kawitacyjnego, Problemy Eksploatacji 1/2006 (60), s. 189–198.

Recenzent:
Włodzimierz WALIGÓRA

Wpływ osadzania nanostrukturalnych powłok na odporność kawitacyjną stali austenitycznej X6CrNiTi18-10

Słowa kluczowe

Kawitacja, erozja kawitacyjna, powłoki nanostrukturalne.

Streszczenie

W pracy przedstawiono wyniki badań kawitacyjnych powłok TiN, CrN oraz WC/a:C-H osadzonych metodą PVD na stali X6CrNiTi18-10. Uzyskano, że nanokrystaliczne powłoki TiN oraz CrN poprawiły odporność kawitacyjną, natomiast nanokompozytowa powłoka WC/a:C-H spowodowała pogorszenie odporności kawitacyjnej. Przeprowadzone badania wykazały, iż wysoka adhezja i dobre własności plastyczne są istotnymi własnościami powłok, przeznaczonymi dla ochrony materiałów przed erozją kawitacyjną.