

# WEAR PROPERTIES OF THERMALLY SPRAYED TUNGSTEN-CARBIDE COATINGS IN PAPER MACHINE ENVIRONMENTS

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## ABSTRACT

Thermally sprayed tungsten-carbide (WC) coatings have proven to be one of the most wear resistant coatings available and a respectable replacement for hard-chromium coatings. They are used in paper machine parts such as calender rolls. However, improved lifetime and performance are continuing considerations, as well as finding more economical alternatives. This study researched the wear phenomena of tungsten-carbide coatings in a paper machine environment. To achieve this, five different feedstock materials and coatings manufactured from these were compared by electron microscopy as well as dry abrasion-, high-speed slurry abrasion- and cavitation erosion tests. Improvements in ductility by changing the matrix material were found, while changing the particle strength had no effect on the behavior of the coatings. The findings suggest further research on altering the matrix of the feedstock could lead to overall improvements in coating quality and component lifetime.

## INTRODUCTION

Wear-resistant coatings are used in paper machine components to lengthen their lifespans, and research on the wear properties of new materials is continuous. An example of a common component wherein carbide coatings are used is the calender roll [1,2]. The environment for components in a paper machine is harsh: speeds of up to 2000 m/min, loads of over 3 kN/m, temperatures of up to 200°C and an abrasive slurry are constantly present [3,4]. The demanding wet conditions in a paper machine have been found to wear the coating out unexpectedly fast in some cases.

Although tungsten-carbide coatings are widely used for wear resistance in dry conditions, further examination is required in order to find out the cause of their deterioration in paper machines. The wear mechanism in tungsten-carbide coatings is complex and a result of many variables [5]. These variables include the volume fraction and size of the carbides as well as the matrix material. The wear properties of hard coatings have been widely studied from different perspectives [6,7], but so far no results describe their wear in paper machines.

For this reason, we aimed to design more specific experiments to simulate the conditions as closely as possible to gain knowledge of the behavior of the coatings. In

this study, high-speed slurry abrasion and cavitation erosion were used to simulate paper machine conditions, while dry abrasion (modified ASTM G65) was used as a reference test. The compared coatings were high-velocity flame sprayed (HVFS) tungsten carbide coatings with varying particle strengths, carbide sizes and matrix compositions.

## METHODS

### Materials

Several different tungsten carbide powders from different suppliers were compared. The powders differ in composition, carbide size and particle strength. Powder 1 was a reference HVFS WC-Co-Cr powder. Powder 2 had low- and powder 3 high particle strengths as reported by the manufacturer. Powder 4 had a more corrosion resistant Hastelloy® C-276 matrix (18% NiMoCrFeCo) and a larger carbide size and powder 5 had a dual carbide distribution. All powders were manufactured by agglomerating and sintering and their nominal particle size distribution was 10-25 µm. The powders are listed below in table 1 and SEM-images are presented in Figure 1. Powder 1 is a currently used commercial powder while the others are experimental powders in development. Some matrix-rich areas can be seen in Figure 1 a) along with some porosity. From Figure 1 b) and c) the effect of particle strength can be compared: the higher particle strength of powder 3 gives in general a denser structure, but it leads to some breakage of particles which are seen as large pores or cavities in the cross-section. Both powders 4 and 5 exhibit a dual distribution of carbide size and the larger amount of matrix in powder 4 is evidenced by the higher cohesion of the particle. Powder 5 on the other hand is quite porous and exhibits large metallic regions.

*Table 1. Characteristics of the WC powders. Particle strengths “n/a” were not disclosed.*

No.	Matrix (WC-)	Carbide size (µm)	Particle strength	Coating thickness (µm)
1	10Co-4Cr	0.5	n/a	335
2	10Co-4Cr	0.5	Low	420
3	10Co-4Cr	0.5	High	464
4	18NiMoCrFeCo	1	n/a	394
5	10Co-4Cr	0.5+2.5	n/a	412

The coating specimens studied in this work were thermally sprayed with an HVFS system using the same spray parameters on stainless steel (AISI 316L) substrates. Sample sizes for the tests were 50x50x5 mm for abrasion, 50x20x20 mm for high-speed slurry abrasion and 20x20x5 mm for cavitation erosion.

### Characterization

The coatings and powders were characterized with a Scanning Electron Microscope (SEM), either a Philips XL30 or a Field-Emission Scanning Electron Microscope (FESEM, Carl Zeiss Microscopy GmbH, Germany). The Vickers hardnesses of the coatings were measured from the cross-section with a Leica VMHT 30A hardness-tester using a load of 300 grams.

The powders were characterized by the powder manufacturers, who supplied the particle strength and carbide-size information. The carbide size was verified visually by SEM.

### Dry-sand abrasion

The surfaces of the samples were ground with a P1200 diamond grinding disk to eliminate the effect of as-sprayed surface quality. This would also be the case in real-life applications.

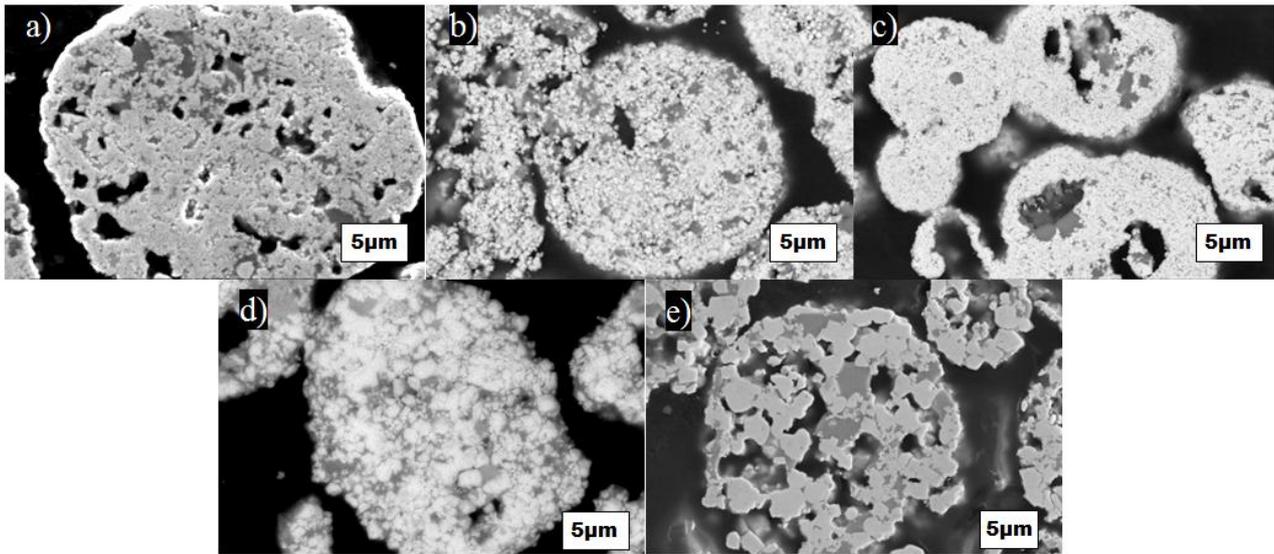


Figure 1. SEM-images of the cross-sections of the used powders 1 (a), 2 (b), 3 (c), 4 (d) and 5 (e).

In the test the samples were pressed against a rotating rubber wheel with a force of 30 N and dry silica (Nilsjö Quartz, particle size 0.1-0.6 mm) was fed between the samples and the wheel to act as an abrasive. The weight of the samples was measured before the experiment and after 30 minutes utilizing a Sartorius CP224 S scale to the precision of  $0.1 \text{ mg} \pm 0.05 \text{ mg}$ .

#### High-speed slurry abrasion

In the experiment a radial velocity of 2000 m/min was used with a tangential force of 77.3 N pressing each sample against a rubber roll. An abrasive slurry, 15 wt. % of kaolin pigment Ansilex 93 and water, was fed between the sample and the roll with a rotator pump with a frequency of 1 Hz. The particle size of the kaolin was less than  $2 \text{ }\mu\text{m}$ . Each experiment lasted for 20 hours; the longest possible time within practical limitations. The test was run twice for each sample to verify the result.

The samples were ground and polished for the test to a mirror-like surface finish of Ra value

$0.02 \text{ }\mu\text{m}$  using grinding discs and finishing with  $3 \text{ }\mu\text{m}$  diamond slurry. The finer surface finish compared with the abrasion test was preferred due to increase the applicability of the test in real-life conditions, thus giving more reliable comparisons between coatings and better understanding of the test method. The samples were weighed before and after the test with a Sartorius CP224 S scale. The precision of the scale was  $0.1 \text{ mg} \pm 0.05 \text{ mg}$ . The samples were cleaned before each weighing ultrasonically in ethanol and dried in a kiln overnight at  $70^\circ\text{C}$ .

#### Cavitation erosion

The cavitation erosion experiment was performed in deionized water using the indirect cavitation method described in ASTM G32 standard. The test duration was chosen as the time when the sample had clearly passed the cavitation incubation time and when the erosion rate was linear. The test specifications are presented in table 2.

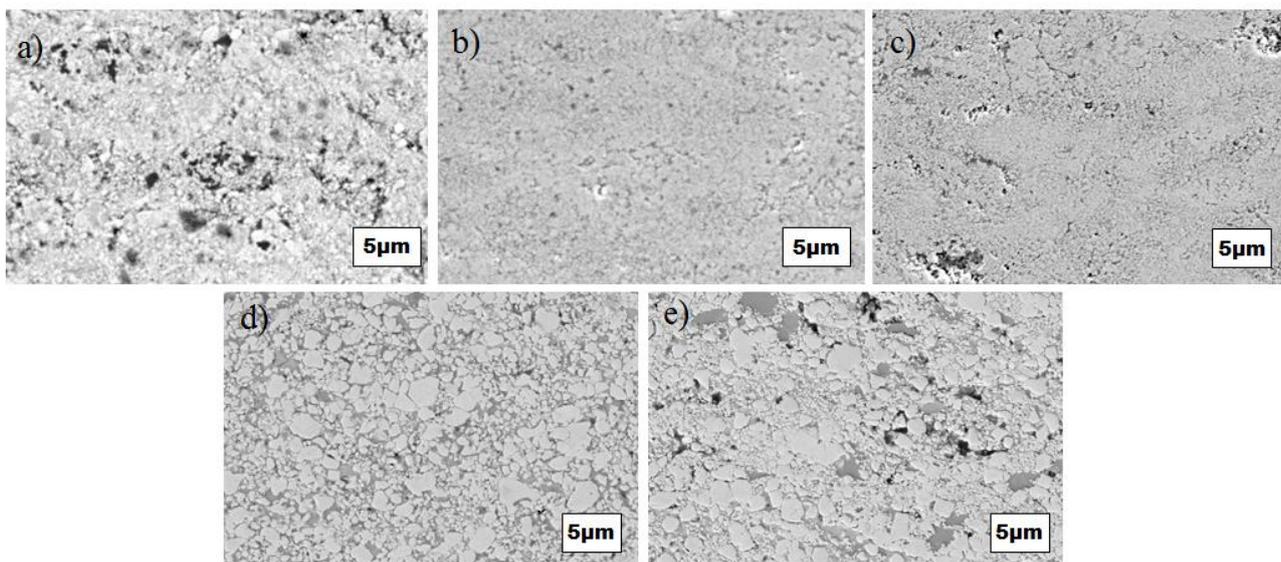
*Table 2. Test specifications for the indirect cavitation experiment.*

Amplitude ( $\mu\text{m}$ )	50.16
Time (h)	3
Temperature ( $^{\circ}\text{C}$ )	17
Tip diameter (mm)	13

The samples were fine ground and polished to a mirror-like surface finish of Ra value 0.02

$\mu\text{m}$ . The samples were then mounted to a sample holder that was immersed in the liquid along with the ultrasonic head and a cooling coil made of copper. The ultrasonic processor was a Sonics VCX 750.

The samples were ultrasonically cleaned in ethanol, dried with hot air and weighed before and after the test with a Mettler AE 163 scale. The precision of the scale was  $0.1 \text{ mg} \pm 0.05 \text{ mg}$ .



*Figure 2. SEM-images of the coatings: 1 (a), 2 (b), 3 (c), 4 (d) and 5 (e).*

## RESULTS

SEM-images of the coatings are presented in Fig. 2. All coatings 1, 2 and 3 retained their fine carbide size. Coating 1 has quite many pores, which is in agreement with the powder structure seen in Figure 1. In colder spray methods such as HVFS the coating structure often is almost a direct result of the powder structure due to low melting degree. Same agreement can be seen in coatings 2 and 3, although coating 2 does seem denser due to pullout of small particles from coating 3.

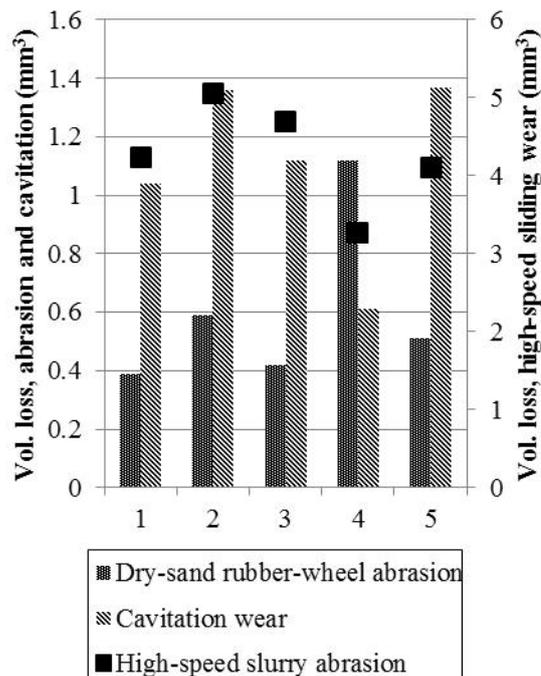
Coating 4 seems very dense while coating 5 had numerous pull-outs of larger carbides. However, both retained their bimodal carbide-size distribution. The larger amount of metal in coating 4 can be seen in Fig. 2 d) which was the case also in the feedstock material. From Fig. 2 e) it is clear that the uneven distribution of carbides in the powder is mirrored in the coating as well. In all coatings the carbides are quite angular, indicating low heating during spraying.

Table 3 presents the results of the experiments and Figure 3 plots them in the same graph. The hardness values of the coatings are very similar, which was to be expected since the materials have nearly equal carbide contents and the HVFS system reliably produces high-quality coatings. The only outlier is coating 4, which has a smaller fraction of hard phase and, therefore, a lower hardness as well. For the rest of the coatings, the variation is minute and within standard deviation.

*Table 3. Summary of results of the dry-sand rubber wheel (DSRW) abrasion, high-speed slurry abrasion (HSSA) and cavitation erosion experiments along with hardness values of the coatings.*

Sample	Hardness (HV)	DSRW (mm <sup>3</sup> )	HSSA (mm <sup>3</sup> )	Cavitation (mm <sup>3</sup> )
1	1150±76	0.39	4.24	1.04
2	1067±81	0.59	5.06	1.36
3	1145±108	0.42	4.69	1.12
4	947±78	1.12	3.27	0.61
5	1043±73	0.51	4.11	1.37
Steel	-	170	586	0.49

For the wear tests, volume loss was calculated presuming zero-porosity from theoretical densities and elemental ratios. The dry abrasion wear seems to follow a similar trend to hardness; only coating 4 differs from the rest, wearing more. In contrast, in high-speed abrasion the WC-18NiMoCrFeCo coating seems to be the most resistant to wear. This is also the case in cavitation erosion, where it fares almost as well as the reference sample of stainless steel.



*Figure 3. The volume loss of the coatings in the dry abrasion-, slurry wear- and cavitation erosion wear tests.*

## DISCUSSION

Compared to sample 1, the reference coating in this study, the powders with low- and high particle strength seem to offer no advantages. Between the two, though, the higher particle strength gives a slightly better resistance to wear in these tests. It is possible that during the relatively cool spraying process the more porous particles did not heat and soften as thoroughly as the denser particles, resulting in poorer cohesion of the coating.

The coating with Hastelloy matrix was softer and more abradable than the other compositions, as expected due to its higher binder content. Poorer adhesion of the matrix with the carbides compared with cobalt also hinders its wear resistance [8]. However, the larger amount of matrix does make the coating more ductile, which can be seen as improved cavitation erosion resistance. Furthermore, the mild corrosive nature of the

high-speed slurry abrasion wear test gives an edge for the corrosion resistant Hastelloy-matrix compared with the coatings with cobalt-chromium matrices. The poorer abrasion resistance and higher wet slurry abrasion resistance of WC-Hastelloy compared to WC-CoCr is also documented by Houdková et al. [9] where corrosion by water was determined to be the differentiating factor. The synergistic effect of hardness, toughness and corrosion resistance on wear rate of cermet coatings has also been confirmed elsewhere. [10, 11]

In coating 5 the dual carbide size was thought to have an advantage by combining homogeneity and shorter binder mean free path, due to the small carbides, with wear resistance, emanating from the large carbides. However, these characteristics were not achieved as no significant changes in its performance were detected comparing with the reference coating. Erosion due to cavitation was the highest, stemming from the large carbides acting as nucleation sites for the cavitating bubbles.

## CONCLUSIONS

In this study five different tungsten-carbide coatings were compared in three wear tests: dry abrasion, high-speed slurry abrasion, and cavitation erosion.

While the coatings performed very similarly, there were two significant findings. First, the superior performance of the WC-18NiMoCrFeCo coating in cavitation erosion and high-speed slurry abrasion revealing the beneficial effect of a ductile- and corrosion resistant matrix against wear in wet as well as cavitating conditions. Second, higher particle strength seems beneficial when selecting coatings against wear. This increased performance likely stems from the more thorough heating during spraying and hence a more cohesive coating structure. While this

cannot be seen in the cross-sections directly the particle strength is the only difference between coatings 2 and 3 and, therefore, the logical explanation. In summary, the manipulation of particle properties seems to be of paramount importance when designing feedstock for thermal spray, especially for cold methods such as high-velocity flame-spraying.

## ACKNOWLEDGEMENTS

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