THE EDGE EFFECT OF SPECIMENS IN ABRASIVE WEAR TESTING

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ABSTRACT

In abrasive wear testing, the specimen edges may exhibit increased wear rates. To determine the extent of edge wear, a series of tests was conducted with the crushing pin-on-disk device. The test pin was divided into two sections, separating the wear area into inner and outer pin areas. The tests were conducted with granite and quartz rocks of varying size.

The edge effect was determined as the difference of the mass loss of a specimen comprising both the inner and outer parts and the mass loss of the inner part alone scaled to the size of the combined pin area, representing a specimen without edge wear. The tests showed increased edge effect with larger rocks, depending on the mechanical strength of the abrasive material. When using only large rocks with good mechanical strength, the edge effect could be as high as 50 % of the total specimen mass loss, whereas with more fragile rocks of smaller size, the edge effect was close to 0 %.

Keywords: abrasive wear, gravel, crushing, edge wear.
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INTRODUCTION

In abrasive wear, the shape of the specimen and the size of the wearing surface are important to the outcome of the wear test. This paper concentrates on the edge wear of the specimen in the crushing pin-on-disk test, where loose gravel from natural rock is used as the abrasive media [1]. Other wear test equipment that may show a similar edge wear effect are, for example, the impeller-in-drum apparatus [2] and the pin abrasion test according to ASTM G-132 standard. Richardson [3] discusses the pin abrasion test where the test material must deform in order to plastically work harden and where the leading edge may not become as fully worked as the rest of the pin. The inability of the material to work harden, in addition to the inherent weakness of the edges, may result in the rounding-off of the specimen. Richardson expects that the edge losses would be less with decreasing abrasive size and harder test material.

In a wear test the total wearing area may contain edges of specimen blocks with flat surfaces, or gaps between two specimens next to each other, as for example in the ASTM G-81 jaw crusher test. These discontinuations in the wear surface or the wearing body can always be expected to have some effect on the wear test results during abrasive wear. The strength of this effect is influenced by several factors, e.g., the size of the discontinuation compared to the size of the abrasive, and the direction of wear with respect to the orientation of the discontinuation.

TEST EQUIPMENT AND TEST SETUP

The tests were accomplished with a crushing pin-on-disk wear tester. During the test a pin of 37 mm in diameter is worn by initially 10 mm – 2 mm natural rock gravel that is loose between the pin and the rotating disk equipped with confining walls. The pin is repeatedly brought into contact with the gravel by a pneumatic piston with a preset normal force of 200 N. The pin is compressed for 5 seconds on the gravel bed, followed by 2.5 seconds when the pin is lifted up from the gravel bed. This cyclic motion is to guarantee that there is always gravel between the pin and the disk. The downward movement of the pin is restricted to about 1 mm from the disk to avoid direct contact between the pin and the disk, which is rotating at 28 rpm. In one test a 500 g batch of gravel is comminuted to smaller size. The standard rock size distribution in the beginning of the test is 50 g of 10mm – 8 mm, 150 g of 8 mm – 6,3 mm, 250 g of 6,3 mm – 4 mm, and 50 g of 4 mm – 2 mm. The test is normally continued for 30 minutes, and the pin mass loss is weighted in 15 minute intervals. The test setup is presented schematically in Figure 1.

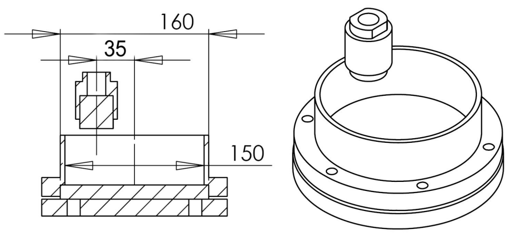

Figure 1. Schematic of the crushing pin-on-disk test device.

<u>Edge wear tests with the crushing pin-on-disk</u>

Figure 2 shows a cross-section of the crushing pin-on-disk test geometry, when an abrasive larger than the gap between the pin and the disk is coming into contact with the pin specimen (A) and leaving the pin (B). In the case A, the abrasive tries to lift the pin upwards against the 200 N normal force supplied by the pneumatic piston when trying to fit between the pin and the rotating disk. This causes the specimen edge to be scratched presumably at a force higher than the applied normal force. In the B case, the abrasive trapped under the pin is leaving the specimen surface, and the normal force F_n pushes the specimen edge along with the abrasive, causing again edge wear.

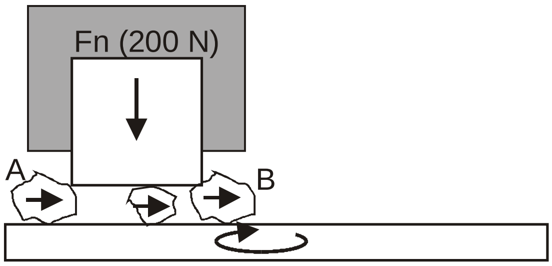

Figure 2. Illustration of the interaction between large rocks and the specimen edges in the crushing pin-on-disk test. The specimen holder is colored dark grey.

To separate the edge wear from the flat surface wear, special test specimens were prepared from S355 structural steel with a hardness of 210 HV5 and from Ralloy® WR6 tool steel with a hardness of 740 HV5. The measured densities of S355 and WR6 were 7.81 g/cm^3 and 7.34 g/cm^3, respectively. WR6 contains rounded vanadium carbides, which together with a tempered martensitic matrix result in good wear resistance. The specimen, shown in Figure 3, is composed of a hollow outer part (pin) with a wall thickness of 3.5 mm, and a solid inner pin of 30 mm in diameter. The parts made of the same test material are joined together with a tight fitting. Before the test, the assembled specimen pair is ground and polished to produce an even surface without height steps between the two parts. A threaded hole for a screw was made to the outer pin bottom so that the inner pin height could be adjusted to a desirable level and to help its removal after the test. With this configuration, both pins could be weighted separately, yielding material wear with minimum edge effect from the discontinuity between the inner and outer pins.

The tests were conducted with Finnish granite and quartzite gravel. Granite is composed mostly of feldspar (>50%), quartz (>10%) and mica, and it is not as abrasive as quartzite, which is almost fully composed of hard quartz. Mechanically granite is stronger and is not comminuted as rapidly during the test as quartzite. Beste and Jacobson [4] measured the hardness of several minerals of Swedish origin. According to their measurements, the hardness of granite and quartz is 800-900 HV and 1200 HV, respectively.

The wear surfaces of the specimens were examined with Zeiss Ultraplus 4004 scanning electron microscope (SEM) after the tests. The edge rounding was examined from cross-sectional samples of the wear test specimens.

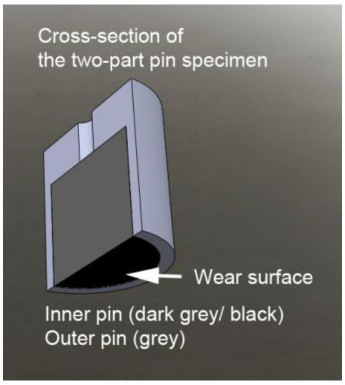

Figure 3. Cross-section of the two-part pin specimen.

RESULTS

All tests were conducted from the beginning to the end with the same inner-outer pin combination to produce extensive wear on the edges of the outer pin. Before actual tests the specimens were worn for 40 minutes to achieve a steady state wear condition. The following test steps were 30 minutes long each. The test sequences with corresponding mass losses are shown in Table 1 for S355 and in Table 2 for WR6.The total mass losses (including both the inner and outer pins) in 280 minute tests were 2.371 g and 0.544 g for S355 and WR6, respectively.

Table 1. Test sequence for S355. The mass loss was measured after each test step.

Test	Abrasive	Test and abrasive size	Mass loss (g) S355 Inner pin	Mass loss (g) S355 Outer pin
1	Granite	Pre-wear	0.18	0.163
2	Granite	Standard	0.214	0.147
3	Granite	10-8 mm	0.068	0.166
4	Granite	6.3-4 mm	0.177	0.131
5	Quartzite	4x 10-8 mm	0.156	0.156
6	Quartzite	Standard	0.131	0.069
7	Granite	Standard	0.107	0.11
8	Granite	Standard	0.103	0.094
9	Granite	Standard	0.11	0.089
Total mass loss (g)			1.246	1.125

The test sequences for S355 and WR6 differ with respect to standard sized granite. For WR6 specimens these test steps are numbers 3-5 and for S355 numbers 7-9. This change in order may have influenced the results, as can be seen when comparing the mass losses in test steps 2 and 7. Tests with abrasive size distributions different from the standard size distribution are indicated in the tables. In the tests with quartzite gravel of 10 mm – 8 mm (steps 5 and 8), the abrasive batch was changed at 7.5 minute intervals. The reason for this was to keep the abrasive size as large as possible. In the standard size distribution tests with quartzite, only one batch of abrasive was used.

Table 2. Test sequence for WR6. The mass loss was measured after each test step.

Test	Abrasive	Test and size	Mass loss (g) WR6 Inner pin	Mass loss (g) WR6 Outer pin
1	Granite	Pre-wear	0.035	0.034
2	Granite	Standard	0.027	0.025
3	Granite	Standard	0.024	0.029
4	Granite	Standard	0.021	0.024
5	Granite	Standard	0.026	0.022
6	Granite	10-8 mm	0.017	0.023
7	Granite	6.3-4 mm	0.02	0.017
8	Quartzite	4x 10-8 mm	0.049	0.055
9	Quartzite	Standard	0.056	0.04
Total mass loss (g)			0.275	0.269

<u>Wear surface and cross-sectional examination</u>

The SEM examination revealed that the S355 wear surface was highly deformed and that a lot of abrasive had adhered to the surface. The highly worn outer edge of the two-part pin specimen is shown in Figure 4, where the SEM specimen is tilted 45° with respect to the wear surface normal. The light grey areas are the metal surface and the dark grey areas abrasive stuck on the surface. Figure 5 is a similar image taken from the WR6 pin outer edge. In this case, the surface has shallower deformation marks and much less adhered abrasive.

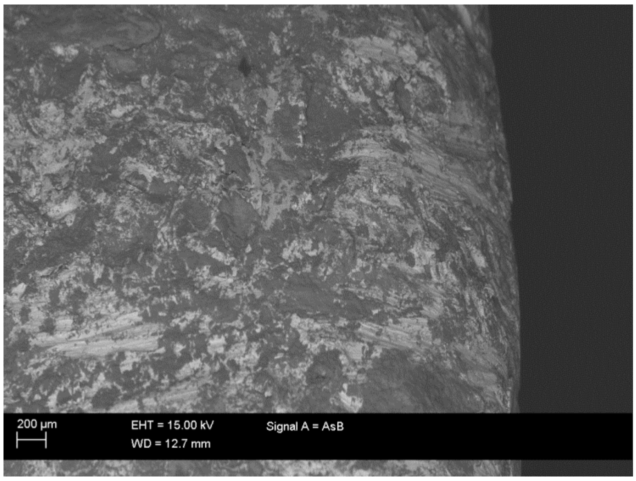

Figure 4. Worn outer edge of the S355 outer pin after the test. Specimen is tilted 45° with respect to the wear surface normal.

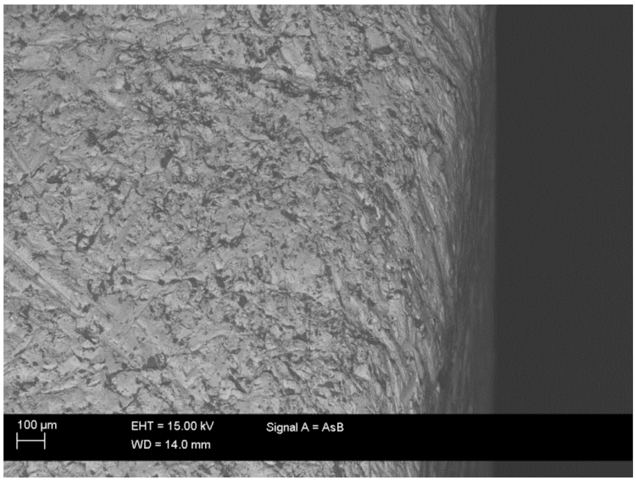

Figure 5. Worn outer edge of the WR6 outer pin after the test. Specimen is tilted 45° with respect to the wear surface normal. Magnification is two times higher than in Figure 4.

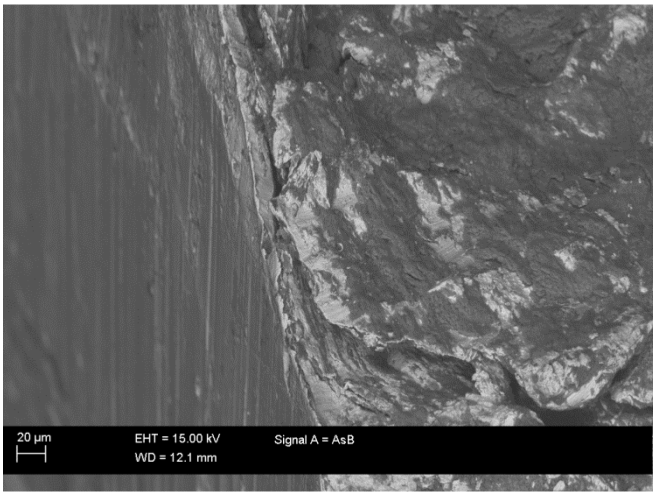

Figure 6. Inner edge of the outer pin of S355 after the test. Specimen is tilted 45° with respect to the wear surface normal. The wear surface is lamellar or flaked close to the edge.

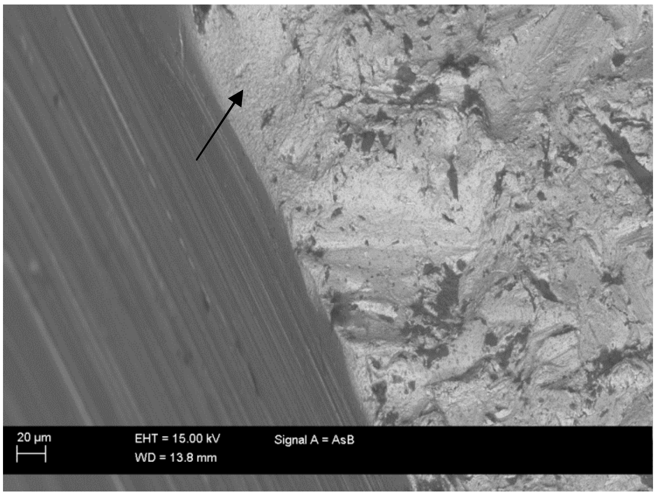

Figure 7. Inner edge of the outer pin of WR6 after the test. Specimen is tilted 45° with respect to the wear surface normal. The arrow points to the marks of fractures close to the edge.

The inner edge of the outer pin is shown in Figures 6 and 7 for S355 and WR6, respectively. There are marks of lamination or flaking on the edge of S355, which is not exceptional for materials where the wear surface deformation is high enough to embed the abrasive in the pin material and to form a layered structure. In the case of WR6, there was a rough fracture surface extending about 100 µm from the inner edge of the pin, as shown in Figure 7. The cross-sections of the outer pins at the beginning and after the wear tests are shown in Figure 8.

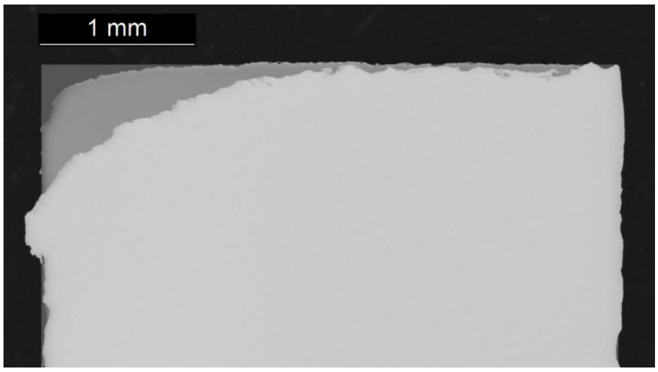

Figure 8. Outer pin cross-sections of both test materials. Dark grey sharp corner is the shape of the pin before the wear test, medium grey is the cross-section of WR6 and light grey the cross-section of S355 after the test.

In the S355 specimen, material is pushed away from the flat wear surface to form a bulge on the side of the pin. The areas of the edges lost during the wear tests, i.e., the grey areas in Figure 8, were measured from four cross-sections taken from the outer pins. The averaged lost areas of WR6 and S355 were 0.161 mm^2 and 0.642 mm^2, respectively. With the known diameter of 37 mm and the measured densities of the materials, the outer pin mass loss due to edge rounding was calculated to be 0.277 g for WR6 and 1.164 g for S355. These are quite close to the weighted total mass losses of the outer pin specimens.

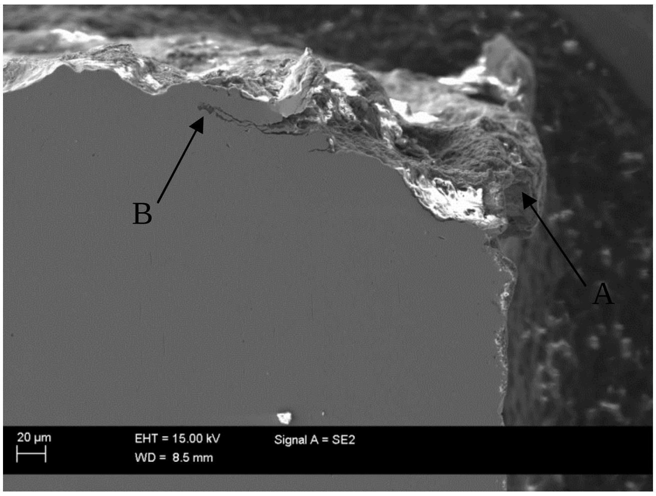

Figure 9. Cross-section of the edge of the S355 inner pin. The edge behind the cross-section protruding from the wear surface (A) and a flake parallel to the wear surface (B) are indicated by the arrows.

The inner pin edges were sharp after the tests for both materials, as shown in Figure 9 for S355. The edge profile, however, varied to some extent in different cross-sections, and for example in Figure 9 a protrusion from the edge can be seen. There is also a 20 µm thick flake pointing towards the edge. The WR6 inner pin edge cross-section with an edge radius of about 20 µm is shown in Figure 10. The edge wear of the inner pins could not to be determined accurately from the cross-sections because of the rather high variations in the edge rounding.

DISCUSSION

The possibility to measure the weight losses of the inner and outer pins separately makes it possible to compare the wear of the material with and without the specimen edge effect. The total flat wearing area of the pin was 1075 mm^2, of which the solid inner pin constituted 707 mm^2 and the hollow outer pin 368 mm^2. As the inner pin showed negligible edge wear, multiplication of the inner pin mass loss by the ratio of the total and inner pin areas, i.e., by 1.52, gives a good approximation to the total mass loss of the two-part pin specimen without the edge effect. The difference between this and the total mass loss measured for both the inner and outer pins gives the mass loss due to the edge wear of the outer pin. In this paper, this difference is called the edge effect.

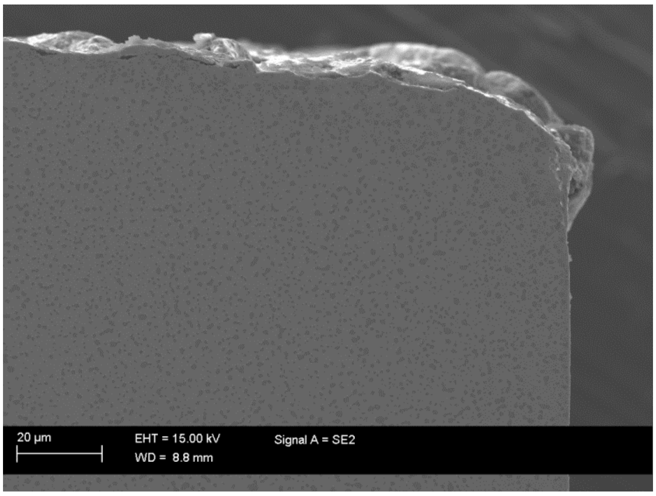

Figure 10. Cross-section of the edge of the WR6 inner pin. The edge radius is about 20 µm.

For better comparison between the materials of varying hardness, the Archard's wear equation [5] can be used:

$$\frac{W}{s} = K\frac{F_N}{H} \rightarrow K' = WH \qquad \text{(Eq. 1)}$$

where W is the volume loss, s the sliding distance, K Archard's wear coefficient, H hardness, and F_N the normal force. In the present case the sliding distance and the normal force are the same for both materials and can therefore be included in the wear coefficient K'. This means that the possible difference in K' between the materials depends on the volume loss and hardness of the material. Materials having a lower coefficient K' show better wear resistance regardless of their hardness. Coefficient K' can be used to compare the wear loss of materials with a large difference in hardness. Figure 11 shows the comparison of coefficient K' between S355 and WR6 at different test steps. The results of the four standard tests have been averaged and the edge effect is included. In all tests WR6 has a lower K'value than S355. If the higher hardness of the wear surface is used instead of bulk hardness, the difference between WR6 and S355 K values should increase, as S355 has much more potential for work hardening than WR6.

The pre-wear values in Figure 11 are multiplied by a factor of 0.75 to compensate for the 40 minute run instead of the standard wear test run of 30 minutes. When comparing the standard wear tests with granite to the pre-wear tests, WR6 results do not show a noticeable difference. The outer pin wear is higher in the S355 pre-wear test, which may be due to the abrasive being able to wear the sharp edge more in the beginning of the test series.

In most of the tests the inner pin wore more than the outer pin. Exceptions to this are the tests conducted with larger rocks that wore the outer pin more than the inner pin. With larger rocks the pin must be pushed upwards for the rock to fit under the pin. The smaller rocks already under the pin lose contact with the wear surface as the pin is lifted, reducing the inner pin wear. Larger size rocks with a narrow size distribution and irregular shape cause fewer rocks to slide between the pin and the disk, possibly reducing the gap between the pin and the disk so that larger rocks cannot anymore fit between them. This behaviour promotes a situation where rocks are pushing against the edge but fewer rocks actually go under the pin, causing less wear to the inner pin but increasing the wear of the outer pin. Comminution of the abrasive also affects wearing of the pin's edge, as rocks of high mechanical strength are not comminuted so effectively but remain larger and promote edge wear.

In the fourth test step with smaller 6.3 mm – 4 mm rocks the size distribution is roughly as narrow as with 10-8 mm rocks. Because of the smaller rock size, more rocks can fit between the pin and the disk at the same time. When comparing the mass losses of this test to the losses obtained with the larger distribution of 10-2 mm, for the outer pin the mass loss is slightly smaller, whereas for the inner pin the mass loss reduction is more notable. The crushing pin-on-disk pin wear is usually highest for the standard size distribution of the abrasives. This can be explained with a preferential variation of rocks trying to fit between the pin and the disk, keeping the gap between the pin and the disk in general larger.

When granite is used as the abrasive media, WR6 shows better K' values than S355. With quartzite the K' value for WR6 is larger than for S355. The hardness of WR6 is not high enough to efficiently protect it from the abrasion caused by the hard quartz phase. On the other hand, S355 is able to deform plastically and therefore quartz particles can easily adhere on its surface. The quartz particles can plough and move material, and the adhered particles behave as obstacles to the abrading quartz. Also the number of abrasive scratches is noticeably increased on the harder WR6 wear surface, while for S355 the change in the wear surface appearance is not as visible.

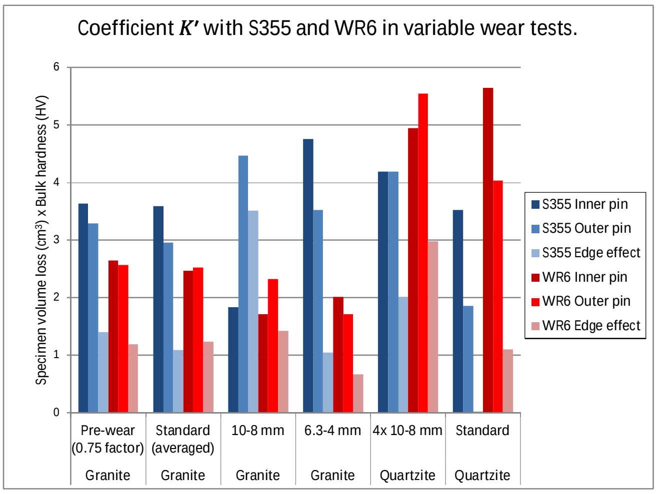

Figure 11. Coefficient K' for S355 and WR6 in different test steps with granite and quartzite.

Edge wear in the crushing pin-on-disk test

The wear surface analysis shows a difference in the wear behaviour of the inner edges of the two steels, depending on their hardness and ductility. When an abrasive makes a scratch over a narrow gap in a flat specimen of ductile material such as S355, the abrasive pushes material over the edges as it ploughs over the gap. If this is repeated several times, the edges on both sides of the gap are intermixed, resulting in a more or less continuous wear surface. The gap still causes a discontinuity in the material in the form of stress fields. Presumably a very narrow gap can transfer compressive stress from one body to another, whereas a tensile stress causes opening of the gap. With WR6 specimens, the edges between the inner and outer pins are rounded and no overlapping is clearly visible. In addition, the SEM analysis shows marks of fracture on the edges. In the weight measurement the gap between the inner and outer pins is forced open, creating a situation where some material may be removed. However, in some cases weighting of the pin pair was conducted before the separation, yielding the same result within 1 mg as after separation. Therefore it can be assumed that the mass loss due to the edge effect originates mainly from the outer pin outer edge.

The relative amount of the edge effect in the combined wear of both pins is shown in Figure 12. It is evident that the edge effect must be taken into account when estimating the reliability of a certain test setup, in particular because it may be different for materials with different mechanical properties. The additional wear caused by the edge effect is, for example 15 % for S355 but as much as 25 % for WR6, when granite with a standard size distribution is used as an abrasive.

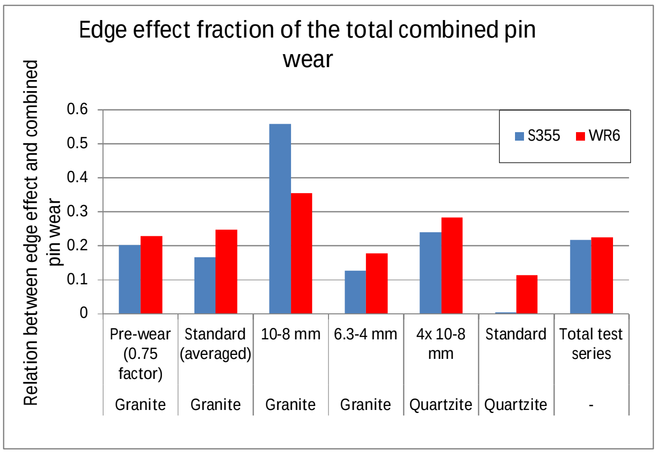

Figure 12. Edge effect fraction of the combined pin wear in different tests, including the total wear of the entire test series.

When the abrasive type or size is changed, there are more fluctuations in the relative amounts of edge wear. With larger abrasive size, the edge wear can be over 50 % of the total pin wear, depending on the pin material hardness. Also a change in the abrasive type can lead to changes in the edge wear, as for S355 the edge effect with standard size quartzite was close to 0 %.

When considering the total wear during all test steps discussed in this paper (Tables 1 and 2), the edge effect accounts for about 20 % of the total pin (inner + outer) wear for both steels.

CONCLUSIONS

Edge wear of the pin in the crushing pin-on-disk test was studied with two steels of different hardness. The following conclusions can be drawn from the test results:

- The use of a solid inner pin and a hollow outer pin was successful to measure the edge wear. The measured weight losses were confirmed with cross-sectional microscopical evaluations.
- In a standard test with the crushing pin-on-disk device, about 80 % of the wear was subjected to the flat pin area. The difference between the two studied steels was around 10 %.
- The results show that for steels the exposed specimen edge in the crushing pin-on-disk test is acceptable, when standard sized abrasive is used.
- The use of larger rocks promotes edge wear by decreasing wear in the flat pin area and by increasing wear of the edges.
- Archard's wear coefficient K' is an alternative way of comparing materials with large differences in hardness.

ACKNOWLEDGEMENTS

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