Research Article

Effect of Tungsten Carbides on Abrasive Wear of Hardfacing Coatings

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The aim of this study is to investigate the abrasive wear loss as well as the wear mechanisms of hardfacing layers with and without tungsten carbides (WC) included in the matrix in different friction wheel test (FWT) configurations. The FWT setup is varied in regard to the materials of the rotating wheels, whereat steel and rubber materials are utilized to achieve varying wear mechanisms as representative conditions for stone milling as well as low density wood cutting processes. Coatings including fine particles of WC highlight the highest resistance against abrasive wear in rubber wheel testing condition, at which microcutting acts as the dominant effect. In comparison to the hardfacings without WC, the mean material loss majorly decreases by about 75%. On the contrary, the mean material loss of fine WC reinforced coatings increases up to 93% compared to the condition without WC if a steel wheel is utilized as rotating counterpart. Thereby, the coatings with comparably coarse WC reveal the minimum material loss with a decrease over 70% compared to the condition without WC. In conclusion, the inclusion of WC in hardfacing coatings significantly increases the wear resistance. The experimental wear test results highlight the fact that in order to achieve the optimal wear resistance the material characteristics of the hardfacings need to be properly defined considering the predominant wear mechanisms under in-service conditions.

1. Introduction

The wear and tear of machinery parts cost the economy 4.5% of the gross national product [1]. Besides adhesion, erosion, fretting, fatigue, and tribochemical processes, a majority concerns the abrasive wear with about 75 to 80% [2]. Especially in mining, agriculture, and forest industry, tools and machinery components are strongly exposed to scratching abrasives like minerals, earth, and wood. Abrasive wear is “the wear due to hard particles or hard protuberances forced against and moving along a solid surface” [3]. Three-body abrasive wear occurs if “wear is produced by loose particles introduced or generated between the contacting surfacing”. Both types lead to “mechanical removal or displacement, or both, of material from the surface”, known as scratching. The loosening of material leads to a weakening of structures and further to a compulsorily replacement of worn parts [4]. Additionally, a progressive dulling of wood chipping tools leads to majorly increased fuel consumption and enhanced fines [5, 6]. In the

worst case, wear may result in a total failure of parts or whole components. A common method to increase service life is the application of hardfacing layers on metal parts [7]. In case of a worn layer, it can be replaced and the tool may be reusable. The definition of the hardfacing layer is usually difficult to handle. Depending on the application of the coated tools or components, different wear mechanisms lead to various wear surfaces. Furthermore, the parts are often cyclically loaded or exposed to impacts, which additionally decrease the lifetime [8, 9]. For such applications, the use of a proper hardfacing layer is necessary, which should contain minor imperfections and no cracks. Coatings with interspersed coarse tungsten carbides (WC) with particle size greater than one millimetre are primarily applied on crushing tools in the processing industry [10], e.g., for wood comminution, because beside a high wear resistance the cutting effect is intensified. The potential of coarse WC included in an iron base to reduce wear [10] is shown on field-near, real life cutting teeth in [11]. The tests were performed utilizing a wear

pot, filled with quartzite stones as abrasives, leading to a matte wear surface. In comparison to martensitic hardfacing layers without carbides, the coatings with coarse WC exhibited the highest wear resistance. On the contrary, it was shown in [8, 11, 12] that the inclusion of such coarse particles induces a massive decrease of lifetime under cyclic loading. The tungsten carbides act like imperfections and majorly reduce the fatigue strength. To decrease the pure abrasive wear behaviour, fine hard particles of tungsten carbides can be included [9]. An inclusion of such small carbides in high density distribution in a nickel base shows a less impact resistance on high energy level than martensitic materials, tested on an impeller-tumbler apparatus [9]. The definition of a proper abrasive wear test process is a difficult task, because of the utilized hard and sharp abrasives; the test equipment is also strongly exposed to wear. Testing and comparing different hardfacing layers in the field is a long lasting process [13]. To reduce field trials and to obtain meaningful results on the wear resistance of such hard layers, several methods have been established in the last decades [14, 15]. One of the most common approach is the usage of a friction wheel test (FWT), known from the normalized standard tests after [16] with wet slurry and steel wheel and [17] with dry sand and rubber wheel. Thereby, abrasives are fed in between the friction zone, leading to a material abrasion. The required sand in case of dry tests is Ottawa silica [17]. Due to higher hardness and abrasivity, alumina is recommended for “modern abrasion-resistant materials” besides silica [18]. Testing coatings including interspersed tungsten carbides with a rubber wheel in the FWT is basically not common. Thereby, the hard and sharp formed carbides act like small cutting teeth on the comparatively soft wheel. A replacement of the soft rubber wheel with a steel friction wheel is a methodology for testing materials at high temperature, used in [19] investigating temperature and load effects. Herein a model shows how the load influences the results when applying a steel friction wheel. The zone of friction can be divided into three sections [19].

- (i) Entrance zone: material is fed to the friction zone, ploughing and rolling under low load and additional multistage crushing with higher load is occurring.
- (ii) Central zone: here is the highest contact pressure, leading to rolling and light crushing by applying low load and multistage crushing and interaction of attached debris on the surfaces.
- (iii) Exit zone: it is the area where the abrasives leave the friction area in rounded or crushed condition.

Another replacement of the rubber wheel with a steel one is shown in [20–23] for ceramic materials utilized in high ambient temperature and strongly exposed abrasive wear like plants in steel industry. In this work the same boundary conditions are applied on FWTs by variation of a steel and rubber wheel. Based on the experimental wear tests and accompanying analysis, the scientific aims of this work are defined as follows:

- (i) Extensive characterization of different hardfacing types by friction wheel tests and metallographic inspections
- (ii) Comparison of wear mechanisms under two different friction wheel compositions for coatings, which are exposed to milling applications and cutting applications of softer materials like wood
- (iii) The effect of included coarse tungsten carbides in hardfacing layers which is compared to other series with fine WC and series without hard particles in the test configuration with steel wheel
- (iv) Recommendations for proper application of hardfacing coatings, e.g., used for high-abrasive cutting tools in the wood harvesting industry (see [8]) or milling applications.

The presented results and described testing concepts as well as the analysis methodologies support a proper choice of hardfacing coatings. As experiments including different wear mechanisms are performed, this study scientifically contributes to holistically investigating the effect of tungsten carbides on abrasive wear of hardfacing coatings. Due to a variation of the FWT configuration, distinctions in the beneficial influence of tungsten carbides on the wear behaviour are observed, which acts as significant finding to optimize the wear resistance of hard-faced components. To validate the experimental results, three-dimensional surface scans are conducted enabling a detailed insight into the varying wear conditions.

2. Materials and Methods

2.1. Used Specimen and Material Characterization. The eleven investigated overlay materials are supplied by different manufactures based on a defined specimen geometry (Figure 1(a)). General knowledge about the kind of production process is available; however, detailed manufacturing process parameters are confident. The base material consists of a mild steel S355J2 sheet with a sheet thickness of 8 mm. The chemical composition of S355J2 is provided in Table 1 [24].

The various layers can be grouped; two of the hardfacing types include coarse WC, manufactured using an interspersing process, like in [25], four included small WC, whereby two series are produced with filled wire (FW), one is processed with plasma transferred arc (PTA) technology, and one is processed with laser cladding (LC). Two reference series are without WC, produced with solid wire (SW) and filled wire (FW). Figures 1(b)–1(d) depict different analysed series with included WC and Table 2 provides an overview.

To achieve an insight into the base chemical composition of the supported test series, a scanning electron microscope (SEM), type CARL ZEISS EVO MA15, is utilized with an energy dispersive X-ray spectroscopy with an acceleration voltage of 15 kV (EDX) from Oxford Instruments. Cuts through the specimen allow Vickers hardness measurements from the top of the layer down to the base material. The applied force amounted 5 kg (HV5). The machine used is a ZWICK ZHU2.5.

TABLE 1: Chemical composition of mild steel S355J2 in weight percent [DIN EN 10025-2] [24].

Base Material	C	Si	Mn	P	S	Cu	Others	Fe
S355J2 [24]	0.24	0.55	1.60	0.035	0.025	0.55	0.24	Balance

TABLE 2: Overview of test series.

Series	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Technology	SW	FW	FW	FW	PTA	LC	SW	SW
Add	None	None	Fine WC	Fine WC	Fine WC	Fine WC	Coarse WC	Coarse WC

FIGURE 1: Specimen geometry and difference of the added WC: (b) small distribution with FW (No. 3), (c) fine distribution with PTA (No. 5), and (d) coarse distribution with interspersing technology (No. 7).

2.2. Wear Test. The self-designed and utilized test rig is based on the standardized ASTM G65 and G105 testing equipment. Abrasion is encompassed with a rotating wheel, where the test specimen is pressed against with defined load of 12 kg

FIGURE 2: Test setup and sample geometry.

of mass based on results of selected pretests. Between the sample and the 40 mm wide wheel, a nozzle is installed to feed abrasive material in the friction zone (Figure 2). The rotational speed is kept constant with 300 rpm and the test procedure is separated in two steps. After initial weighting in the first step the weight is measured after 3000 rounds of rotation and after a second repositioning in the test rig until 6000 rounds are reached. The second step is defined, because of different initial surfaces as a result of the welding process. For evaluating the scratching resistance, the volume loss in between and after the two steps is defined as measurement criterion. Therefore, the weight is measured with a weighing machine of Type WLC/3/A2/C/2 from *Radwag Waagen*, divided through the density of steel (see (1)). The abrasive material is alumina WSK F46 in a sieve size between 300 and 425 microns, which is used because of its sharpness, hardness, and better availability than silica sand.

$$\Delta V [\text{mm}^3] = \frac{\Delta m [g]}{\rho_{\text{Steel}} [g/\text{mm}^3]}. \quad (1)$$

The tank provides 500 g per minute in between sample and rotating wheel. For each series 5 kg of sand is needed and refreshed before each series to ensure comparable testing conditions. The constructive divergences from the standard test configuration were conducted because of the comparably enhanced specimen geometry, which is also utilized for fatigue tests under four point bending; see [8, 26]. Every test series includes three to four specimens. Two different testing configurations are envisaged. All specimens are tested

TABLE 3: Results from EDX analysis in weight percent with an acceleration voltage of 15 kV.

		Chemical composition in weight-%								
	Area	Fe	Ni	Cr	Si	V	C	Co	W	Others
No. 1	Matrix	89.66		5.72	2.05		2.57			
	Hard phase									
No. 2	Matrix	85.56		5.62	0.95	0.67			2.58	4.62
	Hard phase									
No. 3	Matrix	6.4	82.5				6.3		4.8	
	Hard phase						9.5		90.5	
No. 4	Matrix	77.2					17.4		5.4	
	Hard phase						43.7		56.3	
No. 5	Matrix	5.5	76.4		4.61		4.44		9.05	
	Hard phase						6.98		93.02	
No. 6	Matrix		81.85		3.02				15.13	
	Hart phase						4.21		95.79	
No. 7	Matrix	60.5					2.8		36.7	
	Hard phase						4.7	18.2	77.1	
No. 8	Matrix	82.4					3.4		14.2	
	Hard phase	5.5					5.9	5.8	82.8	

TABLE 4: Overview of Vickers HV5 hardness test results.

Series	1	2	3	4	5	6	7	8
Mean	625.0	725.7	516.2	785.8	910.3	876.4	938.8	837.5
STD	59.7	19.3	158.5	86.3	224.9	229.1	321.8	227.1

in the first configuration with adopted, hardened steel wheel as rotating counterpart. The samples without coarse WC are tested with the rubber wheel. Therefore, a wear resistant rubber with a hardness of 60 ± 5 Shore-A is applied. Samples with coarse WC cannot be tested in the rubber configuration, because the sharpness of the tungsten grain leads to a “cutting” effect on the comparatively softer rotating body, leading to an unfeasible testing condition.

3. Results and Discussion

3.1. Material Characterization of Tested Specimen. The results of the EDX analysis of each testing series are shown in Table 3. Every series is differed in the matrix and the composition in case of an analysis including WC.

The alloys of series Nos. 1, 2, 4, 7, and 8 are based on iron. Comparing the matrix of series No. 1 and No. 2 it is recognizable that in series No. 2 tungsten is additionally included. Nickel alloys are analysed in series Nos. 3, 5, and 6, those series with fine WC (Figures 3(a) and 3(b)); fine WC are also added to the iron based series No. 4. The matrixes of the hardfacing layer, which include coarse WC (Nos. 7-8), are on iron base. An overview of the results by the EDX analysis is provided in Table 3, and SEM photographs from the alloys are illustrated in Figures 3(a)–3(h). Comparing the layers with added coarse tungsten carbide (Nos. 7-8), differences are recognizable regarding the distribution of the particles within the matrix. While series No. 7 reveals a comparatively tight arrangement of WC (cf. Figures 1(d) and 3(g)), series No. 8 is quite slightly represented (Figure 3(h)).

A comparison of the evaluated Vicker HV5 hardness condition (applied test load of 5 kg) of the investigated test series is depicted in Figure 4. Some of the specimens are delivered with a different height of hardfacing layer. Hence, the height of the layer is normalized by the actual layer thickness. The test series which are conducted with solid and filled wire show, except series No. 3, quite a homogeneous hardness distribution over the thickness. Test series three exhibits one peak with a hardness of about 800 HV5. This value can be explained by the included small tungsten carbides. The Ni-base of test series No. 3 is softer than the test series with iron balance (No. 1, No. 2), which show approximately the same hardness over layer thickness between 600 and 725 HV5. The other investigated series show an inhomogeneous hardness distribution over the height of the hardfacing layer (Figure 4(b)). This kind of “zigzag” distribution is caused by the high content of tungsten carbides, whereby a local increase of hardness over a value of 1000 HV5 is measured for the WC particles. Table 4 summarizes the mean hardness and standard deviation of the different coatings over the layer thickness.

3.2. Wear Mechanisms. Due to the use of varying FWT configurations, different wear mechanisms occur between the friction wheel and test sample. Focusing on the alloys without WC and fine WC, which are tested with steel and rubber wheel, different surface structures are illustrated.

The combination of the hardened steel wheel and the hardfacing layer acts as a kind of mill. The alumina sand is rotating in between the counterparts (Figure 5(a)), whereat it

FIGURE 3: SEM images from hard phase including tested layers.

FIGURE 4: Vickers HV5 hardness over normalized thickness of the hardfacing layer from test series 1–5 (a) and series 6–10 (b).

FIGURE 5: Explanation of the differences of the two types FWT configuration and friction surfaces generated with steel and rubber wheel as counterpart.

continuously crushes to smaller parts (Figure 6(b)), leading to a gritty and matte surface on the specimen (Figure 5(b)) [19]. Because of the ongoing breaking process of the abrasives and the shattered wear surface it cannot be excluded that micro impacts shatter the specimen surface as well. Scans in real colour visualization show the gritty wear area if a hardened steel wheel is used, independent if fine tungsten carbides are included. Cross-sectional cuts through the worn area depict the shattered surface caused by the rolling and cracking abrasives between rotating steel wheel and specimen (Figure 7).

On the contrary, with the rubber wheel the relative sharp sand exhibits the opportunity to be embedded in the soft

material and acts in combination as a kind of cutting tool (Figure 5(a)), also mentioned in [27]. This kind of test represents a pure abrasive load [9]. The undefined chipping geometry of the alumina leads to continuing microcuts on the surface, represented by ploughs on the specimen. The surface after testing with rubber wheel is mostly wavy; after an initiating microcut, the ongoing ploughing process leads to a corrugated, smoothed, and shiny surface (Figure 7). If fine WC are included, in rubber wheel configuration the particles are obviously laid open on the worn surface. A low quantity of pulled-out fine particles is visible. Grinding along the hardfacing layer leads, besides crushing of the abrasives, further to dulling of the particles (Figure 6(c)).

FIGURE 6: Light microscope pictures of new (a) and worn sand after a series with steel wheel (b) and rubber wheel (c).

FIGURE 7: Real colour surface scans and cross section microscopy images of three series, tested with steel and rubber wheel, show the varying roughness caused by the different wear mechanism.

Interspersed coarse carbides (in Nos. 7-8), which are partly well embedded in the steel matrix, are flat abraded by the steel wheel and the moving abrasives. In front of the fixed carbide, increased material loss is apparent and behind the particle material loss is decreasing. Progressing abrasive wear leads to a reduction of the surrounded matrix and the adhesive effect decreases towards the ground material, resulting in the fact that tungsten particles are pulled out and holes occur. The mentioned wear mechanisms are displayed by a 3D surface scan and a real colour surface photograph in Figure 8.

3.3. Wear Test Results. Contrary results are investigated by the wear tests with variation of steel and rubber wheel by means of same configuration of mass load, abrasives, feed rate of abrasives, sliding speed, and sliding distance (Figures 9(a) and 9(b) and 10(a) and 10(b)).

Generally it can be stated that the material is more abrasively loaded with the rubber wheel configuration, whereat an increased volume loss is detected. The utmost resistance

FIGURE 8: 3D surface scan of a worn hardfacing layer with included coarse tungsten carbide (>1 mm).

against abrasive wear with adopted steel friction wheel is reached with alloys No. 7 and No. 8 with an inclusion of coarse WC up to 2 mm in size. Test series No. 7 demonstrates with 44.6 mm^3 volume loss the lowest wear followed from series No. 8 with 106.2 mm^3 . No. 1 (SW) and No. 2 (FW) are showing the second highest resistance against wear (332.8 and 321.7 mm^3 of volume loss) within the configuration of the steel friction wheel and 6000 rounds of rotation. Materials Nos. 3, 4, 5, and 6 exhibit a relative high material removal despite an inclusion of small WC utilizing the steel friction wheel. A reason for the lower wear resistance of layers with included small WC could be the potential impacts or shocks, because of the rotation of the abrasives in between the friction wheel and the specimen.

A contrary result is observed by the test with rubber wheel. Where test series No. 1 and No. 2 exhibited the lowest volume loss with steel friction wheel, the two series are demonstrating the highest material loss from the tested series in rubber wheel configuration. The most resistant series in this configuration are the alloys with included small WC. All of these show a minor mean material loss less than 400 mm^3 after 6000 rotations of the rubber wheel, whereby the PTA-alloy manifests the highest resistance against this type of wear

FIGURE 9: Volume loss of the tested series after 6000 rotations of the friction wheel made from steel (a) and a rubber wheel (b).

FIGURE 10: Comparison of the mean loss of volume with steel friction wheel (a) and rubber friction wheel (b).

with about 200 mm^3 material loss. A similar wear behaviour of alloys with included small WC is shown in [9] where a high resistance against pure abrasive loading with a rubber based FWT is recognized, but on the contrary they have low resistance if the load changes to high impact and the small carbides are removed from the alloy. In Figures 10(a) and 10(b), the volumes loss over the sliding distance of the steel and the rubber wheel is displayed. It is recognizable that the volume reduction slightly decreases from 3000 to 6000 rotations after repositioning in the test rig. This can be explained because of the increase of friction surface after a run-in period, followed by decreasing contact pressure. Table 5 summarizes the mean values and the STDs of the two configurations in the FWT.

4. Conclusions

This work investigates the wear behaviour of different hard-facing layers with and without tungsten carbides (WC) under steel and rubber friction wheel compositions to achieve different wear mechanisms. In total, the abrasive wear resistance of eight different hardfacing layers is evaluated. Alloys with coarse WC reveal the highest wear resistance under friction steel wheel abrasion with a maximum volume loss of about 100 mm^3 after 6000 revolutions. In comparison, a mean volume loss of about 350 mm^3 is observed in case of the test series without WC and up to about 800 mm^3 in case of the specimens including comparably fine WC within the matrix if the same steel wheel configuration is applied during

TABLE 5: Results from tribometry, in mm³ volume loss.

Series	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Base	Fe	Fe	Ni	Fe	Ni	Ni	Fe	Fe
Volume loss after 3000 rotations (Steel-Wheel)	mm ³							
Mean	151.3	122.6	304.1	543.0	426.8	412.4	20.7	57.3
STD	80.3	44.5	162.2	210.5	186.9	226.8	9.6	27.8
Volume loss after 6000 rotations (Steel-Wheel)	mm ³							
Mean	332.8	321.7	514.3	785.0	624.2	614.6	44.6	106.2
STD	201.5	77.9	231.6	277.1	173.7	266.0	13.8	44.7
Volume loss after 3000 rotations (Rubber-Wheel)	mm ³							
Mean	853.5	549.9	208.1	263.3	116.8	133.8	Not tested	
STD	193.1	122.4	7.4	40.5	35.1	62.8		
Volume loss after 6000 rotations (Rubber-Wheel)	mm ³							
Mean	1479.8	1057.3	386.4	422.5	199.6	310.0	Not tested	
STD	363.5	226.4	46.9	80.6	49.5	79.6		

the tests. Focusing on rubber wheel testing, coarse WC induce a damage of the soft wheel; hence, an experimental investigation is not feasible. However, due to the differing wear mechanism compared to the steel wheel, the specimens including fine WC within the matrix demonstrate a mean volume loss up to 400 mm³, and the samples without WC demonstrate a mean value of about 1200 mm³. In summary, the alloys with included coarse tungsten carbides reveal a high potential for the usage under abrasive load. Tests with steel friction wheel show that a lower amount of WC within the hardfacing layer does not significantly reduce the wear resistance compared to a higher amount of WC. As every WC within the hardfacing layer may act as kind of defect or imperfection, which can majorly reduce the fatigue strength under cyclic loading [8], it is of utmost importance to obtain an adequate amount and distribution of coarse WC particles. In conclusion, the optimization of the wear and fatigue performance of hard-faced coatings including WC strongly depends on a compromise between the resulting wear and fatigue strength. Especially in case of components, which are exposed to both abrasive wear and mechanical loadings, special attention needs to be laid on the effect of such layers on the fatigue and wear resistance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The authors are pleased to participate in further discussion and to provide further information where possible.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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