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To cite this article: V Wesling *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **480** 012030

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Hydroabrasive wear on high carbide infiltration materials

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Abstract. Hydroabrasive wear, a subtype of erosion, is a frequently occurring wear phenomenon. The type and extent of the damage depend on a large number of material characteristics and process conditions. In this research project, high carbide infiltration materials used in deep drilling technology were tested for their resistance to this erosive stress. The flow angle was varied stepwise between 15° and 90°. The resulting damage was quantified by volumetric material loss. Furthermore, the wear mechanisms were determined by surface examinations using SEM. The result of this project is an improved understanding of the effect of different process and material parameters on the tribological system. An improved knowledge of the critical quantities will allow the estimation of the effects of changes in tribological systems under erosive load and finally a reduction of material removal in process plants by adaptation of single variables.

1. Introduction

Wear is a complex system property that is influenced by many parameters. Erosion wear, caused by a particle-laden flow, is a frequently occurring wear phenomenon. A subtype of erosion is hydroabrasion, in which the particles are carried in a water flow. The damaging effect is caused by the impacting particles on the surface, whereby the damaging effect is decisively dependent on the angle of impact and the properties of the sample material. Hydroabrasion occurs in a large number of technical applications, for example in pipeline construction, hydropower turbines or in deep drilling technology. The type and extent of the damaging effect depend on a large number of material characteristics and process conditions.

One of the most important parameters of erosive wear is the angle at which the particle-laden flow hits the surface of the material. The impulse acting on impact can be divided into two components, one perpendicular and one parallel to the surface. The different wear mechanisms act differently depending on the amounts of the respective components. At a low angle of impact, and thus a very high parallel impulse component, the affected material is mainly removed by micro-chipping or microploughing. At very high angles of impact, the vertical impulse component predominates, whereby the surface is removed by fatigue wear. The result is subsurface cracking at the location of maximum hertzian pressure parallel to the surface that leads to plate-shaped breakouts. Between these extreme cases, the mechanisms mentioned above have a superimposing effect and micro-chipping and surface breakdown can be observed at the same time. In addition, ductile materials are abraded more quickly by micro-chipping, whereas hard and brittle materials tend to be abraded by breaking or shattering [1].



2. Experimental and materials

2.1. Materials

Within the frame of these investigations, two rolled steel materials and four infiltration materials used in deep drilling technology with a high carbide content were investigated. The steel materials are S355 and the highly wear-resistant steel Creusabro 8000 [2]. Its structure consists of martensite, bainite and retained austenite, which promises an increased wear resistance.

The infiltration materials, Materials 01 - 04, are pseudo alloys of a high copper content binder with embedded tungsten carbides. The resistance to abrasion is produced by the carbides, while the ductile matrix has to withstand shock loads. In the production of these materials [3], a powder mixture of the carbides is given in a graphite form. The remaining matrix material, the low-melting solder, is placed on top. When this arrangement is heated in an inert gas atmosphere, the liquid solder infiltrates into the capillaries of the fixed bed, where it bonds with the powder contained therein. By the superposition of gravity, adhesion and cohesion of the liquid metal, low pore densities can be achieved. In the case of these infiltration materials, a binder of copper, approximately 30 wt.% nickel, 22 wt.% manganese and a small percentage of zinc was used.

2.2. Hydroabrasive wear testing

The testing is carried out in a test rig (Figure 1) specially developed by the Institute of Welding and Machining (ISAF). This test bench enables the testing of components and material samples at different flow angles. The abrasive material is introduced into the highly accelerated water jet in front of the jet nozzle, which accelerates it in the direction of the sample. The tests were conducted with the set of parameters listed in Table 1.

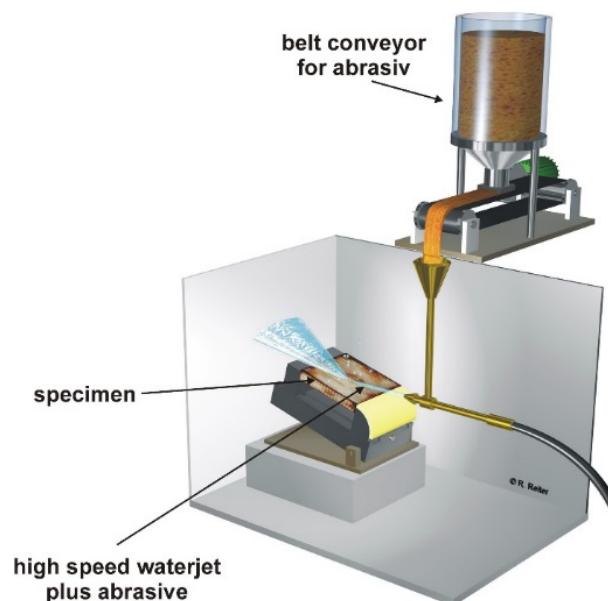


Figure 1. Principle of the test rig.

Table 1. Testing parameters.

Testing parameter	Variations
Abrasive	Broken quartz sands
Particle sizes	0 μm – 1000 μm
Mass flow	150 g/min
Angle of impingement	15°, 30°, 45°, 60°, 75°, 90°
Flow velocity	95 m/s

2.3. Metallographic examination methods

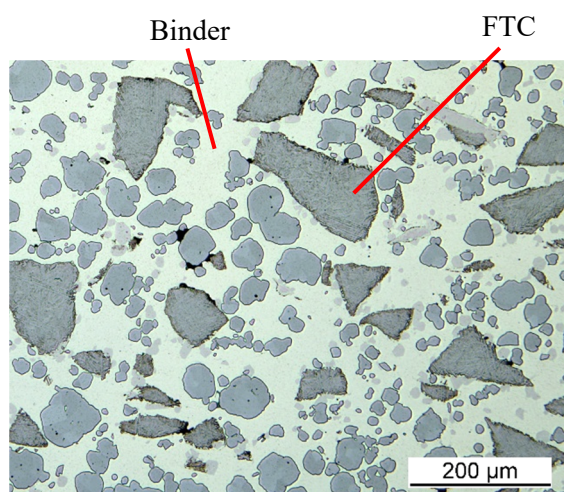
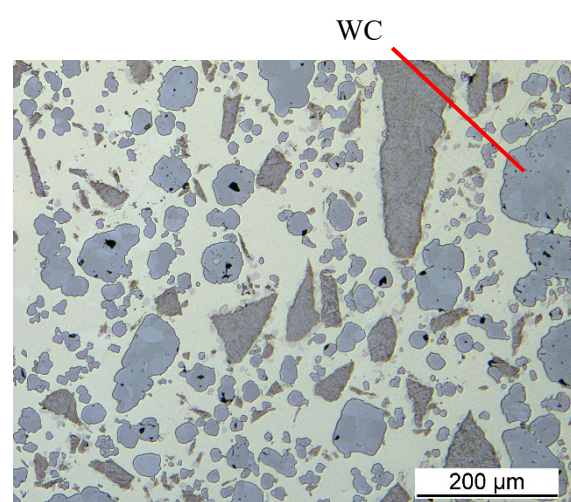
Specimens of the infiltration materials were embedded in a warm embedding agent, grinded and polished in a Mecatech polishing machine with diamond abrasive past (6 μm , 3 μm and 1 μm) and finally polished with OP-S suspension (0,04 μm). The light microscopic examinations were conducted with a Leica DM6 M. Further information about the material behaviour is provided by the investigations of the surfaces in the SEM (CamScan Serie 4, acceleration voltage 10 kV, working distance 35 mm). The specimens were cleaned after the experiment and vapor-plated with gold to prevent charging of the embedded quartz particles.

3. Results and discussion

In this chapter, the results of the tests of S355, Creusabro 8000, and Material 01 - 04 are presented with angles of impingement of 30°, 60° and 90°. Testing with these angles allows an assessment of the resistance of the materials to the different wear mechanisms. In order to ensure the comparability of the results, the volumetric material loss is considered.

3.1. Microstructural characterization of the infiltration material

Material 01 (Figure 2) and Material 02 (Figure 3) contain block-shaped fused tungsten carbide (FTC) and tungsten monocarbide (WC). These materials differentiate in the size of the FTC and WC, and in the mixing ratio of the two carbide types. Material 02 has a higher proportion of WC. Material 01 has 35% WC and 25% FTC, while Material 02 has 40% WC and 15% FTC.

**Figure 2.** Material 01.**Figure 3.** Material 02.

Due to its inner structure, which consists of fine WC and W₂C lamellas [4], the FTC has a higher material hardness and fracture toughness than the WC. The reinforcement in Material 03 (Figure 4) only consists of block-shaped FTC, with a degree of filling of 45%.

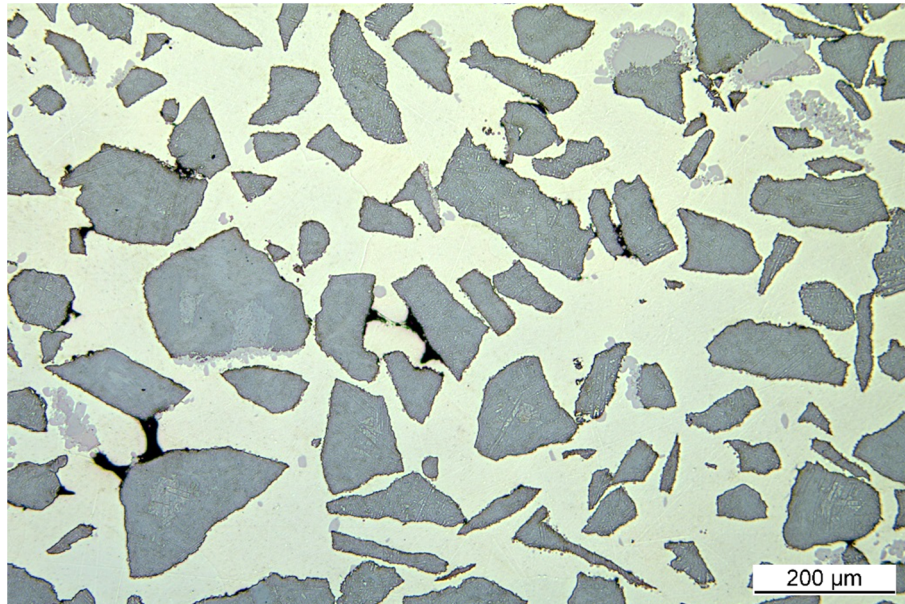


Figure 4. Material 03.

The Material 04 (Figure 5) also uses a multimodal reinforcement consisting of FTC and WC. There are fine-grained WCs in the binder between the large FTCs. The large FTCs should withstand the abrasive attack of the larger particles, while the fine-grained WCs should prevent the binder from being washed out. The reinforcement contains 25% WC and 35% FTC.

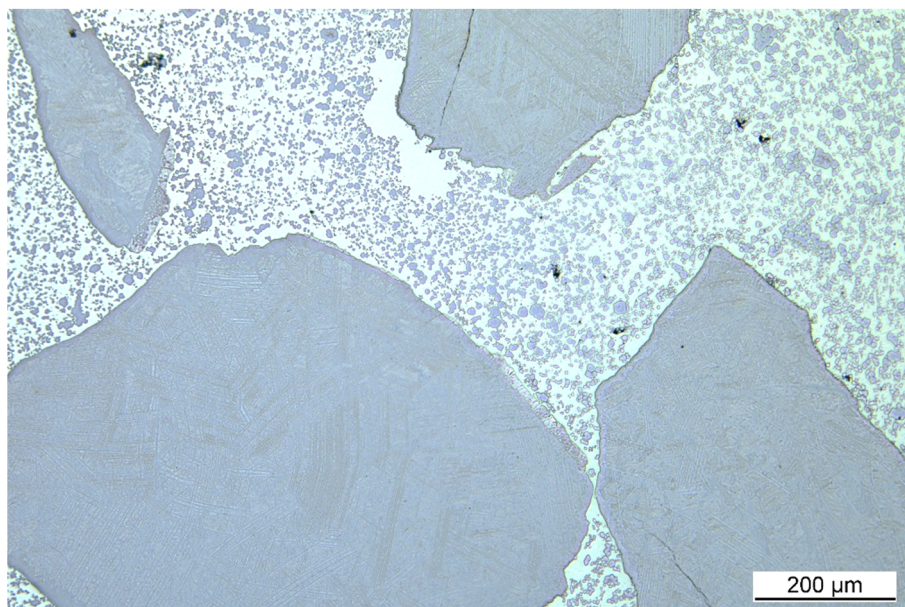


Figure 5. Material 04.

3.2. Angle of impingement 30°

At this angle of impingement (Figure 6), Material 03 and 04 have the lowest volumetric loss. The highest material loss can be found at S355 and Material 02. The graphs of the materials Creusabro 8000 and Material 01 are close to each other.

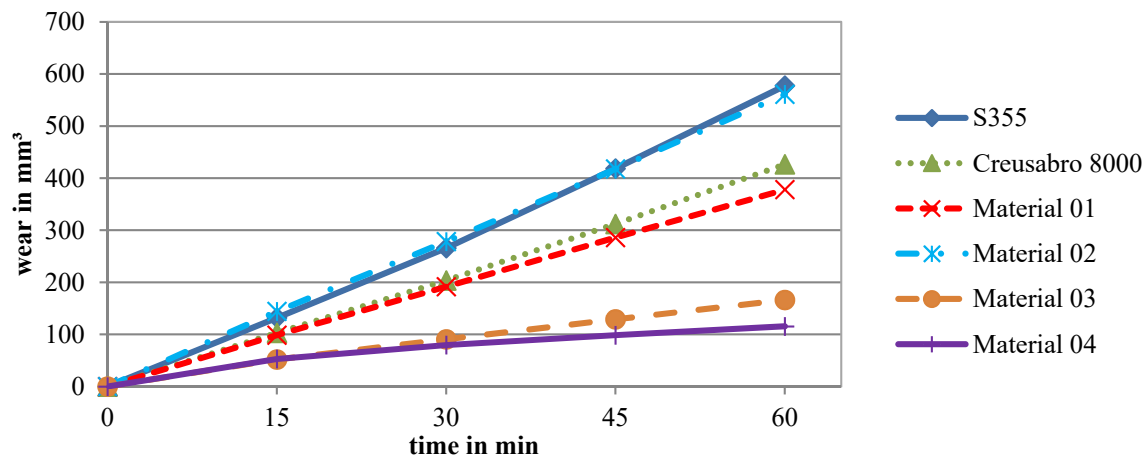


Figure 6. Volumetric wear, angle of impingement 30°.

3.3. Angle of impingement 60°

As the angle of impingement increases (Figure 7), the wear of infiltration materials increases. Material 02 has such a high wear rate that the test had to be stopped after 45 min due to the failure of the specimens. The volumetric wear of Material 04 is also the lowest here. The material loss of Material 03 is the second lowest, whereby the difference to the wear of Creusabro 8000 is considerably smaller than at the angle of impingement of 30°.

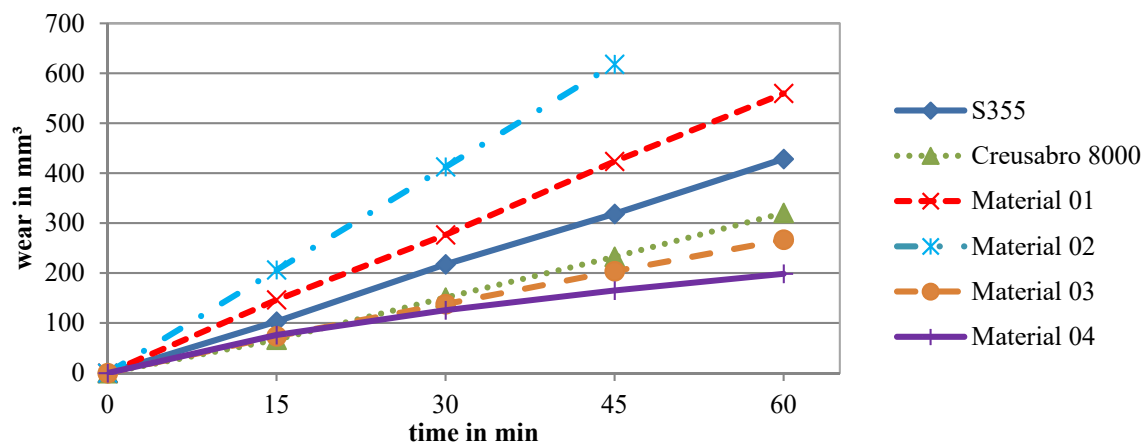


Figure 7. Volumetric wear, angle of impingement 60°.

3.4. Angle of impingement 90°

In the case of impact wear (Figure 8), the materials S355, Creusabro 8000 and Material 03 are close to each other. Material 02 shows the worst wear behaviour in this case. The lowest material loss was determined here at Material 04. Additionally, the Material 04 shows a higher wear rate in the first testing interval. The wear rate drops from $4.3 \text{ mm}^3 \text{ min}^{-1}$ in the first interval to $2.0 \text{ mm}^3 \text{ min}^{-1}$ in the last interval.

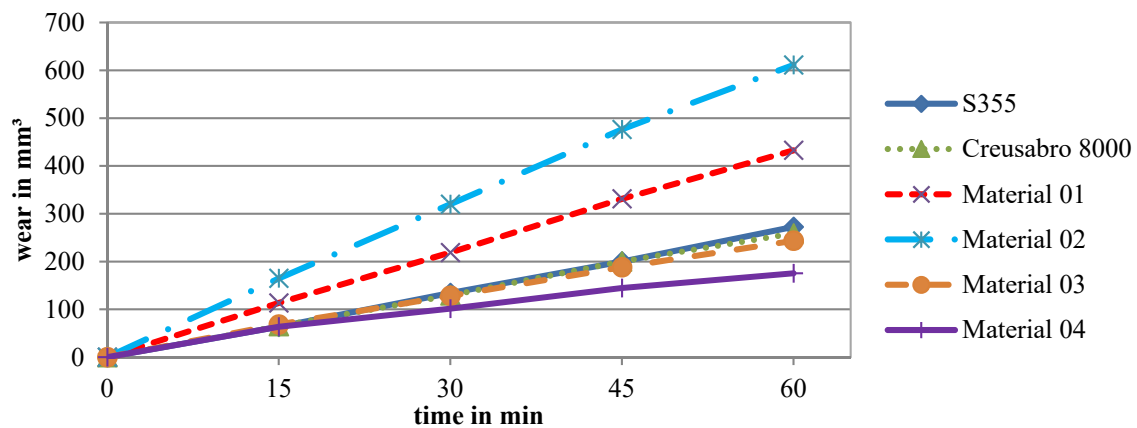


Figure 8. Volumetric wear, angle of impingement 90°.

3.5. Surface characterization after abrasive wear

The surface of a sample made of S355 (Figure 9) shows clear traces of the micro-chipping after the wear test. Occasional deformations of the surface and embedded quartz particles can be observed.

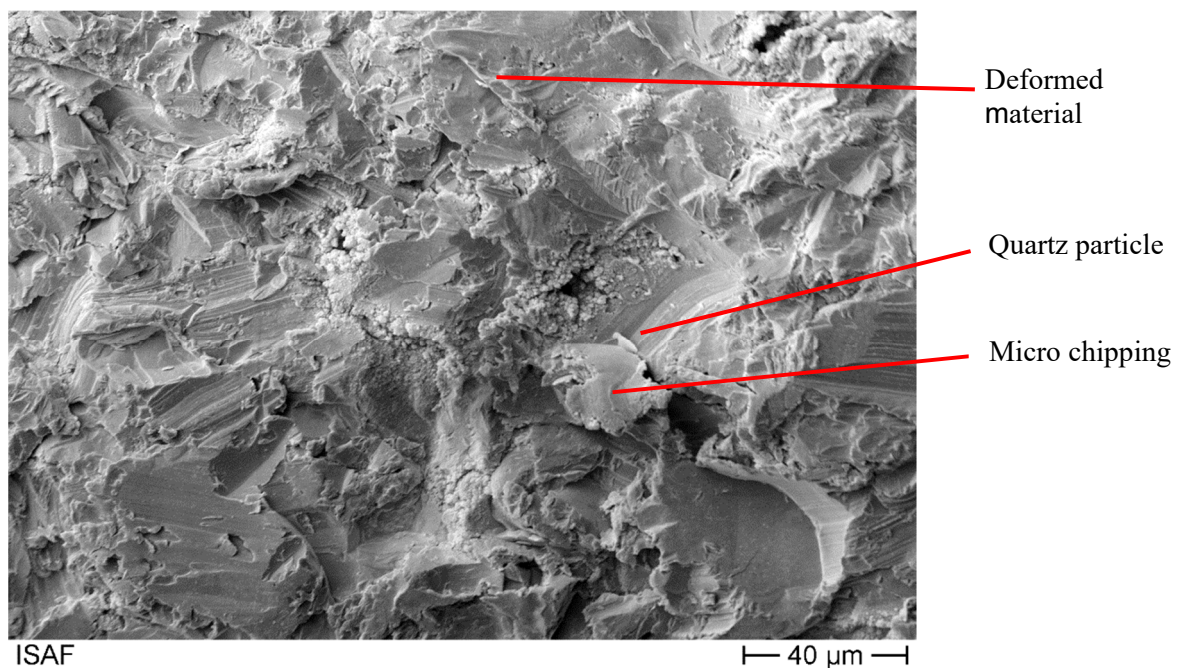


Figure 9. S355, SEM, angle of impingement 60°.

The examination of Material 01 (Figure 10) shows more signs of reshaping and shattering, but also isolated traces of micro-chipping. Furthermore, glass-fractured edges, surfaces and even splinters can be detected. This mainly concerns the brittle WC, which breaks very quickly on impact of quartz particles. The larger hard phases at the left edge of the image are large FTC particles. These have no visible cracks.

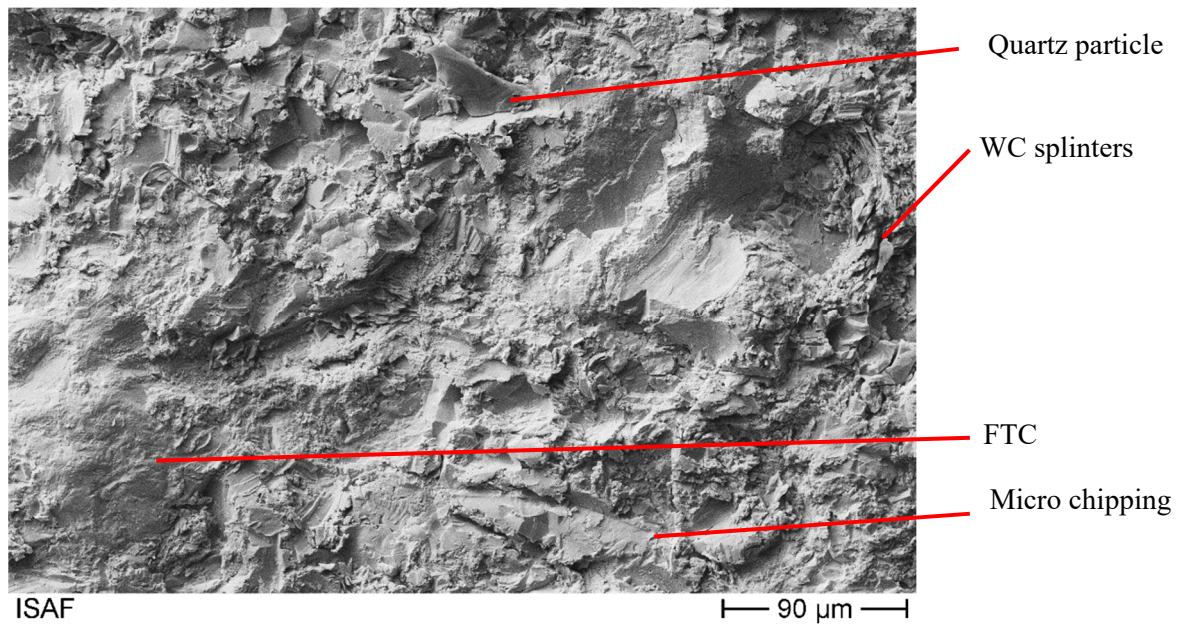


Figure 10. Material 01, SEM, angle of impingement 60°.

3.6. Comparison of wear rates

Since not all specimen showed linear wear behaviour over time and premature specimen failure occurred, the wear rates are considered in the following. These wear rates were calculated over the last intervals of the respective samples, which have a comparable gradient. The materials S355 and Creusabro 8000 show a significantly higher wear rate at a low angle of impingement. It can therefore be deduced that these materials are more susceptible to micro-chipping and ploughing, but can withstand surface shattering or deformation well. The high carbide materials have the highest wear rates at a medium angle of impingement. This proves a lower susceptibility to micro-chipping. However, the different behaviour of these materials in the case of pure impact wear indicates different resistance to surface shattering.

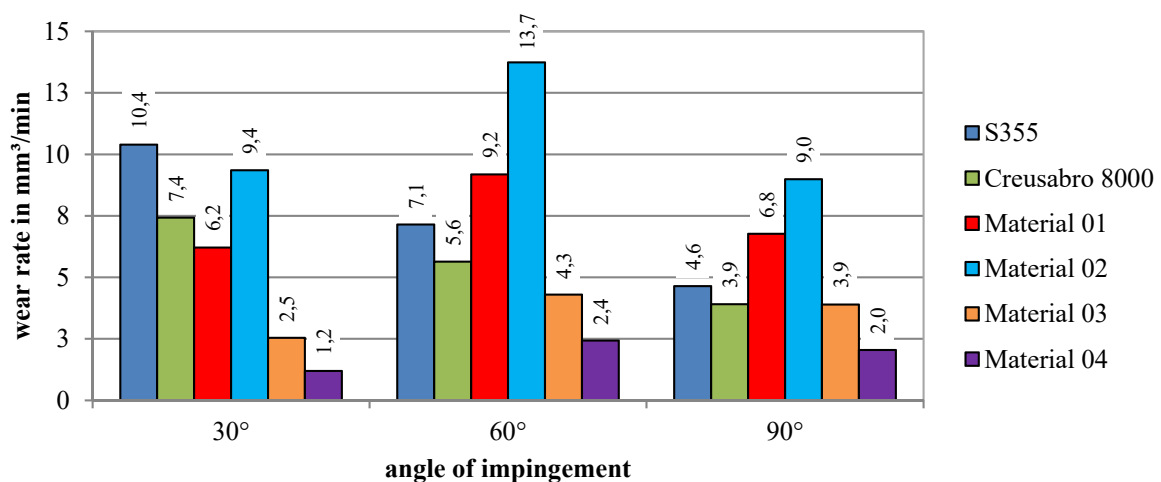


Figure 11. Wear rates at different angles of impingement.

Material 01 and 02 show higher wear rates than Material 03 and 04. This can be explained by the different fracture susceptibility of the carbides. The large WC particles in the materials tend to a brittle

fracture behaviour, while the FTC particles have a significantly higher fracture toughness. Therefore, the WC particles of the materials Material 01 and Material 02 do not offer any relevant resistance to the impacting quartz particles, which means that the binder can be removed more quickly by the erosive stress. On the other hand, the small WC particles in Material 04 protect the binder from being washed out by the small quartz particles in the water jet. Due to the lower particle size, their tendency to break decreases. At the same time, the impacts of the larger quartz particles are absorbed by the FTC particles, which leads to lower wear rates of the Material 03 and Material 04.

Overall, the Material 04 shows the highest resistance at all flow angles.

4. Conclusions

At low angles of impingement, highly carbide-containing infiltration materials such as Material 03 and Material 04 show a higher resistance to hydroabrasive stress than steels such as Creusabro 8000. However, the precondition for this is that sufficiently fracture-resistant hard particles such as FTC are used as reinforcement. When more brittle hard particles such as WC are used, the breakage of the carbides by impacting particles reduces the wear resistance significantly. The exception are fine particles, as in Material 04, which lie between larger carbides, as these do not have to endure high impact loads. Only Material 04 was able to show a significantly lower wear rate than S355 in the high angle of impingement range. In this case, the strengths of the different hard materials were combined in a multimodal reinforcement, which increased the resistance to the predominant wear mechanisms at all investigated angles.

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