GLOBAL BRAKE SAFETY COUNCIL

EFFECTS OF 'BLACK STEEL'
AND ITS CONTRIBUTION TO PREMATURE BRAKE PAD REPLACEMENT AND BRAKE PAD FAILURE

Abstract

The Global Brake Safety Council (GBSC) has seen an increase in disc brake pads that are prematurely replaced and/or failed before reaching the end of the friction lining life cycle. These premature failures have been due to:

1) Rust related issues such as "rust jacking" (which causes separation of the friction lining from the steel disc brake shoe).

2) Fluctuation in critical functional dimensions.

One of the leading causes for both of these issues is the increased use of mill scale steel, commonly known as 'black steel' (non-pickled and oiled steel). Unlike the OE, the North American aftermarket has little or no steel specifications for the disc brake shoes allowing black steel to be used increasingly for brake pad manufacturing.

GBSC conducted field research of discarded disc brake pads from job shops and engaged in discussions with metallurgists, major disc brake pad manufacturers and OE brake foundation engineers to get to the root cause of the premature disc brake pad replacement and the effects of black steel used for disc brake shoe manufacturing.

Mill scale, the flaky surface of hot rolled steel that is comprised of iron oxide, which is embedded in and around the bond line of the friction lining and the disc brake shoe, causes a weaker bond which is more susceptible to rust jacking. These iron oxides are also painted over after the disc brake pad is fully assembled, which compromises the adhesion of paint on the steel disc brake shoe.

Disc brake pad manufacturers, using black steel, heavily shot blast the disc brake shoes after they have been stamped in efforts to remove the mill scale. This heavy shot blasting can deform and compromise critical dimensions of the disc brake shoe causing fit, function, and safety issues in the brake caliper assembly.

GBSC randomly selected leading aftermarket disc brake pad brands to carry out an intensive study to further analyze the above mentioned disc brake pad failures and the effects of black steel.

The parts were put through a standard 96 hour salt spray test per ASTM B117, in accordance with OE requirements, in which the disc brake shoe must not exceed a maximum of 5% red rust. ***All of the painted disc brake pads failed to meet this requirement even before the 20 hour interval. The only disc pad sets to meet the salt spray rust requirements were the zinc coated disc brake pads. Upon inspection at different intervals of the salt spray test, almost all disc brake pad sets showed severe out of tolerance measurements in critical functional areas. Some disc pad sets were out of specification in the critical areas right out of the box.***

Metallographic cross-sections of some of the disc brake pads, including black steel samples and suspected black steel manufactured disc brake pads, were prepared in accordance with ASTM E3-11 and ASTM E407-07. They were examined using metallographic procedures incorporating Scanning Electron Microscopy, X-Ray Spectrometry, and Microstructural Analysis. ***Iron oxides (mill scale) were found embedded in subsurface locations of the black steel samples and in the bond layer of suspected black steel disc brake pads. No iron oxides were found in disc brake pads manufactured with disc brake shoes made from SAE 1010 hot rolled, pickled, and oiled steel.***

<u>GBSC recommends that all disc brake shoes be manufactured using hot rolled, pickled, and oiled (HRPO) steel.</u>

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Introduction

Global Brake Safety Council (GBSC) *was established with the intent to uphold the highest standards in brake safety and is dedicated to responsible manufacturing in the automotive industry. Utilizing over 150 years of combined industry experience, this group of technical experts is composed of: professional engineers, OE design engineers, product development, and R&D professionals. This team is committed to raising awareness of issues that are critical to public safety through education.*

Members of this council are recipients of the Automotive News PACE Award in the Manufacturing Process Category for providing a compelling example of an innovative solution to an unsatisfactory but accepted process in the automotive industry. See Appendix A for a list of the council members.

In the last 15 years there has been an exponential increase in the number of off-shore brake pads supplied into the North American aftermarket. North Americans are driving less, yet replacing their disc brake pads more frequently (in many instances, significantly before the friction lining has been worn to a replacement level). The prematurely replaced pads are ending up in landfills and the piles are rising at an alarming rate. The consumer is paying for premature replacement of their disc brake pads.

GBSC engaged job shops across North America to collect discarded disc brake pads, which they analysed to learn about major issues contributing to premature brake pad replacement. Sorting through thousands of discarded disc brake pads, GBSC found a recurring and disturbing trend – many of the pads had friction lining which had started to or had completely separated from the steel disc brake shoe, while other pads showed severe corrosion. Many of these pads had failed long before their expected friction lining wear; see Appendix B for examples.

Concerned with this trend, the GBSC took their investigation to disc brake pad manufacturers and initiated discussions on the root causes of premature disc brake pad replacement and brake pad failure. GBSC quickly learned that in the aftermarket, in many cases, mill scale steel commonly known as 'black steel' is being used as an alternative to the pickled and oiled steel for the production of disc brake shoes. The majority of this black steel is supplied from off-shore, low-cost countries.

When Original Equipment Manufacturer (OEM) brake foundation engineers were approached for their input on the use of black steel, they emphasized that the disc brake shoe is a foundation component of the brake system and is directly related to the safety of the vehicle. The disc brake shoe's ability to retain the friction lining material and operate safely must <u>not</u> be compromised. For this reason, OEMs specify that disc brake shoes must be produced from pickled and oiled steel.

To learn more about black steel, GBSC engaged metallurgists from major North American steel suppliers. After learning about how a disc brake pad is manufactured, the steel suppliers stated that black steel was completely unsuitable for this application. The steel suppliers unanimously agreed that black steel contains oxide layers that are not an integral part of the steel and will not support bonding of adhesives or paint, which on the disc brake shoes are generally used for friction lining attachment and corrosion protection, respectively.

GBSC immediately launched a comprehensive study on the effects of black steel and its contribution to premature disc brake pad replacement and disc brake pad failure.

In this study, FMSI 7706-D833 disc brake pads were used as the testing model. Thirty two (32) disc brake pads, in sets of four (4), from eight (8) different major aftermarket disc brake pad brands were selected for testing.

GBSC utilized NUCAP Industries Inc.'s R&D Center laboratory to perform the salt spray testing in accordance with ASTM B117. Exova Canada Inc.'s laboratories were utilized for the metallographic procedures incorporating Scanning Electron Microscopy, X-Ray Spectrometry, and Microstructural Analysis with cross-sections prepared in accordance with ASTM E3-11 and ASTM E407-07.

Disclaimer

For privacy, the names of all manufacturers and brands have been omitted. The samples sets used in these tests were manufactured by major disc brake pad manufacturers and purchased directly from a variety of retailers. The names of the manufacturers and brands are known only to the members of the GBSC.

Test Sample Sets

Table 1 below summarizes the eight (8) sample sets that were tested during this study.

Sample Set N°.	Service Grade	Friction Grade	Lining Attachment Method	Brake Pad Manufacturer Location
1	**Economy grade-1**	Semi-Met	Adhesive	India
2	**Economy grade-2**	Semi-Met	Adhesive	Canada
3	**Premium grade-1**	Semi-Met	Adhesive	USA
4	**Premium grade with zinc plating**	Ceramic	Mechanical	USA
5	**Mid grade-1**	Ceramic	Adhesive	India
6	**OES**	Semi-Met	Adhesive	USA
7	**Premium grade-2**	Ceramic	Adhesive	India
8	**Mid grade-2**	Semi-Met	Adhesive	China

Table 1 - Disc brake pad sample identification

Testing Procedures

A range of tests and measurements were selected as per comparative disc brake pad testing procedures (see Appendix C), to analyse how disc brake shoe quality, method of friction attachment and coating type affect disc brake pad quality. Measurements gathered included:

- Initial abutment measurements.
- Initial flatness measurements.
- Salt spray corrosion testing.
- Abutment measurements (at different stages of corrosion testing).
- Flatness measurements (at different stages of corrosion testing).
- Lining delamination measurements, if applicable (after corrosion testing).

The data from these tests was collected and compared to the critical dimension tolerances of the D833 OE drawing.

A Coordinate Measuring Machine (CMM) was used in order to ensure the measurements were accurate and consistent. The CMM was programmed specifically to use a touch probe to measure critical dimensions.

Critical Dimension Measurements

It is an essential requirement in the automotive industry that the disc brake shoe profile be designed with respect to the brake caliper. In order for a disc brake shoe to function safely, a set of critical dimensions are defined. Critical dimensions differ from one design to another. As shown in Table 2, D833 has three (3) critical dimensions; the two (2) abutment dimensions shown below in Figure 1 and the disc brake shoe flatness in Table 2.

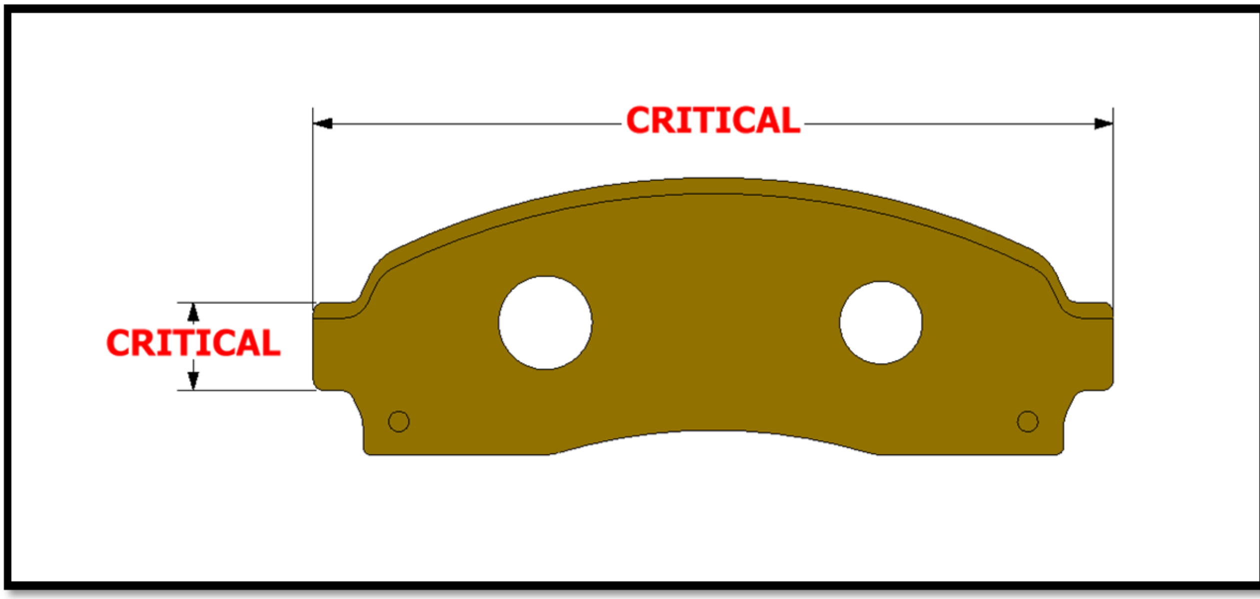


Figure 1 - Critical dimension representation

Due to the disc brake shoe paint characteristics and its effects on measurements, the OE pad assembly part drawing [1] was referenced to identify the appropriate critical tolerances with respect to the disc brake shoe coating. Table 2 below shows the OE critical dimensions used in the dimensional analysis:

OE Tolerances (with paint)	
Abutment Width	153.94 – 154.20 mm
Abutment Height (left-side and right-side)	16.94 – 17.20 mm
Flatness	0.16 mm maximum

Table 2 - OE tolerances

For each sample, measurement data was collected from the left abutment height, the right abutment height and the abutment span. As presented in **Error! Reference source not found.**, the CMM touch probe contacted each critical face at multiple points.

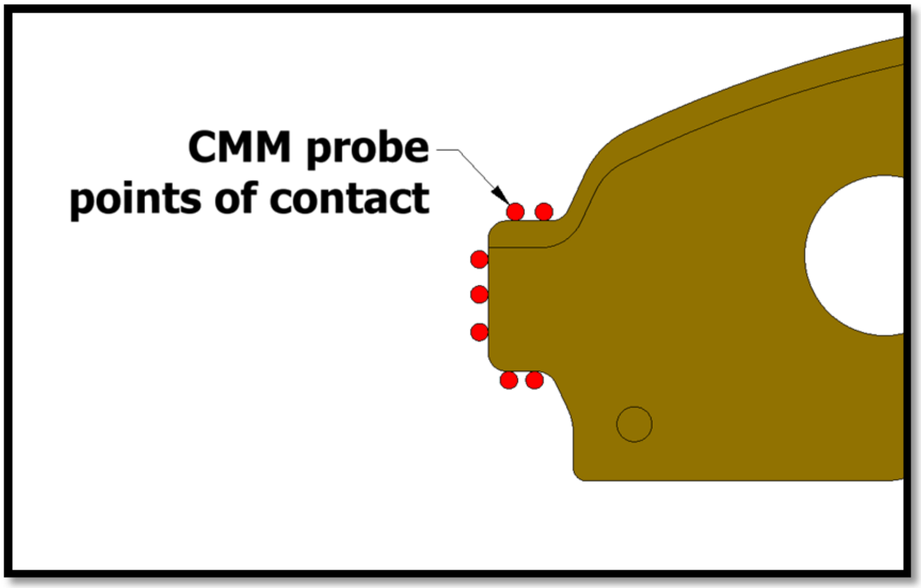


Figure 2 - CMM points of contact on the abutments (left abutment shown)

Flatness

The flatness of a disc brake shoe has a direct effect on the consistency of lining wear, pad compressibility and generation of noise during braking [2]. In recent years, OE manufacturers have greatly reduced the tolerance band for flatness of disc brake shoe in brake pad designs. Consequently, in this analysis the CMM probe was utilized to measure the overall flatness of each sample by using 30 contact points as shown in **Error! Reference source not found.**.

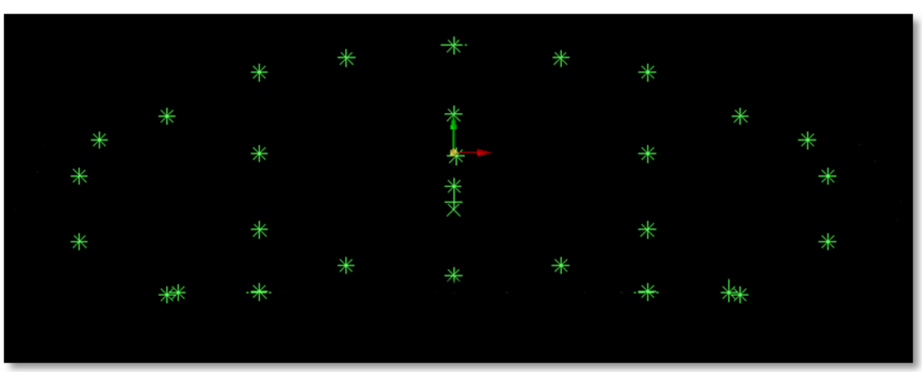


Figure 3 - Flatness points collected from CMM

Results

Initial Measurements

The CMM data shows for samples 7 and 8 that the critical dimension values were already out of specification before corrosion testing indicating that these disc brake shoes were not manufactured with respect to caliper and OE requirements.

Tables 3 and 4 represent the CMM data collected from measuring the critical dimensions of the D833 samples before the testing was initiated. The OE critical dimensions are listed at the top of the table for reference. The text in red colour represents the dimensions that are outside the OE tolerance limits.

		OE Tolerance (with paint): 153.94 - 154.20 mm			
		Abutment Width [mm]			
Sample Set N^{o}.	**Service Grade**	**Pad 1**	**Pad 2**	**Pad 3**	**Pad 4**
1	**Economy grade-1**	154.15	154.15	154.08	154.13
2	**Economy grade-2**	153.97	153.95	153.95	153.97
3	**Premium grade-1**	154.08	154.13	154.08	154.05
4	**Premium grade with zinc plating**	153.97	154.00	154.08	154.05
5	**Mid grade-1**	154.15	154.13	154.10	154.15
6	**OES**	154.10	154.13	154.15	154.13
7	**Premium grade-2**	154.25	154.20	154.28	154.20
8	**Mid grade-2**	153.90	153.95	154.05	153.95

Table 3 - Initial CMM measurements, abutment width

		OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height **LEFT-SIDE** [mm]				Abutment Height **RIGHT-SIDE** [mm]			
Sample Set N°.	**Service Grade**	**Pad 1**	**Pad 2**	**Pad 3**	**Pad 4**	**Pad 1**	**Pad 2**	**Pad 3**	**Pad 4**
1	**Economy grade-1**	17.12	17.09	17.17	17.07	17.09	17.12	17.12	17.17
2	**Economy grade-2**	17.12	17.15	17.20	17.07	17.04	17.02	17.09	17.07
3	**Premium grade-1**	16.97	17.17	17.17	17.17	17.02	17.15	17.12	17.17
4	**Premium grade with zinc plating**	17.12	17.12	17.12	17.12	16.97	17.02	17.04	17.02
5	**Mid grade-1**	17.12	17.15	17.07	17.09	17.17	17.17	17.15	17.17
6	**OES**	17.04	17.04	17.04	17.09	17.04	17.07	17.04	17.07
7	**Premium grade-2**	17.12	17.15	17.17	17.15	17.12	17.12	17.15	17.15
8	**Mid grade-2**	16.94	16.92	16.97	16.97	16.94	16.99	16.94	16.97

Table 4 - Initial CMM measurements, abutment heights

Flatness

The data in Table 5 shows the calculated data from thirty two (32) different samples versus the OE flatness requirement.

		OE Tolerance: 0.16 mm maximum			
		Flatness (30 points) [mm]			
Sample Set N°.	**Service Grade**	**Pad 1**	**Pad 2**	**Pad 3**	**Pad 4**
1	**Economy grade-1**	0.18	0.23	0.25	0.18
2	**Economy grade-2**	0.23	0.08	0.18	0.23
3	**Premium grade-1**	N/A	N/A	N/A	N/A
4	**Premium grade with zinc plating**	0.15	0.15	0.20	0.15
5	**Mid grade-1**	0.18	0.15	0.18	0.15
6	**OES**	0.18	0.13	0.13	0.15
7	**Premium grade-2**	0.33	0.20	0.20	0.30
8	**Mid grade-2**	0.38	0.23	0.33	0.25

Table 5 - Initial CMM measurements, flatness

Corrosion Test (ASTM B117 Standard)

Corrosion of the steel disc brake shoe is a serious issue in disc brake systems. In many cases, disc brake pads must be replaced due to rust making them unusable while there is still significant friction lining material left on the brake pads. Disc brake shoes were examined for the formation of red rust, after an ASTM corrosion test. To better simulate the actual conditions a disc brake pad endures during its lifecycle, the paint was intentionally compromised in a tumbling operation, simulating cycle wear and road debris. Rust forms and progressively grows on the surface of steel when it is exposed to humid air [3]. Excessive rust formation in critical areas can severely impact the operation of the disc brake pad and possibly cause delamination (separation) of the friction lining from the disc brake shoe.

We inspected and analysed the following effects at each stage of corrosion testing:

- Condition and retention of lining material.
- Severity of oxidation.
- Condition of paint.
- Specific areas most affected by oxidation.

The changes in critical dimensions as a result from oxidation were recorded. The following elements were measured:

- Change in abutment dimensions.
- Change in flatness.
- Friction delamination.

To illustrate the procedure and highlight some of the varied results, photographs were taken from the front and the back of the disc brake pads. Furthermore, photos of the same disc brake pads will be presented in each stage of corrosion testing. The following samples were focused on for this study:

- Sample No. 1.1: Economy grade-1 (see Figure 4).
- Sample No. 4.1: Premium grade using zinc coated disc brake shoe (see Figure 5).
- Sample No. 5.4: Mid grade-1 (see Figure 6).
- Sample No. 6.1: OES (see Figure 7).

All corrosion tests were carried out in an Auto Technology CCX-3000 cyclic corrosion chamber. Photos and measurements were collected after 20, 40, 60, 80, and 96 hours of testing. The following report illustrates the condition of samples after each stage of testing.

Initial Sample Conditions

Figure 4 - Sample 1.1 - Economy grade-1 (Initial)

Figure 5 - Sample 4.1 - Premium grade using zinc coated disc brake shoe (Initial)

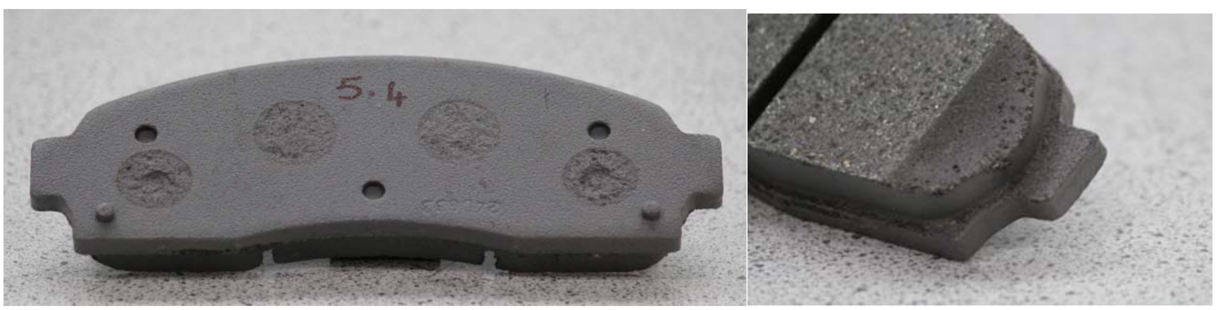


Figure 6 - Sample 5.4 - Mid grade-1 (Initial)

Figure 7 - Sample 6.1 - OES (Initial)

Observations After 20 Hours of Testing

Sample 1.1: Economy grade-1 (See Figure 8):

- Significant red rust visible around the edges and corners, particularly areas where the paint was compromised during the tumbling process.
- Heavy red rust build-up between the disc brake shoe surface and the entire lining perimeter.
- Visible red rust on disc brake shoe surface already exceeds OEM specification of 5% maximum after 96 hour salt spray.
- Red rust formation visible on surface of semi-metallic lining material.

Sample 4.1: Premium grade using zinc coated disc brake shoe (See Figure 9):

- No red rust visible anywhere on the disc brake shoe.
- Significant zinc hydroxide formation visible around disc brake shoe edges.
- Some zinc hydroxide present on disc brake shoe surface.
- No visible corrosion on lining material.

Sample 5.4: Mid grade-1 (See Figure 10):

- Significant red rust visible around the edges and corners, particularly areas where the paint was compromised during the tumbling process.
- Rust collecting in blind holes on disc brake shoe surface.
- Heavy red rust build-up between disc brake shoe surface and the entire lining perimeter.
- Visible red rust on disc brake shoe surface approaching 50%.
- Minimal red rust formation visible on surface of semi-metallic lining material.

Sample 6.1: OES (See Figure 11):

- Significant red rust visible around the edges and corners, particularly areas where the paint was compromised during the tumbling process.
- Red rust build-up between disc brake shoe surface and some parts of the lining perimeter.
- Visible red rust on disc brake shoe surface approaching OEM specification of 5% maximum after 96 hour salt spray.
- Red rust formation visible on surface of the lining material.

Figure 8 - Sample 1.1 - Economy grade-1 (20 Hours)

Figure 9 - Sample 4.1 - Premium grade using zinc coated disc brake shoe (20 Hours)

Figure 10 - Sample 5.4 - Mid grade-1 (20 Hours)

Figure 11 - Sample 6.1 - OES (20 Hours)

Observations After 40 Hours of Testing

Sample 1.1: Economy grade-1 (See Figure 12):

- Increasing red rust visible around the edges and corners.
- Red rust build-up between the disc brake shoe surface and the lining perimeter expanding.
- Visible red rust on disc brake shoe surface exceeding 25%.
- Red rust formation increases on the surface of semi-metallic lining material.

Sample 4.1: Premium grade using zinc coated disc brake shoe (See Figure 13):

- Minimal red rust visible, mainly along the disc brake shoe chamfer area.
- Zinc hydroxide still visible around disc brake shoe edges and surface with no apparent increase.
- No corrosion showing on lining material.

Sample 5.4: Mid grade-1 (See Figure 14):

- Increasing red rust visible around the edges and corners.
- Rust and an unknown dark substance is collecting in blind holes on the disc brake shoe surface.
- Red rust build-up between the disc brake shoe surface and the lining perimeter is expanding.
- Visible red rust on disc brake shoe surface exceeding 50%.
- Minimal red rust formation visible on the semi-metallic lining material.

Sample 6.1: OES (See Figure 15):

- Increasing red rust visible around the edges and corners.
- Red rust build-up between the disc brake shoe surface and the lining perimeter is expanding.
- Visible red rust on the disc brake shoe surface at 5%, primarily at edges.
- Red rust formation not significantly changed on the lining material.

Figure 12 - Sample 1.1 - Economy grade-1 (40 Hours)

Figure 13 - Sample 4.1 - Premium grade using zinc coated disc brake shoe (40 Hours)

Figure 14 - Sample 5.4 - Mid grade-1 (40 Hours)

Figure 15 - Sample 6.1 - OES (40 Hours)

Observations After 60 Hours of Testing

Sample 1.1: Economy grade-1 (See Figure 16):

- Red rust prevalent on most edges and corners.
- Red rust build-up between the disc brake shoe surface and the lining perimeter continues to expand and shows signs of separation from the disc brake shoe surface.
- Visible red rust on the disc brake shoe surface increases to approximately 35%.
- Lining material begins to noticeably deteriorate from corrosion.

Sample 4.1: Premium grade using zinc coated disc brake shoe (See Figure 17):

- Red rust increasing at the chamfer area.
- Paint adhesion starts to fail in various areas, exposing zinc plating on the brake shoe.
- Zinc hydroxide still visible on the disc brake shoe edges and surface with no apparent increase.
- Visible red rust on the disc brake shoe surface at 5%.
- No corrosion showing on lining material.

Sample 5.4: Mid grade-1 (See Figure 18):

- Red rest prevalent on all edges and corners.
- The unknown dark substance increases in the blind holes on the disc brake shoe surface.
- Red rust build-up between the disc brake shoe surface and the lining continues to expand.
- Visible red rust on the disc brake shoe surface exceeds 85%.
- Red rust formation is more visible on edges of semi-metallic lining material.

Sample 6.1: OES (See Figure 19):

- Notable increase in red rust visible around the edges and corners.
- Red rust build-up between the disc brake shoe surface and the lining perimeter continues to expand.
- Visible red rust on disc brake shoe surface exceeds 5%, primarily at the edges.
- Red rust formation is increasing on surface of the lining material.

Figure 16 - Sample 1.1 - Economy grade-1 (60 Hours)

Figure 17 - Sample 4.1 - Premium grade using zinc coated disc brake shoe (60 Hours)

Figure 18 - Sample 5.4 - Mid grade-1 (60 Hours)

Figure 19 - Sample 6.1 - OES (60 Hours)

Observations After 80 Hours of Testing

Sample 1.1: Economy grade-1 (See Figure 20):

- Red rust prevalent on nearly all the edges and corners.
- Red rust build-up between the disc brake shoe surface and the lining perimeter continues to expand and shows an increased separation from the disc brake shoe surface.
- Visible red rust on the disc brake shoe surface exceeding 50%.
- Lining material continues to noticeably deteriorate from corrosion.

Sample 4.1: Premium grade using zinc coated disc brake shoe (See Figure 21):

- Red rust begins to spread from the initial location and appears to form where the peeling paint has created channels for rust to collect.
- Paint adhesion fails more rapidly, exposing more zinc coated surface.
- Zinc hydroxide still visible on the disc brake shoe edges and surface with minimal increase.
- Visible red rust on the disc brake shoe surface exceeding 5%.
- No corrosion showing on lining material.

Sample 5.4: Mid grade-1 (See Figure 22):

- Red rest prevalent on all the edges and corners.
- The unknown dark substance fills the blind holes and collects in the other cavitation sites.
- Red rust build-up between the disc brake shoe surface and lining continues to expand showing signs of local corrosion.
- Visible red rust on the disc brake shoe surface approaching 100%.
- Red rust formation visible on the edges and surface of the semi-metallic lining material.

Sample 6.1: OES (See Figure 23):

- Continued increase in red rust visible around the edges and corners.
- Red rust build-up between the disc brake shoe surface and lining perimeter continues to expand.
- Visible red rust on the disc brake shoe surface exceeding 5%.
- Red rust formation increasing on the surface of lining material.

Figure 20 - Sample 1.1 - Economy grade-1 (80 Hours)

Figure 21 - Sample 4.1 - Premium grade using zinc coated disc brake shoe (80 Hours)

Figure 22 - Sample 5.4 - Mid grade-1 (80 Hours)

Figure 23 - Sample 6.1 - OES (80 Hours)

Observations After 96 Hours of Testing

Sample 1.1: Economy grade-1 (See Figure 24):

- Red rust still prevalent on nearly all the edges and corners.
- Red rust build-up between the disc brake shoe surface and the lining perimeter continues to expand and shows an increased separation from the disc brake shoe surface.
- Visible red rust on the disc brake shoe surface approaching 70%.
- Lining material continues to noticeably deteriorate from corrosion.

Sample 4.1: Premium grade using zinc coated disc brake shoe (See Figure 25):

- Red rust continues to form where the peeling paint has created channels for rust to collect.
- No further paint adhesion failure noticed.
- Zinc hydroxide still visible on the disc brake shoe edges and surface with minimal increase.
- Visible red rust on the disc brake shoe surface exceeding 5%.
- No corrosion showing on lining material, however, minimal red rust formation on the lining surface.

Sample 5.4: Mid grade-1 (See Figure 26):

- Red rust covers all the edges and corners.
- The unknown dark substance fills the blind holes and collects in the other cavitation sites.
- Red rust build-up between the disc brake shoe surface and lining continues to expand causing deeper corrosion.
- Visible red rust on the disc brake shoe surface approaching 100%.
- Red rust formation prevalent on the edges and surface of the semi-metallic lining material.

Sample 6.1: OES (See Figure 27):

- Continued increase in red rust visible around the edges and corners.
- Red rust build-up between the disc brake shoe surface and lining perimeter continues to expand.
- Visible red rust on the disc brake shoe surface approaching 10%.
- Red rust flaking off the surface of lining material.

Figure 24 - Sample 1.1 - Economy grade-1 (96 Hours)

Figure 25 - Sample 4.1 - Premium grade using zinc coated disc brake shoe (96 Hours)

Figure 26 - Sample 5.4 - Mid grade-1 (96 Hours)

Figure 27 - Sample 6.1 - OES (96 Hours)

Dimensional Analysis During and After Corrosion Test

This analysis investigated the changes in critical dimensions that resulted from the corrosion test. As oxidation layers grew on the disc brake shoe surface, it was expected to see an increase in the critical dimension measurements. A significant increase can have direct effects on the functionality of the disc brake shoe in the caliper assembly.

Observations

- Many samples showed an initial reduction in size from the tumbling process. The change was always less than 0.05 mm. This is possibly due to residual stresses activating during tumbling, or the removal of paint and lining material residue from the disc brake shoe abutments. However, it is not known.
- Most pads showed sharp initial increase in dimension during the first 20 hours of salt spray, then levelling out to slower growth.
- All pads showed similar growth in the critical dimensions measured throughout the test. Most grades averaged 0.10 mm growth, with individual deltas ranging from zero growth to 0.23 mm.
- Pads from sample set 3 - different from the other grades - showed the greatest average increase in dimensions, 0.25 mm. Some dimensions increased by approximately 0.50 mm. Visual observation shows where large areas of paint that severely blistered off, which appears to have also rusted, possibly due to metal pigment content (see Figure 28).
- Pads from sample set 4, with paint over zinc coating, showed erratic changes in dimensions, inconsistent with the growth patterns of the other sets. These pads are the only ones recorded that had patterns of dimensional increase followed by a decrease on some of the samples (see Figure 29).

Figure 28 - Pad from sample set 3

Figure 29 - Pad from sample set 4

Dimensional Analysis of the Abutment Width

Figures 30 through 41 show the changes to the critical dimensions of the disc brake shoes as they are measured before, during, and after corrosion testing.

Sample set 1: Economy grade-1 (See Figure 30):

- Dimensional growth of all samples in this set exceeded the upper tolerance limit.

Sample set 4: Premium grade using zinc coated disc brake shoe (See Figure 31):

- Samples 4.1, 4.2, and 4.4 remained within tolerance throughout the test.
- Anomaly noticed in sample 4.3 between 10-40 hours. Dramatic decrease in measurement at 40 hours possibly due to zinc hydroxide flaking off.

Sample set 5: Mid grade-1 (See Figure 32):

- Dimensional growth of samples 5.1, 5.3, and 5.4 exceeded the upper tolerance limit.
- Sample 5.2 remained within tolerance.

Sample set 6: OES (See Figure 33):

- Dimensional growth of all samples in this set exceeded the upper tolerance limit.

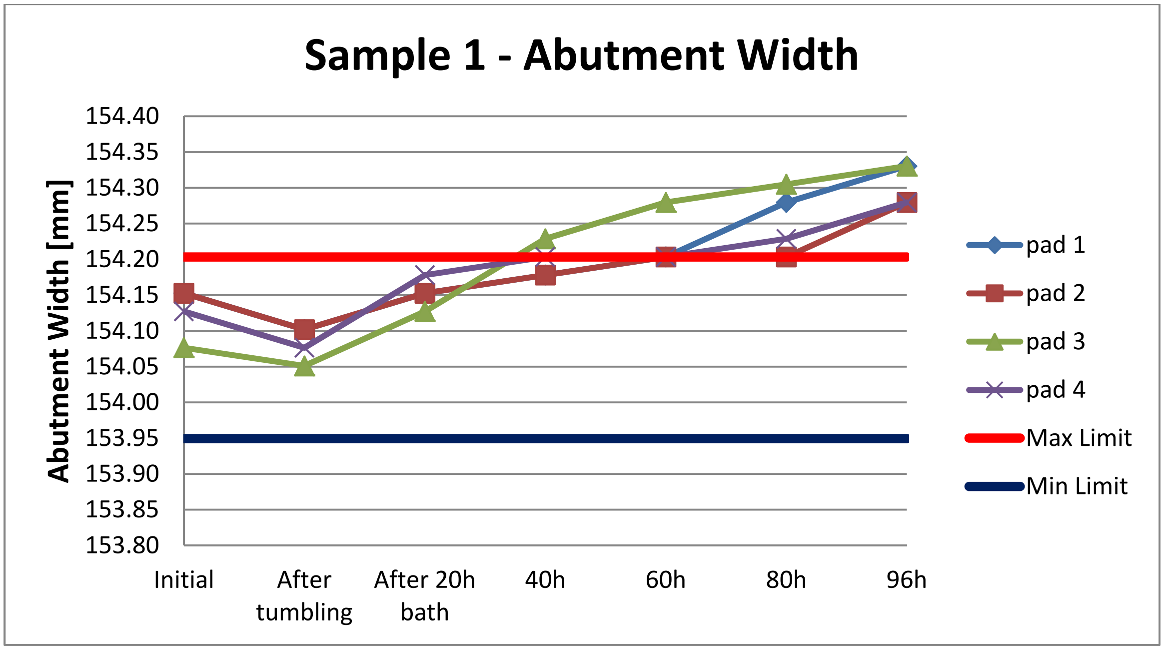


Figure 30 - Sample set 1 - Economy grade-1

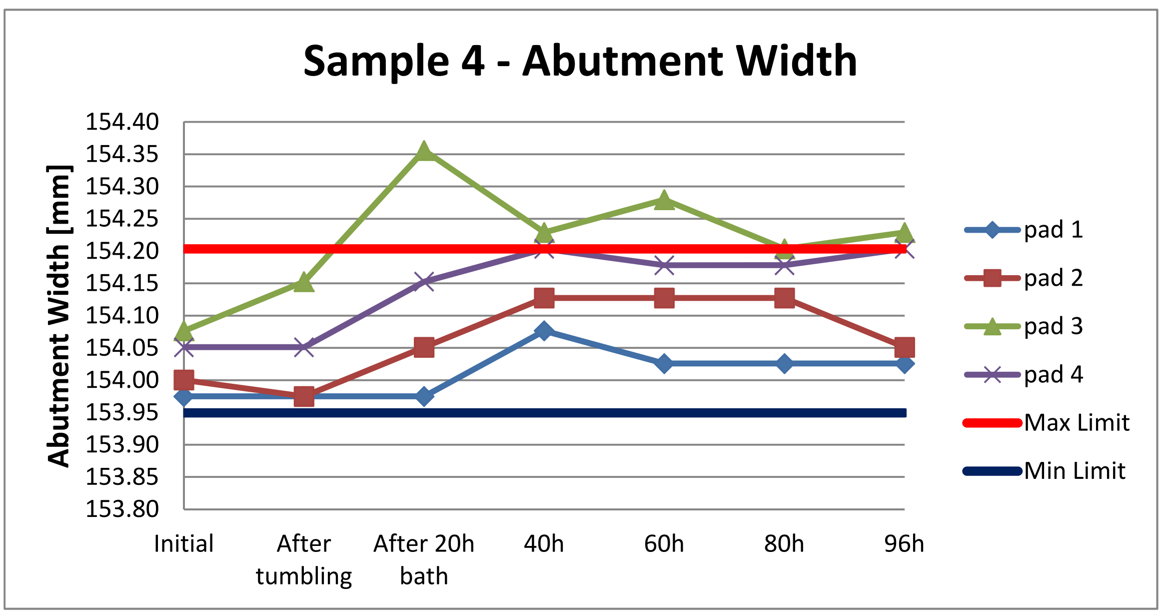


Figure 31 - Sample set 4 - Premium grade using zinc coated disc brake shoe

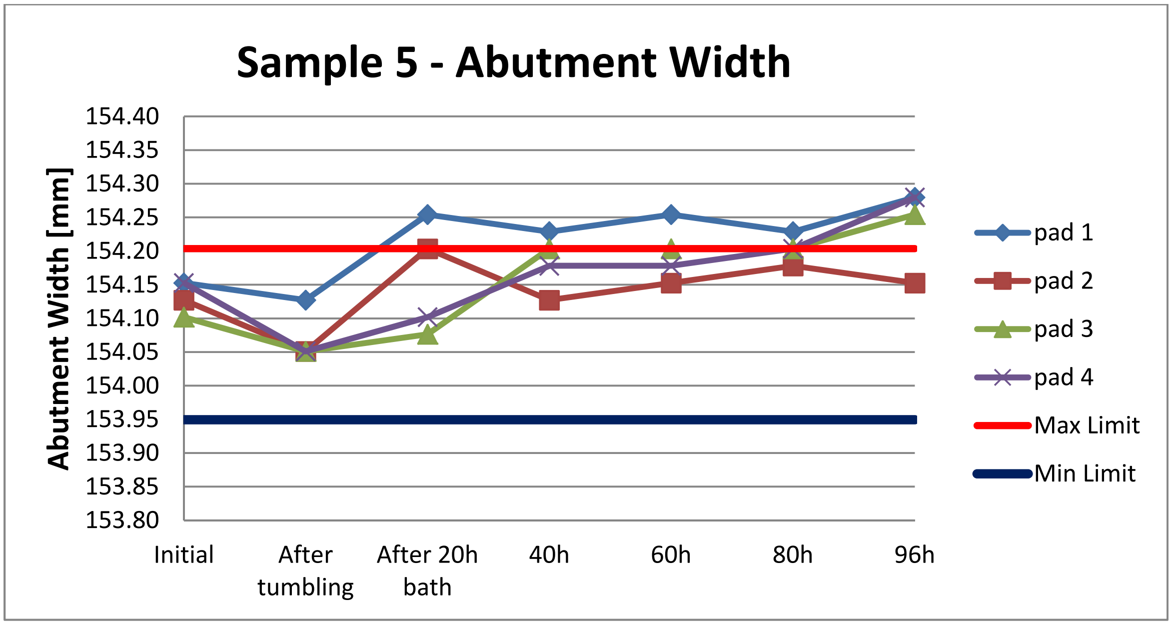


Figure 32 - Sample set 5 - Mid grade-1

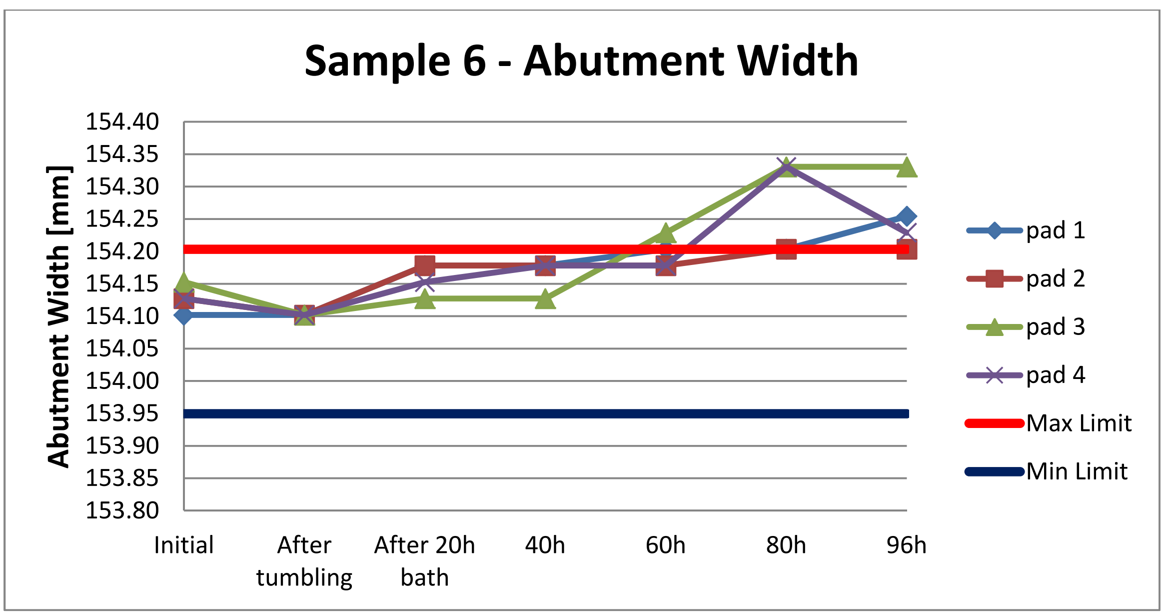


Figure 33 - Sample set 6 - OES

Dimensional Analysis of the Abutment Height (Left-Side)

Sample set 1: Economy grade-1 (See Figure 34):

- Dimensional growth of all samples in this set exceeded the upper tolerance limit.

Sample set 4: Premium grade using zinc coated disc brake shoe (See Figure 35):

- Samples 4.1 and 4.2 remained within tolerance.
- Sample 4.3 exceeded the upper tolerance limit past 80 hours.
- Anomaly noticed in sample 4.4 starting around 20 hours.

Sample set 5: Mid grade-1 (See Figure 36):

- Dimensional growth of all samples in this set exceeded the upper tolerance limit.

Sample set 6: OES (See Figure 37):

- Dimensional growth of samples 6.2 and 6.4 exceeded the upper tolerance limit.
- Samples 6.1 and 6.3 remained within tolerance.

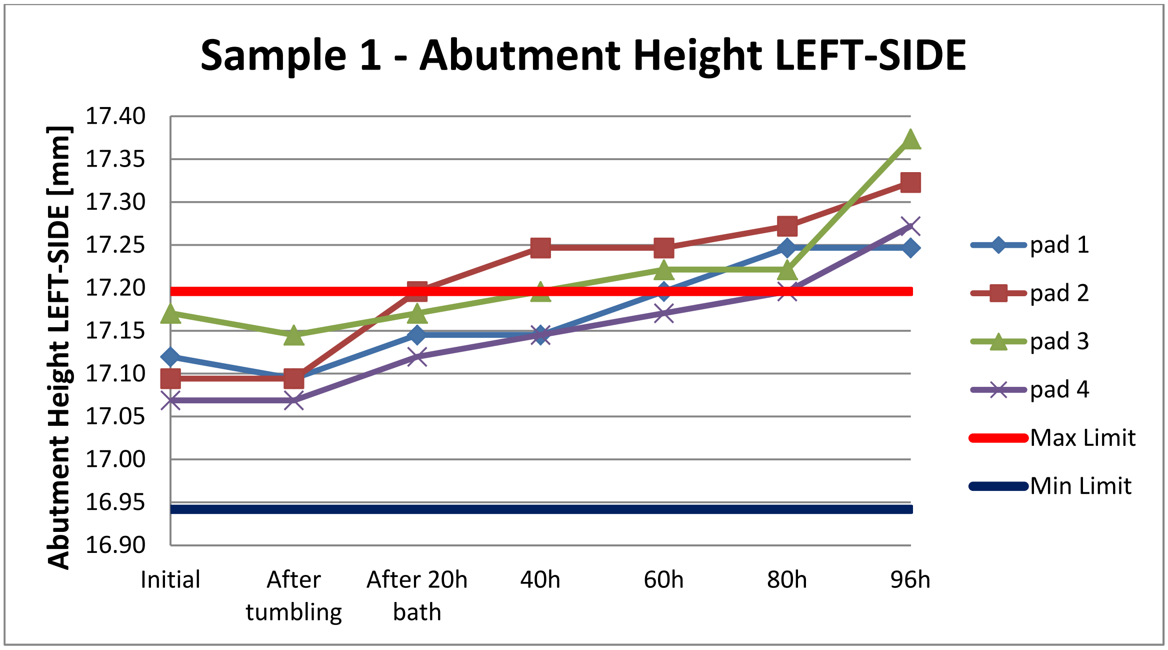


Figure 34 - Sample set 1 - Economy grade-1

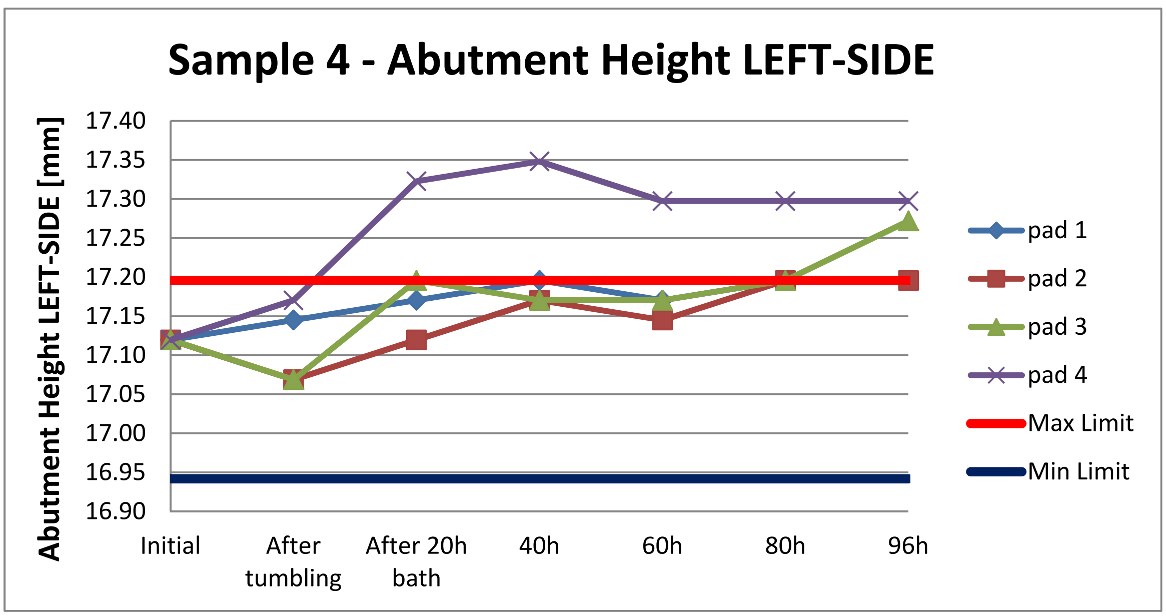


Figure 35 - Sample set 4 - Premium grade using zinc coated disc brake shoe

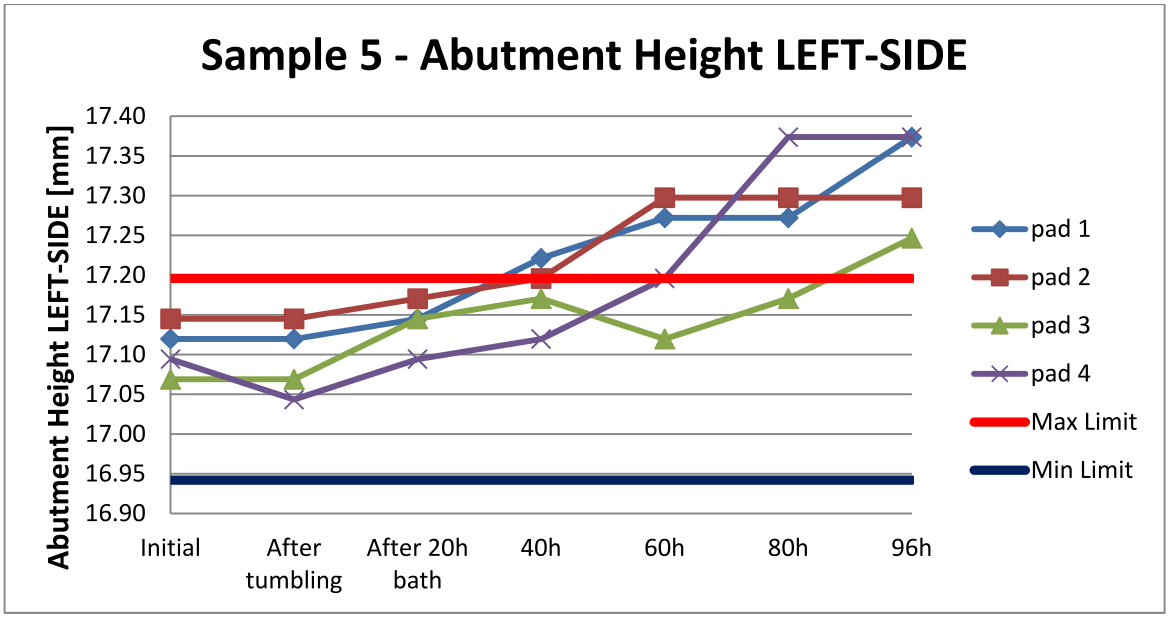


Figure 36 - Sample set 5 - Mid grade-1

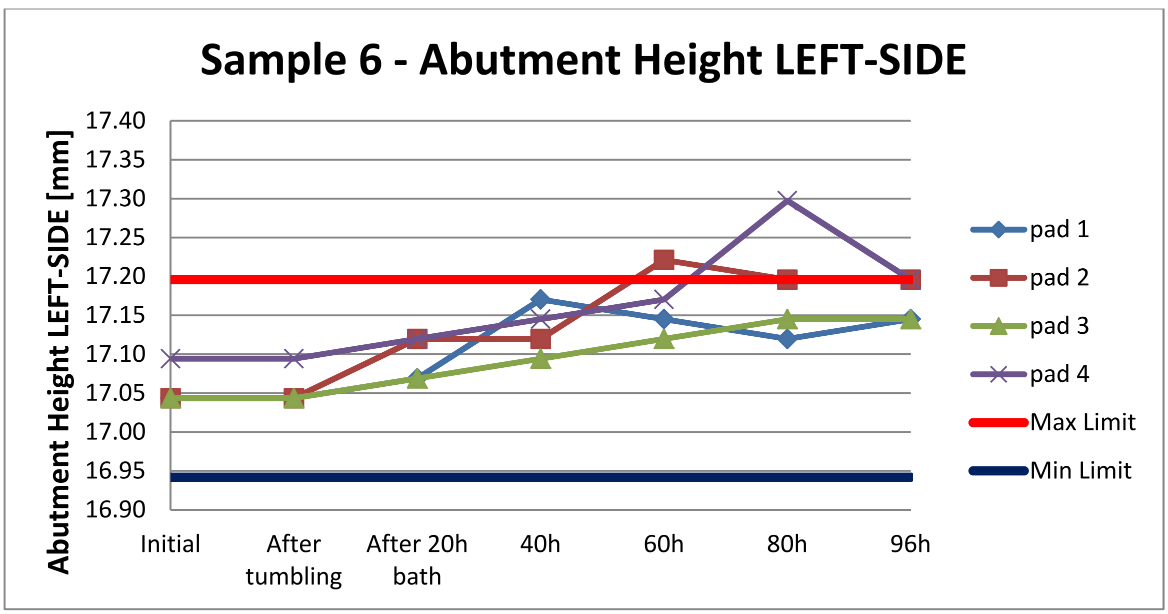


Figure 37 - Sample set 6 - OES

Dimensional Analysis of the Abutment Height (Right-Side)

Sample set 1: Economy grade-1 (See Figure 38):

- Dimensional growth of all samples exceeded the upper tolerance limit.

Sample set 4: Premium grade using zinc coated disc brake shoe (See Figure 39):

- Sample 4.1 is within tolerance.
- Samples 4.2 and 4.3 exceeded the upper tolerance limit after 40 hours.
- Anomaly noticed in sample 4.4 starting around 20 hours.

Sample set 5: Mid grade-1 (See Figure 40):

- Dimensional growth of all samples exceeded the upper tolerance limit.

Sample set 6: OES (See Figure 41):

- Sample 6.2 reached the upper tolerance limit at 80 hours.
- Samples 6.1, 6.3, and 6.4 remained within tolerance.

For dimensional analysis on the remaining samples please refer to Appendix D.

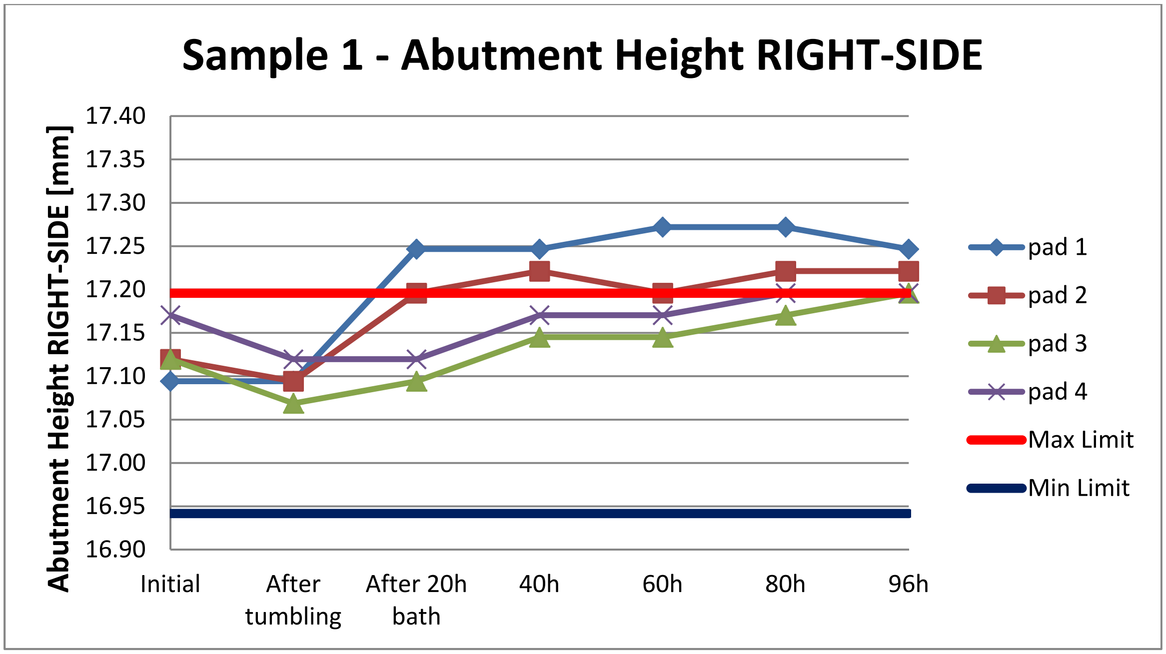


Figure 38 - Sample set 1 - Economy grade-1

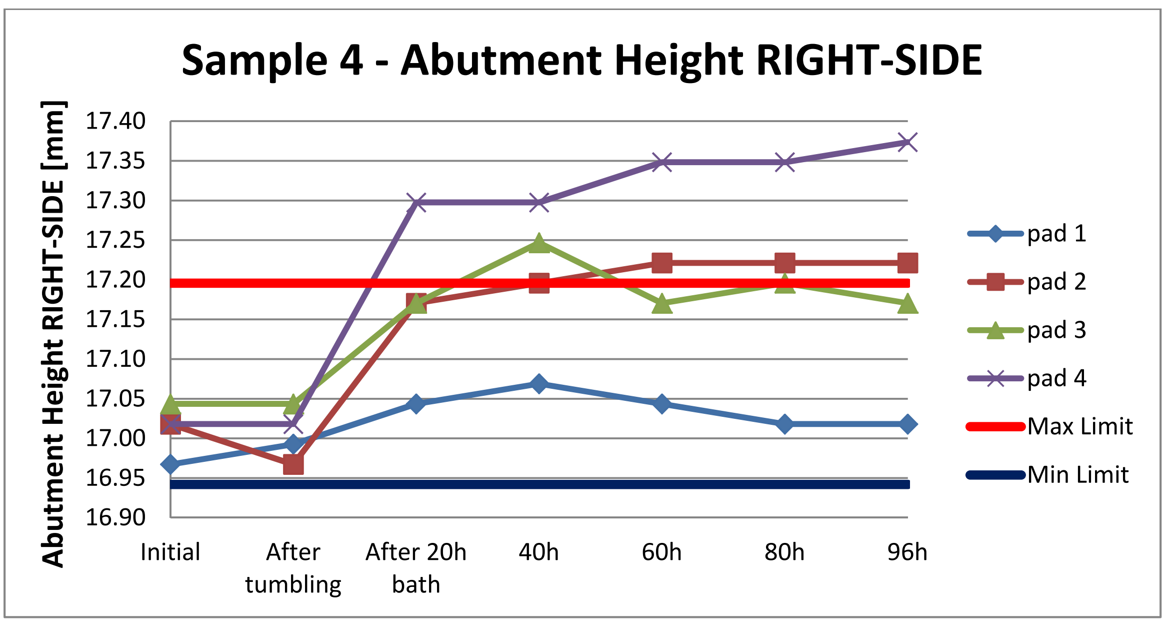


Figure 399 - Sample set 4 - Premium grade using zinc coated disc brake shoe

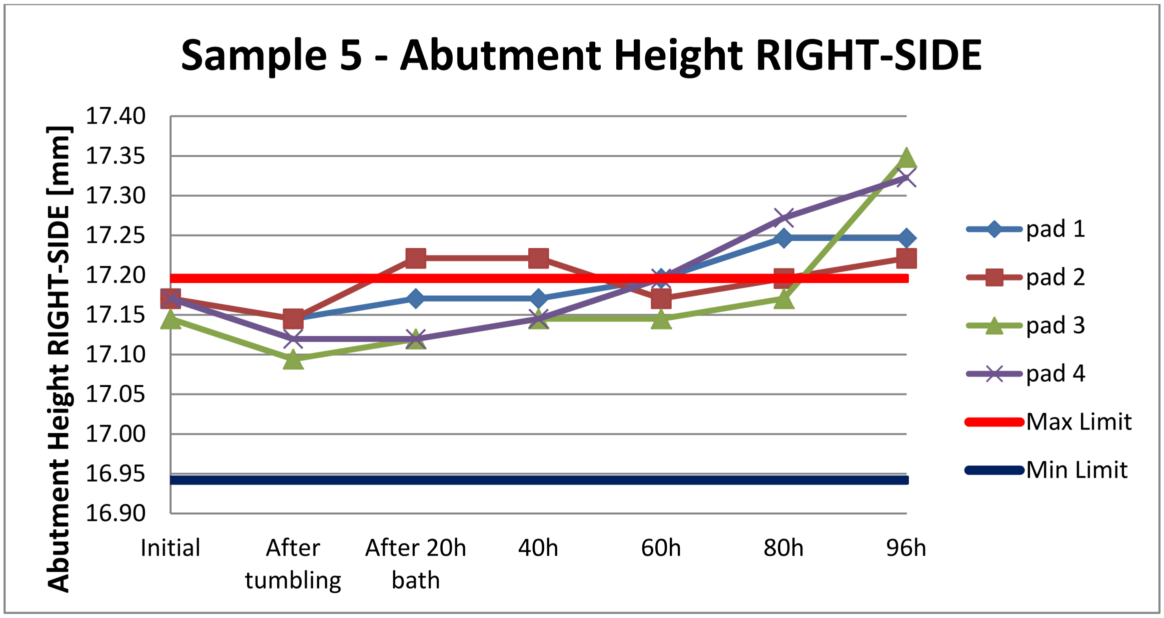


Figure 40 - Sample set 5 - Mid grade-1

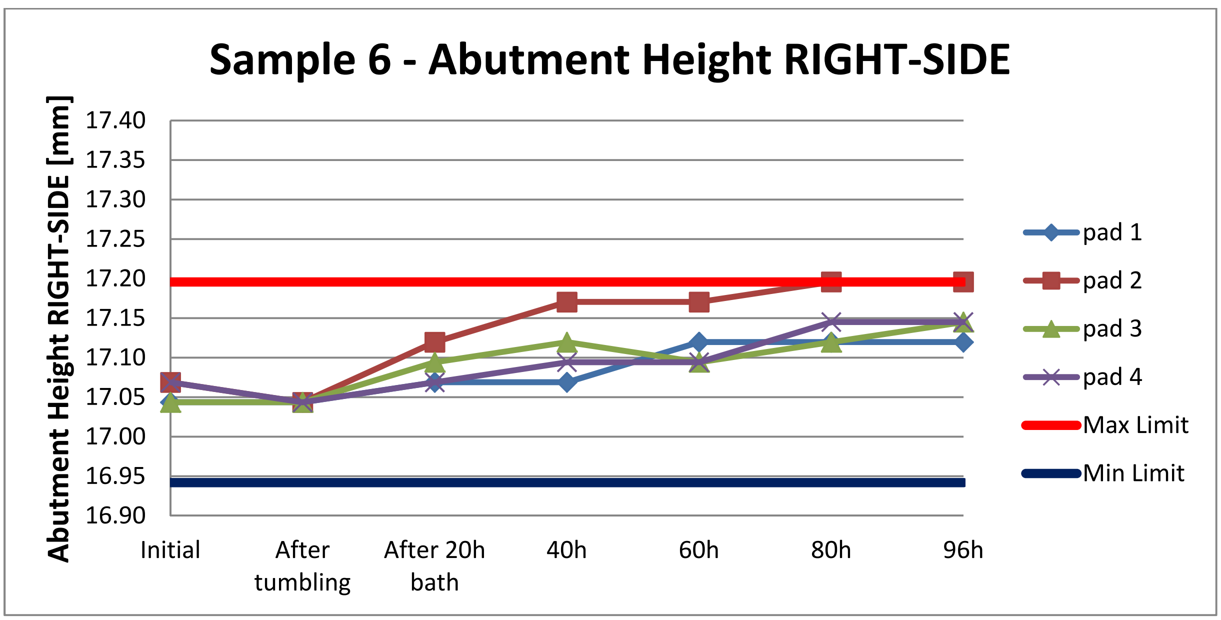


Figure 41 - Sample set 6 - OES

Surface Analysis

To validate our test observations, new disc brake shoe sets were purchased from the same disc brake pad manufacturers as those suspected of using black steel, and sent to Exova Canada Inc., an independent testing laboratory. Coupons of shot blasted Q235B mill scale black steel were also sent. For the full surface analysis test matrix and a description of samples used, please refer to Appendix E.

The metallographic analysis involved preparation of metallographic cross-sections in accordance with ASTM E3-11 of specified areas of the disc brake shoes and steel coupons followed by these tests:

- Scanning Electron Microscope (SEM) examination in combination with x-ray spectrometry to semi-quantitatively determine the approximate chemical compositions.
- Microstructural analysis of the metallographic cross-sections in etched condition in accordance with ASTM E407-07 utilizing a metallographic microscope.

The preliminary report is available in Appendix E. Image excerpts from this report [6] are shown in Figures 42-49.

Sample 2: Black steel – shot blasted

- Embedded particles were found at some surface locations, see Figure 42.
- Oxide particles had a maximum length of approximately 30 microns. The grains were deformed at the surface, see Figure 43.

Sample 3: Black steel – shot blasted with adhesive

- Several embedded particles were found at some subsurface locations, see Figure 44.
- Oxide particles had a maximum length of approximately 55 microns. The grains were deformed at the surface, see Figure 45.

Sample 7: D833 Disc brake shoe– SAE 1010 HRPO, painted

- No oxides or embedded particles were found, see Figure 46.
- No grain deformation was observed, see Figure 47.

Sample 8: D833 Disc brake shoe – suspected Black steel, painted

- An oxide layer with a thickness of approximately 10 microns was observed inside the blind hole. An embedded oxide layer was observed at the surface interface of steel and friction, see Figure 48.
- The grains were deformed at the surface; the oxide layer is shown in Figure 49.

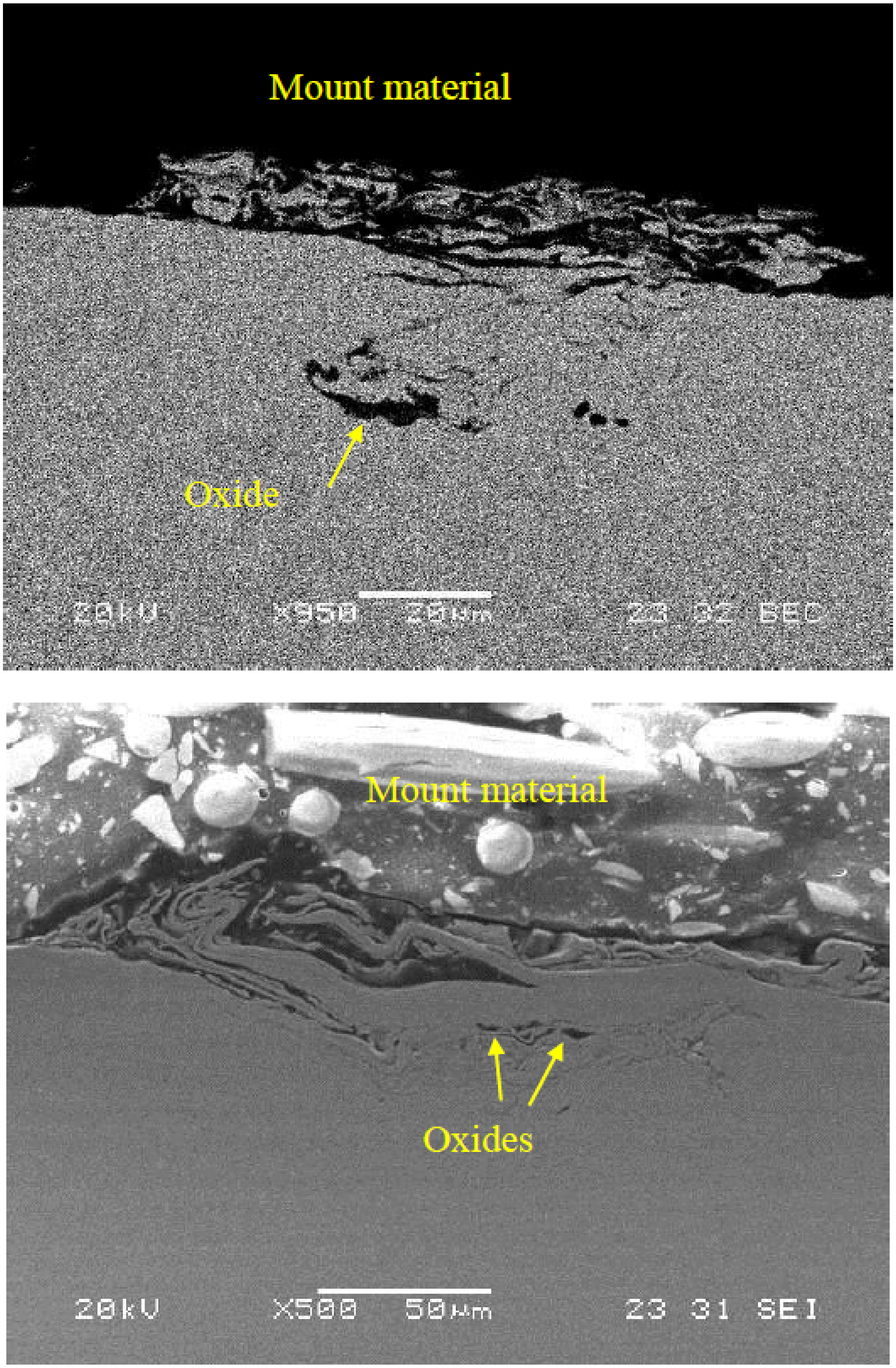


Figure 42 - Sample 2: Black steel, shot blasted - SEM Image [6]

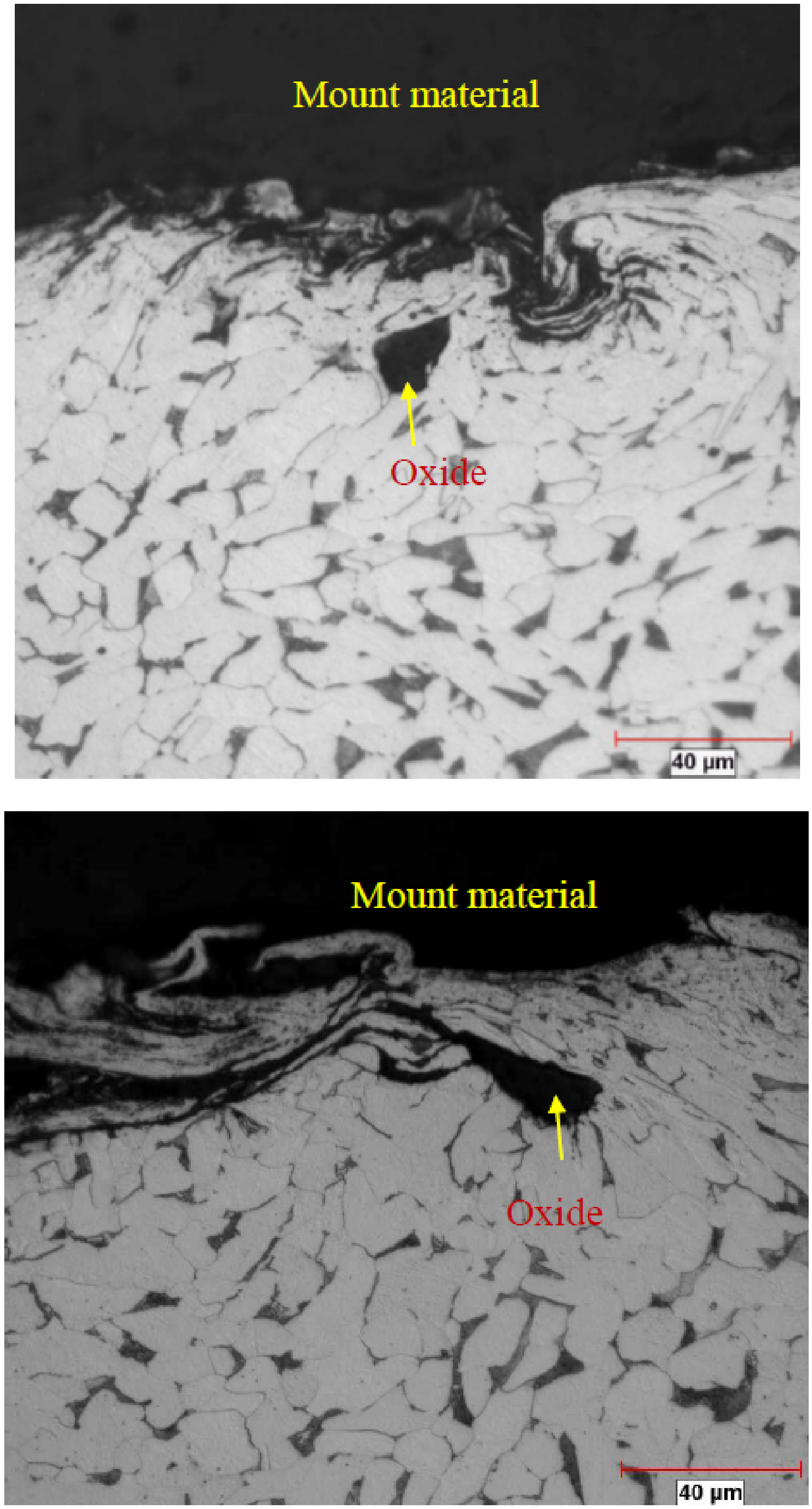


Figure 43 - Sample 2: Black steel, shot blasted - Metallographic Microscope Image [6]

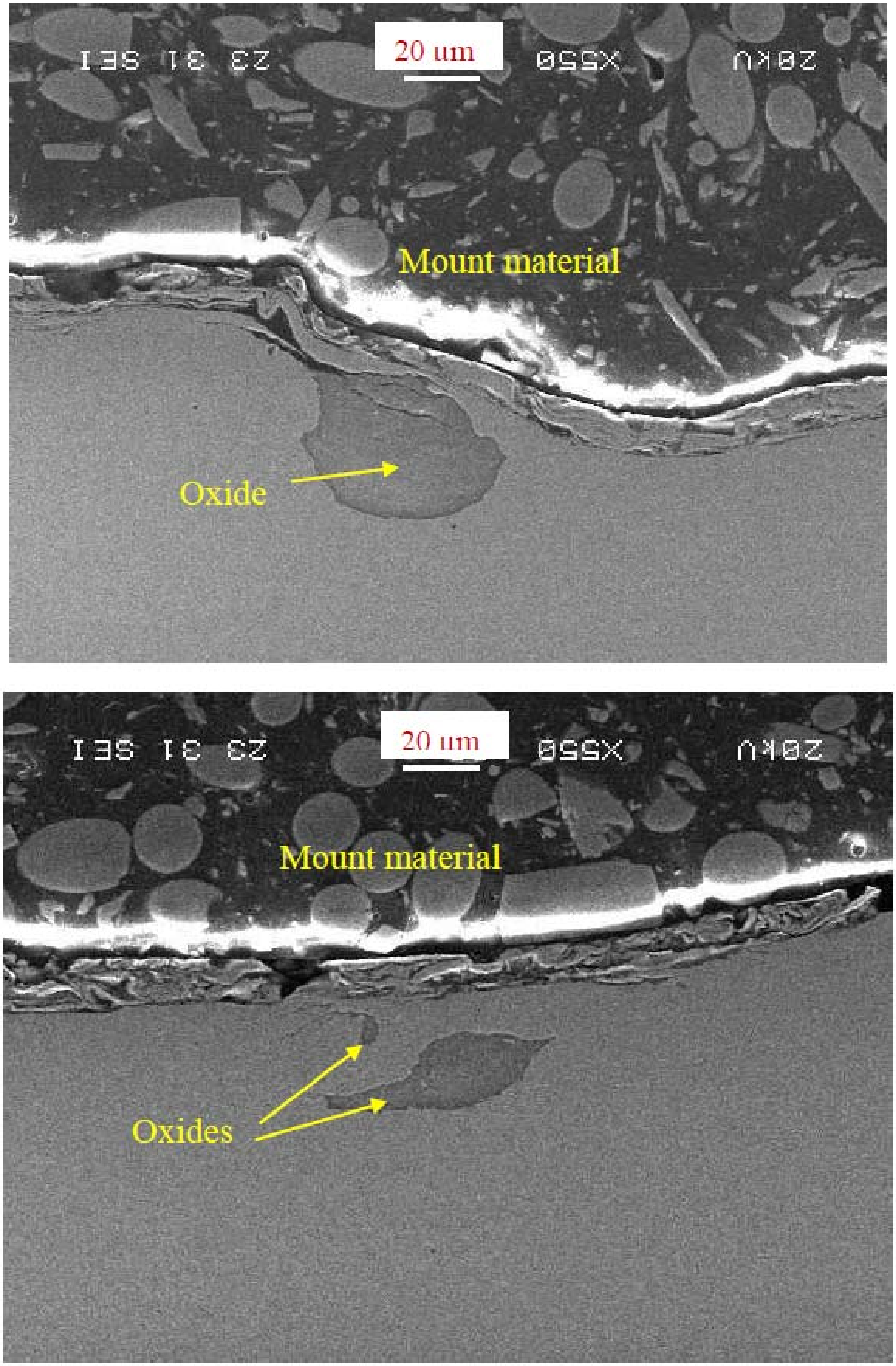
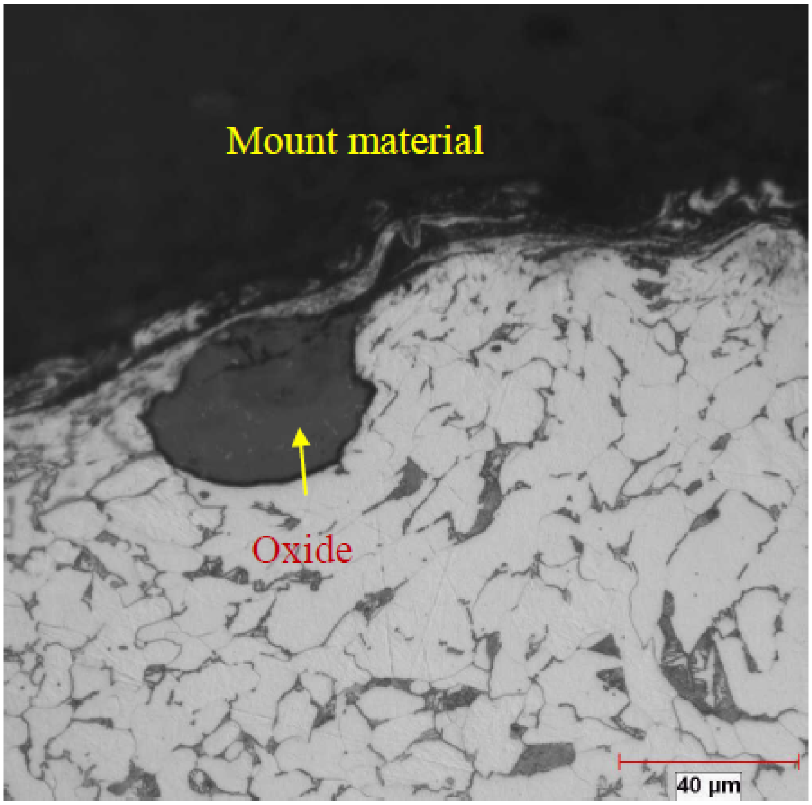


Figure 44 - Sample 3: Black steel, shot blasted with adhesive - SEM Image [6]



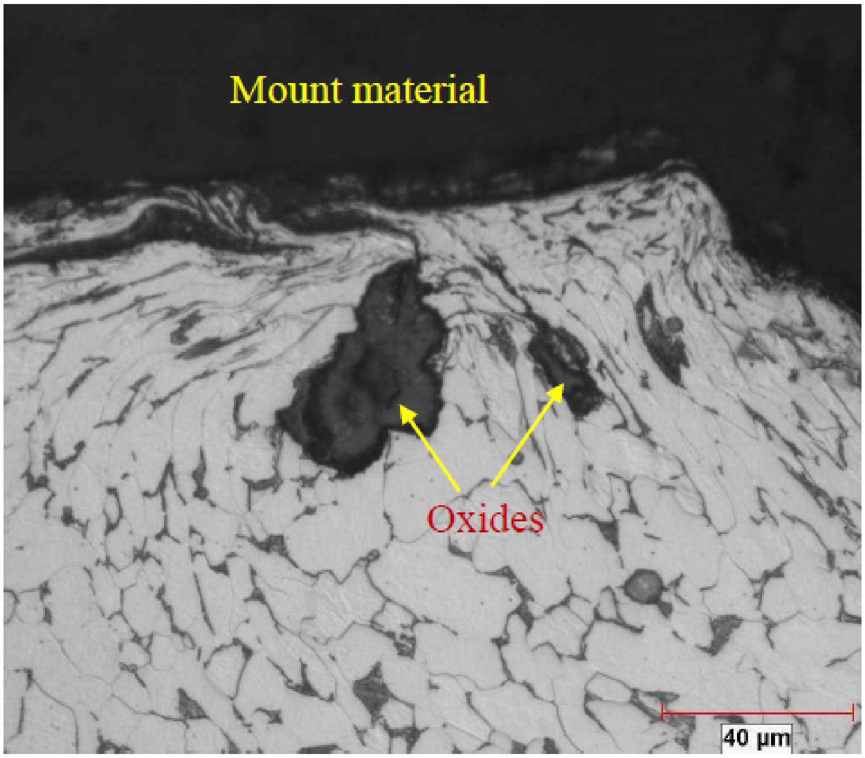


Figure 45 - Sample 3: Black steel, shot blasted with adhesive - Metallographic Microscope Image [6]

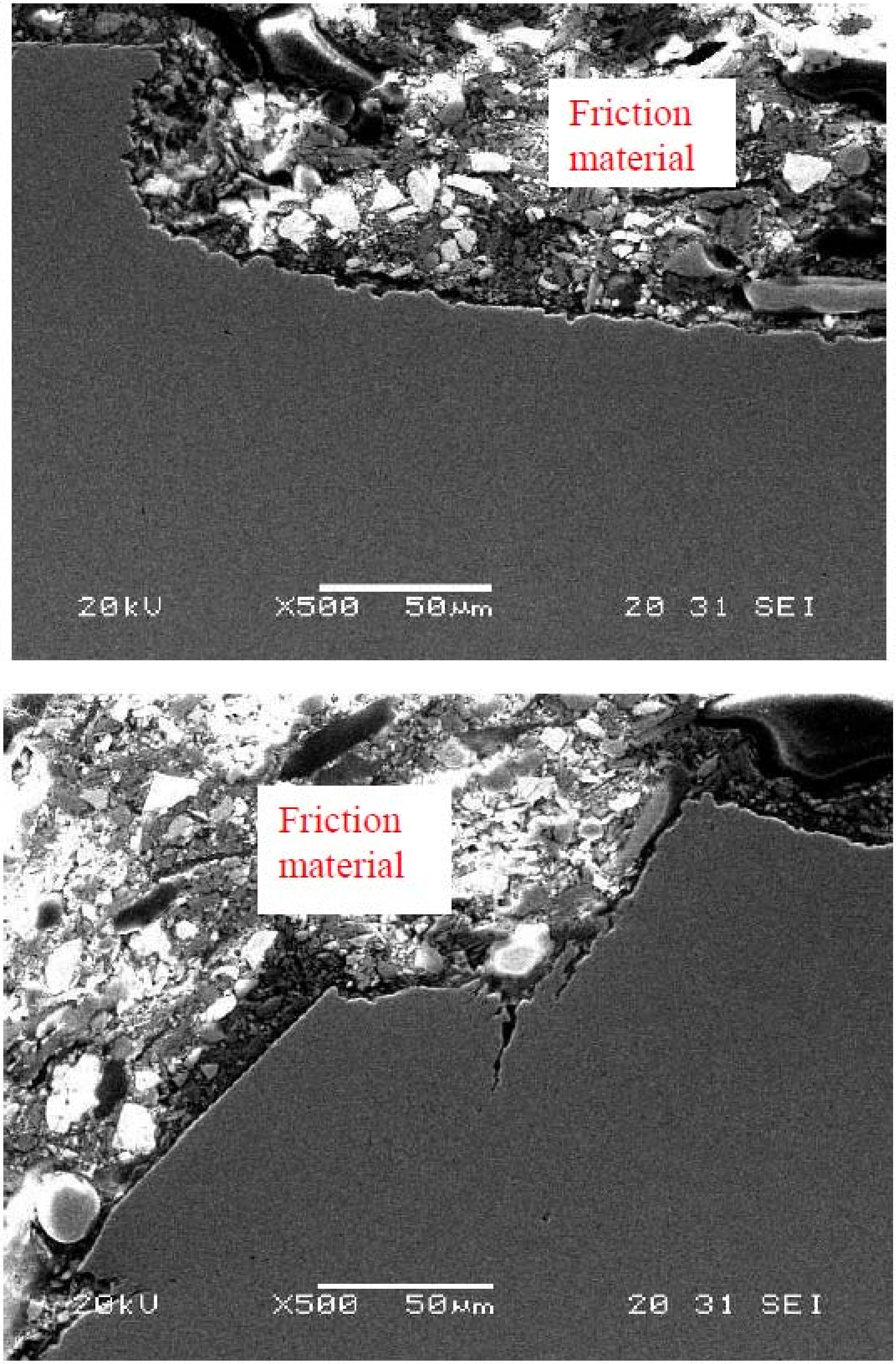


Figure 46 - Sample 7: Disc brake shoe - SAE 1010 HRPO, painted - SEM Image [6]

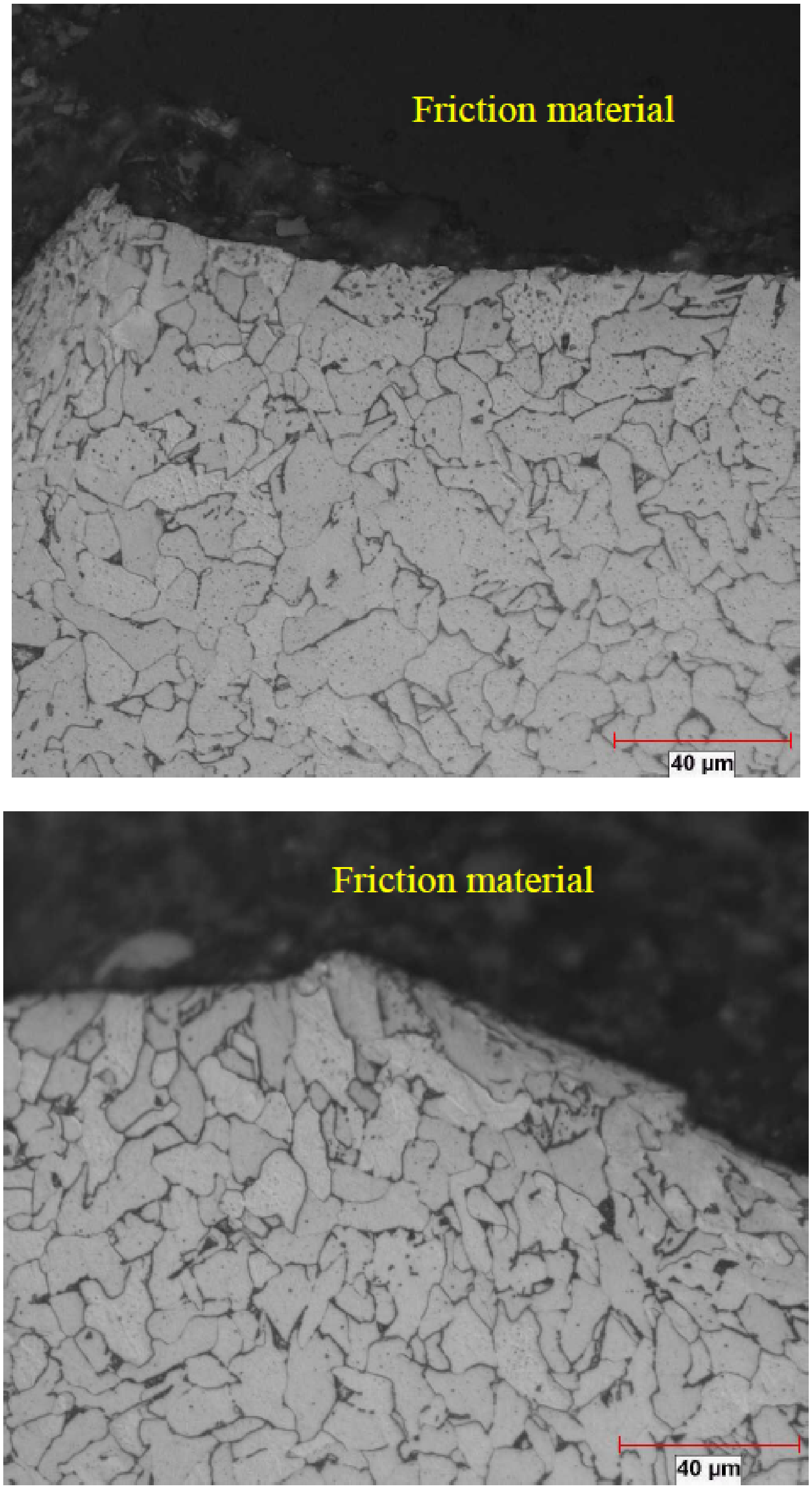
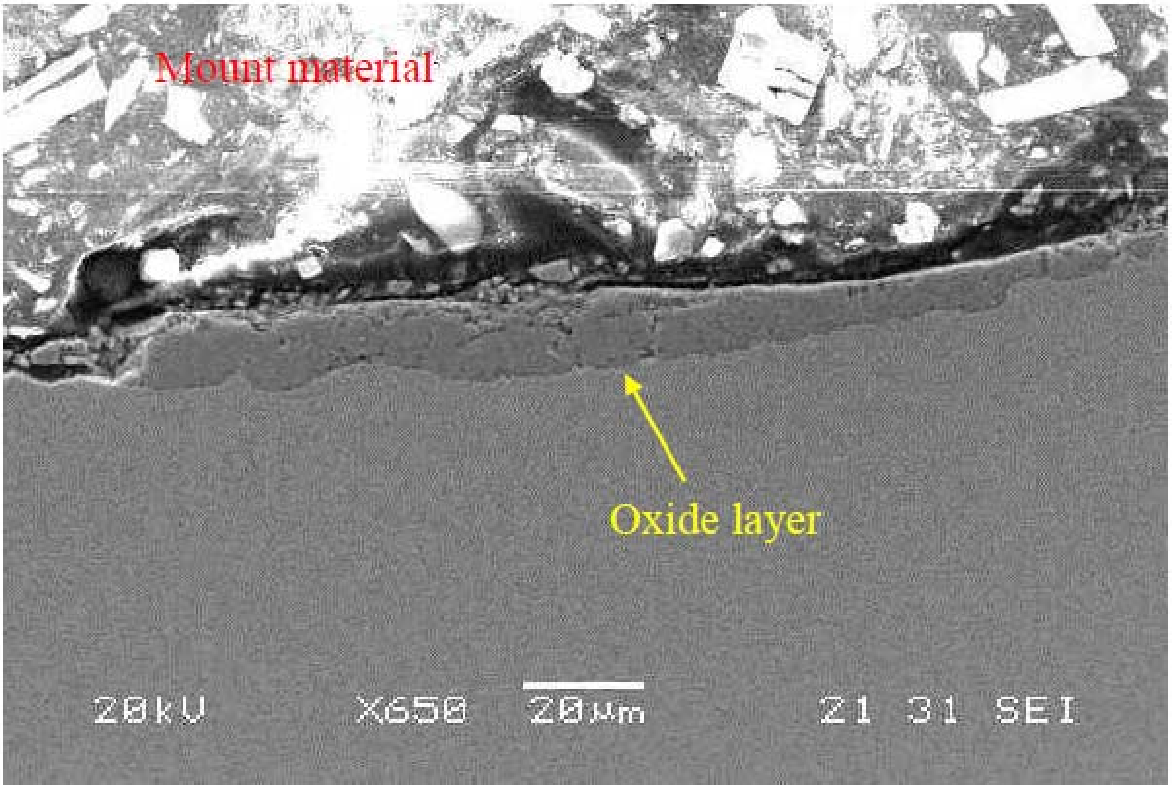


Figure 47 - Sample 7: Disc brake shoe - SAE 1010 HRPO, painted - Metallographic Microscope Image [6]



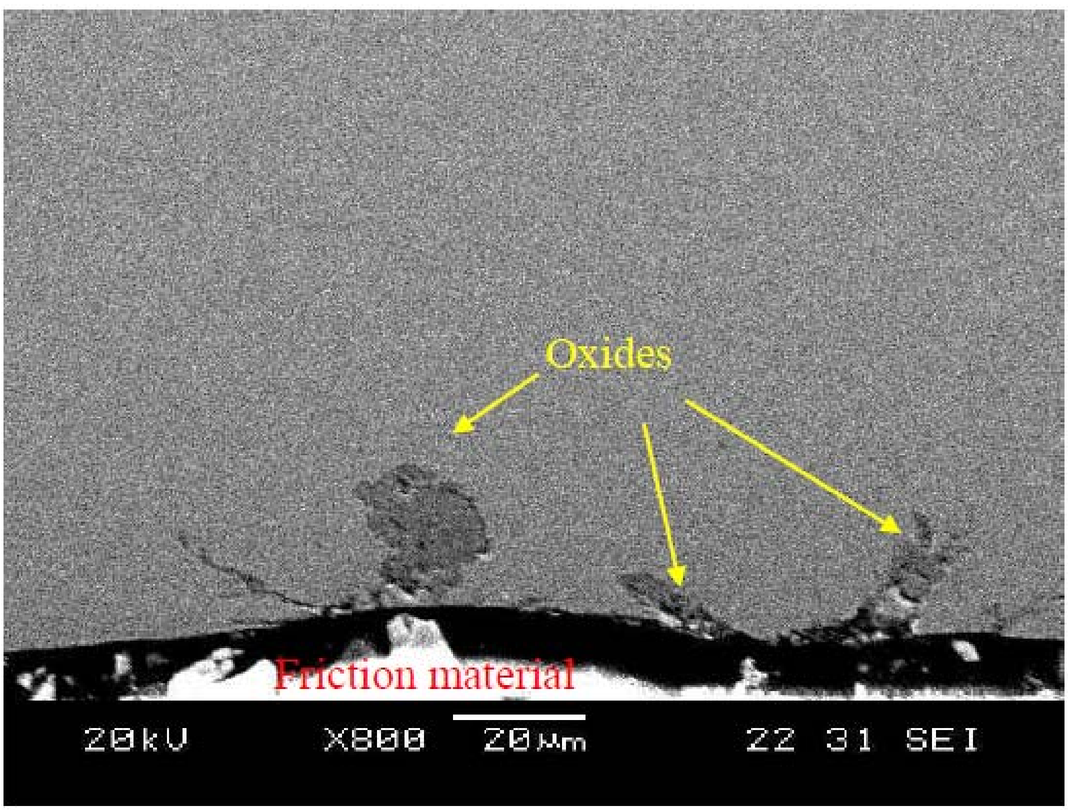


Figure 48 - Sample 8: Disc brake shoe - suspected black steel, painted - SEM Image [6]

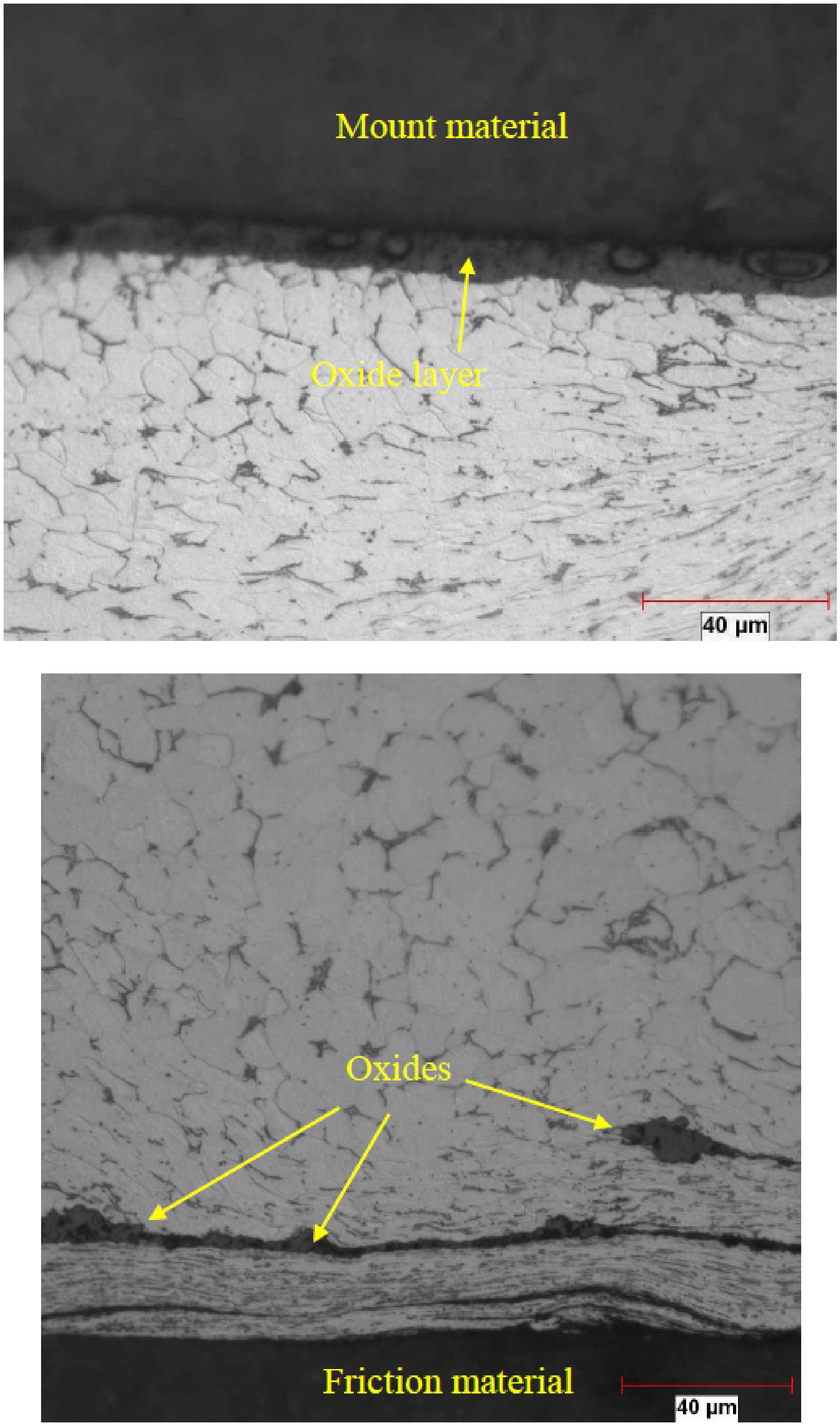


Figure 49 - Sample 8: Disc brake shoe - suspected black steel, painted - Metallographic Microscope Image [6]

Discussions

This report was intended to compare the quality of various aftermarket pad sets, including an OES pad set. As the tests show, several issues seriously affecting quality are present in many aftermarket pad sets. This indicates that the quality requirements of the OEM pad are not being followed and perhaps not even known by many of the manufacturers tested. At this time it should be noted that the National Highway Traffic Safety Administration (NHTSA) regulates brake safety and braking performance only to new vehicles with OEM pads installed [7]. No significant safety or performance regulation exists which apply to aftermarket brake pad suppliers to the North American market.

CMM Dimensional Analysis

The results of the dimensional analysis are summarized below:

- Of the thirty two (32) disc brake pads measured prior to testing, many of the pads from sets 7 and 8 had critical dimensions already out of the OE specified tolerance. Evidently, these samples were manufactured out of the operational limits of the OEM even before they were subjected to salt spray. The frequency of the out of tolerance parts indicates poor dimensional capabilities in the stamping process. It is also possible the manufacturer does not know what the actual dimensional tolerances are for this particular vehicle application and has designed their tooling based on incomplete reverse engineering.
- Sets 1, 2, 7, and 8 each had flatness exceeding the maximum tolerance on several pads. This could partially be for the same reasons as above, especially considering how far out of tolerance these disc brake shoes were. The OES set and set 4 each had one pad slightly over the maximum flatness specification. It is reasonable to conclude that the same residual stresses that pulled in on the abutment dimensions may also have disrupted the flatness on all of the pads during the tumbling operation.

Corrosion Test

The only pad set that did not exceed the 5% maximum red rust specification within the first half of the 96 hour salt bath was set 4 which had zinc electroplating. Zinc prevents corrosion by forming a physical barrier and acting as a sacrificial anode. Zinc hydroxide reacts in the atmosphere with carbon dioxide to yield a thin, resistant, stubborn and fairly insoluble dull gray layer of zinc carbonate, which adheres to the underlying zinc, further protecting it from corrosion [3]. Zinc hydroxide also does not expand significantly during corrosion like red rust does.

Zinc electroplating, while excellent in its attachment to the metal it is applied to, is also known for providing poor adhesion properties with regards to paint. So it was not surprising to see the paint on all of the set 4 samples to show such rapid paint separation. The peeling paint created nucleation sites for red rust to form, oxidize further and cavitate. The zinc plated pads would likely have tested better without any paint at all.

The OES pad set, which presumably used pickled and oiled steel, still failed the salt spray test, though not as quickly and severely as the aftermarket pads without zinc plating. Mild rust inhibitors used during washing and light-duty phosphate coating for paint adhesion are typically used on OEM and OES shoes. This would explain why the OES pad had better paint retention than the other pads.

It is evident from the amount of red rust formation and the speed with which it occurred on all of the other aftermarket pads, that no rust protection was applied to the shoes other than paint. The test results prove that any paint compromised by road debris, wear, etc., becomes worthless as corrosion protection during a disc brake pad's actual service cycle. In addition, several observations indicate that some properties of the disc brake shoes were actually facilitating red rust formation, such as the presence of mill scale.

Mill scale occurs during the hot rolling process in steel making, when the combination of temperature and oxidization from water cooling causes very thin layers of iron oxide to form on the surface of the steel. Steel that still has these layers is often called black steel, because of the coloration of the oxides. These oxides are ceramic, not metallic, and are not attached to the steel [8]. If they are not properly removed using a process of acid cleaning called pickling, those layers will remain on the surface of the disc brake shoe. Any substance bonded to the surface of a disc brake shoe that still has this scale will not be bonded to the steel disc brake shoe wherever the scale is present. Further, such scale will actually accelerate red rust and the resulting corrosion, as it supplies new nucleation sites for rust to grow, with pre-oxidized material available to facilitate the spread.

A less expensive method commonly used for removing mill scale is shot blasting. Many brake pad manufacturers will use shoes that were not pickled, but instead are shot blast after the stamping operation to remove mill scale. While shot blasting does effectively remove some of the layers of oxide, it does not remove all of them. In fact, the hard, abrasive oxides are actually imbedded into the surface of the steel, creating deep nucleation sites and micro-fractures where corrosion can do even more damage. Also, because the shot blasting is done after the disc brake shoes are stamped, the process can significantly affect the dimensions and create surface stresses.

Pad sets 1, 5, 7 and 8 had an unknown black substance that immediately became dislodged from the disc brake shoe surface, collecting in any cavities, such as blind holes in the disc brake shoe and inside corners. Sets 1 and 5 had the most visible, but all the above showed discoloration all over the disc brake shoe. Any crevices or 'pits' where this substance collected had increased red rust formation. All of the above pads had the easily recognizable surface texture of shot-blasted disc brake shoes, when they were inspected prior to testing. The same pads also displayed corrosion behavior consistent with disc brake shoes that still had excessive traces of mill scale.

Causing even greater alarm was the amount of red rust building up all around the base of the lining material, where it is attached to the disc shoe. Because many friction material formulations contain dissimilar metals, and cured lining has abundant nucleation sites, the lining attachment to the disc brake shoe is particularly vulnerable to oxidization and corrosion. Rust cavitation between the lining material and the disc brake shoe is a well-known phenomenon commonly called 'rust jacking', as the lining is physically pried from the disc brake shoe as a result. Sometimes rust jacking is partial, affecting performance and causing excessive noise. Sometimes the lining separates entirely, leaving no friction material at all. Once rust jacking has started happening in an installed brake pad, the entire brake system is compromised. Considering this fact, too much emphasis cannot be placed on the importance of protecting this attachment.

Dimensional Analysis During and After Corrosion Test

Measurements taken during and after the salt spray test show that, predictably, abutment dimensions will increase when surface rust occurs. Whether or not the steel used was properly pickled and oiled, or simply shot blast, did not seem to have any impact on how much rust formed at the edges of the shoes. Considering that mill scale occurs only on the surface of the raw steel used in stamping, it would necessarily follow that mill scale would not be present on the abutment surfaces of a stamped shoe. Rather than mill scale, it is simply the failure of paint as corrosion protection that allows rust accumulation on all the disc brake shoes.

The only disc brake pad set that recorded a completely different dimensional change was, again, the pads with zinc electroplate. Abutment dimensions increased then decreased in some cases. It was observed that the paint was not adhering to the zinc plating, but partially peeling off in some areas and accumulating in others. It can be concluded that the displaced paint could affect the critical dimensions as it moves and peels away. Again, these pads would have likely performed better with no paint at all.

Surface Analysis

The presence of oxide particles embedded beneath the surface, and the grain structure deformation found on black steel coupons prove that the shot blasting process not only fails to remove all of the oxides, it actually embeds oxide particles into the steel.

The pad suspected of being made with mill scale black steel had the same grain deformation and embedded oxide particles as found on the black steel coupons. The micrographs clearly showed embedded oxides and localized oxide layers where the lining and steel are supposed to bond. These oxides interfere with lining attachment and provide nucleation sites for the formation of red rust, leading to rust jacking, as described earlier.

Conclusions

Results from salt spray, dimensional analysis, shear and surface analysis testing prove the existence of black steel in the randomly selected batch of disc brake pads available in the North American market. The presence of mill scale in these pads accelerated the rate of oxidation in all salt spray tests performed and resulted in fluctuations in critical functional dimensions of the disc brake shoe. The industry salt spray standard, ASTM B117, requires corrosion resistance of 96 hours of continuous exposure to salt. All of the uncoated samples tested failed this test and didn't make it past the 20 hour mark. The zinc coated pad outperformed all other samples in this test.

Paint is used as a protectant against corrosion. Due to the harsh environments brakes operate in, this thin layer of paint can quickly flake off as it goes through the brake cycle. Zinc electroplating on the other hand is a superior and effective method of rust protection and is an accepted industry standard. Our tests prove that paint, when compromised, on disc brake pads, is ineffective as a rust protection and facilitates the acceleration of red rust.

Finally, metallographic analysis of the surface was performed and the results confirmed the presence of mill scale (iron oxides) embedded in sample pads, as well as deformed grain structure, which is consistent with compressive stresses caused by the shot blasting process. The disc brake pad utilizing the HRPO steel did not have any oxides or grain deformation present.

Embedded oxide particles trapped under the lining material create ideal conditions for corrosion, eventual rust jacking and ultimate failure of the brake system.

Unsafe brake pads introduced into the North American market are a safety hazard. The lack of any industry regulation allows irresponsible manufacturers to offer consumers unsafe brake pads. Randomly selected pads by the GBSC used in this test prove these pads are readily available to consumers in this market.

The only effective method of removing mill scale (iron oxides) is to pickle and oil the steel. The most effective method of protection for brake pads is zinc coating, not just paint.

Recommendations

The GBSC makes the following recommendations:

- Disc brake pad manufacturers must ensure that the disc brake shoes they are sourcing are stamped by responsible disc brake shoe manufacturers.
- Disc brake shoe manufacturers must engineer their products with due diligence and proper understanding of the disc brake shoe’s functional requirements.
- Disc brake shoes must be stamped from steel that has been pickled and oiled to remove all layers of mill scale (iron oxides) and surface impurities to ensure that:
    - Rust formation is not further facilitated by nucleation sites from oxides which are on and embedded in the surface of the steel.
    - Plating/paint adhesion is not compromised by oxide layers which are not attached to the steel.
    - Tooling is not prematurely worn and damaged by hardened inclusions present in the steel.
- Shot blasting should not be considered an acceptable method of removing all mill scale from disc brake shoes.
- Shot blasting the disc brake shoe after it has been stamped to the required tolerances may deform and compromise critical dimensions of the disc brake shoe causing fit, function, and safety issues in the brake caliper assembly.
- Superior methods of corrosion protection should be considered instead of paint. Zinc electroplating is an obvious example, considering its performance during testing. However, pads with only zinc plating should be tested to validate the conclusions that it would work better without paint. Also, other coatings may have similar capabilities as zinc plating and could be investigated.

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Appendix A

Global Brake Safety Council Members

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Table 6 - GBSC Members

To find out more about the GBSC and to join the mission of raising awareness of brake safety please visit www.gbscouncil.com

Appendix B

Failed Disc Brake Pad Field Samples

(a)

(b)

(c)

(d)

Figure 50 - Failed Disc Brake Pad Field Samples - Rust jacking

Images (a) to (d) show examples of severe rust jacking. Notice there is plenty of friction lining remaining on the pad in (b). Rust Jacking in (d) is more severe and has lifted a significant portion of friction lining off the shoe.

(a) (b)

(c) (d)

(e) (f)

Figure 51 - Failed Disc Brake Pad Field Samples - Cracked and Sheared Linings

Image (a) lining cracked and sheared off prematurely, (b) Zinc coated disc brake shoe with mechanical retention, where the friction was worn down to the metal, (c) The entire friction lining has come off due to lining and shows bond failure, (d & e) Early onset of Rust Jacking on new friction lining, (f) Batch of failed field brake pads from North American job shops.

Appendix C

Disc Brake Pad Dimensional and Oxidation Testing Procedures for Comparative Purposes

1. Eight (8) pad sets from six (6) different manufacturers are ordered.
2. Manufacturer's name, lining origin, attachment method and type of lining material will be recorded.
3. Sample numbers need to be assigned to each set and each individual part. For instance, sample number "**1.2**". The first digit represents the set number and the decimal place indicates the pad in that set.
4. Each pad must have its sample number engraved clearly into the lining material.
5. Photos are taken of each pad which need to show the condition of the painted steel shoe and lining material.
6. Critical abutment dimensions and flatness of all pads will be measured using a CMM probe module (Renishaw TP20) and Renishaw Stylus with specifications: M2 CYL D2R L20 EWL7.2 (P/N: A-5000-7812).

Figure 52 - CMM probe module and stylus

7. CMM will be programed to gather measurement points for abutments and flatness. The images below illustrate the points that will be collected:

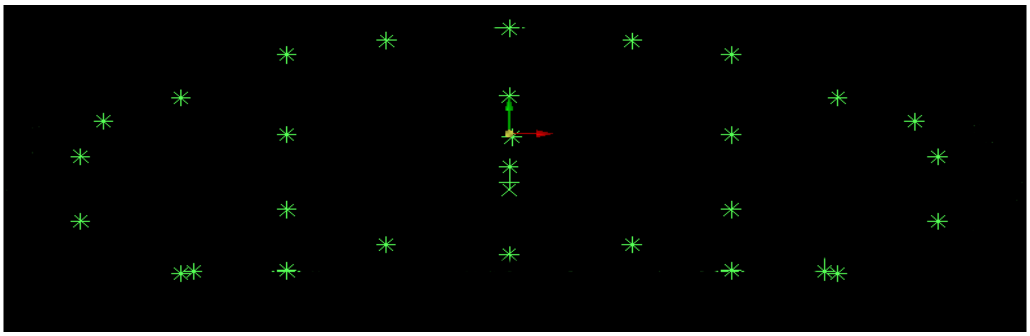

Figure 53 - Position of points taken with CMM probe for flatness

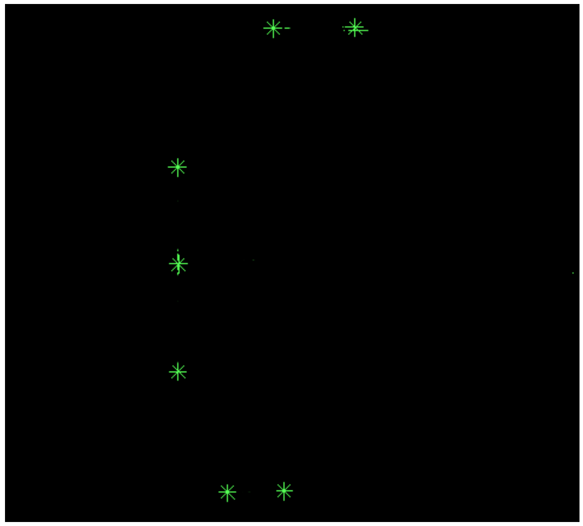

Figure 54 - Position of points taken with CMM probe for left-side and right-side abutments

8. Tumbling process: pads are tumbled ‘dry’ for 10 minutes using ¾” ceramic media. Cleaning/rust inhibitor solution must not be used during tumbling.
9. Pads must be wiped free of debris and solution residue after tumbling.
10. Photos are taken of each pad, as per the instructions in step 5.
11. CMM measurements taken for all pads as per the instructions in step 7.
12. Corrosion test will be conducted for 20 hours. Corrosion test specifications are:
    - Test standard: ASTM B117
    - Salt composition: 5% NaCl
    - Chamber temperature: 35°C
    - Bubble tower temperature: 48°C
    - Air saturator tower pressure: 16 PSI
    - Supported angle of parts: 15-30°

13. Photos will be taken after the corrosion test, per step 5.
14. CMM measurements, per step 7.
15. Corrosion test for another 20 hours (40 hours in total).
16. Photos will be taken after the corrosion test, per step 5.
17. CMM measurements, per step 7.
18. Corrosion test for another 20 hours (60 hours in total).
19. Photos will be taken after the corrosion test, per step 5.
20. CMM measurements, per step 7.
21. Corrosion test for another 20 hours (80 hours in total).
22. Photos will be taken after the corrosion test, per step 5.
23. CMM measurements, per step 7.
24. Corrosion test for another 16 hours (96 hours in total).
25. Photos will be taken after the corrosion test, per step 5.
26. CMM measurements, per step 7.
27. Analyse and report findings.

Appendix D

Dimensional Analysis - Full report

Initial CMM

Sample Set N°.	Brand	OE Tolerance (with paint): 153.94 - 154.20 mm Abutment Width [mm] Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	154.15	154.15	154.08	154.13
2	Economy grade-2	153.97	153.95	153.95	153.97
3	Premium grade-1	154.08	154.13	154.08	154.05
4	Premium grade with zinc plating	153.97	154.00	154.08	154.05
5	Mid grade-1	154.15	154.13	154.10	154.15
6	OES	154.10	154.13	154.15	154.13
7	Premium grade-2	154.25	154.20	154.28	154.20
8	Mid grade-2	153.90	153.95	154.05	153.95

		OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	17.12	17.09	17.17	17.07	17.09	17.12	17.12	17.17
2	Economy grade-2	17.12	17.15	17.20	17.07	17.04	17.02	17.09	17.07
3	Premium grade-1	16.97	17.17	17.17	17.17	17.02	17.15	17.12	17.17
4	Premium grade with zinc plating	17.12	17.12	17.12	17.12	16.97	17.02	17.04	17.02
5	Mid grade-1	17.12	17.15	17.07	17.09	17.17	17.17	17.15	17.17
6	OES	17.04	17.04	17.04	17.09	17.04	17.07	17.04	17.07
7	Premium grade-2	17.12	17.15	17.17	17.15	17.12	17.12	17.15	17.15
8	Mid grade-2	16.94	16.92	16.97	16.97	16.94	16.99	16.94	16.97

		OE Tolerance: 0.16mm maximum			
		Flatness [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	0.18	0.23	0.25	0.18
2	Economy grade-2	0.23	0.08	0.18	0.23
3	Premium grade-1	NA	NA	NA	NA
4	Premium grade with zinc plating	0.15	0.15	0.20	0.15
5	Mid grade-1	0.18	0.15	0.18	0.15
6	OES	0.18	0.13	0.13	0.15
7	Premium grade-2	0.33	0.20	0.20	0.30
8	Mid grade-2	0.38	0.23	0.33	0.25

Table 7 - Initial CMM Dimensional Analysis

CMM after Tumbling

Sample Set N°.	Brand	OE Tolerance (with paint): 153.94 - 154.20 mm — Abutment Width [mm] Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	154.10	154.10	154.05	154.08
2	Economy grade-2	153.92	153.92	153.92	153.95
3	Premium grade-1	154.05	154.05	154.05	154.03
4	Premium grade with zinc plating	153.97	153.97	154.15	154.05
5	Mid grade-1	154.13	154.05	154.05	154.05
6	OES	154.10	154.10	154.10	154.10
7	Premium grade-2	154.20	154.18	154.15	154.18
8	Mid grade-2	153.87	153.92	153.97	153.87

		OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	17.09	17.09	17.15	17.07	17.09	17.09	17.07	17.12
2	Economy grade-2	17.09	17.12	17.17	17.07	17.02	17.02	17.07	17.07
3	Premium grade-1	16.94	17.12	17.17	17.17	17.04	17.15	17.12	17.17
4	Premium grade with zinc plating	17.15	17.07	17.07	17.17	16.99	16.97	17.04	17.02
5	Mid grade-1	17.12	17.15	17.07	17.04	17.15	17.15	17.09	17.12
6	OES	17.04	17.04	17.04	17.09	17.04	17.04	17.04	17.04
7	Premium grade-2	17.12	17.12	17.12	17.15	17.09	17.12	17.15	17.15
8	Mid grade-2	16.92	16.94	16.97	16.97	16.92	17.02	16.94	16.92

		OE Tolerance: 0.16mm maximum			
		Flatness [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	0.18	0.13	0.23	0.18
2	Economy grade-2	0.25	0.08	0.20	0.20
3	Premium grade-1	NA	NA	NA	NA
4	Premium grade with zinc plating	0.15	0.15	0.20	0.18
5	Mid grade-1	0.15	0.13	0.15	0.10
6	OES	0.18	0.18	0.15	0.15
7	Premium grade-2	0.28	0.20	0.18	0.28
8	Mid grade-2	0.38	0.25	0.36	0.28

Table 8 - CMM Dimensional Analysis after Tumbling

CMM after 20 Hours of Salt Spray

Sample Set N°.	Brand	OE Tolerance (with paint): 153.94 - 154.20 mm Abutment Width [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	154.15	154.15	154.13	154.18
2	Economy grade-2	154.10	153.92	154.00	154.03
3	Premium grade-1	154.10	154.18	154.18	154.08
4	Premium grade with zinc plating	153.97	154.05	154.36	154.15
5	Mid grade-1	154.25	154.20	154.08	154.10
6	OES	154.18	154.18	154.13	154.15
7	Premium grade-2	154.23	154.20	154.18	154.20
8	Mid grade-2	153.92	153.95	154.00	153.87

Sample Set N°.	Brand	OE Tolerance (with paint): 16.94 - 17.20 mm Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	17.15	17.20	17.17	17.12	17.25	17.20	17.09	17.12
2	Economy grade-2	17.17	17.15	17.17	17.07	17.07	17.02	17.12	17.07
3	Premium grade-1	16.99	17.22	17.27	17.50	17.04	17.35	17.27	17.27
4	Premium grade with zinc plating	17.17	17.12	17.20	17.32	17.04	17.17	17.17	17.30
5	Mid grade-1	17.15	17.17	17.15	17.09	17.17	17.22	17.12	17.12
6	OES	17.07	17.12	17.07	17.12	17.07	17.12	17.09	17.07
7	Premium grade-2	17.12	17.17	17.12	17.17	17.17	17.20	17.20	17.20
8	Mid grade-2	17.02	16.94	16.94	16.99	16.94	17.04	16.97	16.97

Sample Set N°.	Brand	OE Tolerance: 0.16mm maximum Flatness [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	0.18	0.13	0.25	0.15
2	Economy grade-2	0.25	0.05	0.20	0.25
3	Premium grade-1	NA	NA	NA	NA
4	Premium grade with zinc plating	0.20	0.20	0.25	0.20
5	Mid grade-1	0.18	0.15	0.15	0.10
6	OES	0.20	0.18	0.13	0.20
7	Premium grade-2	0.25	0.20	0.15	0.20
8	Mid grade-2	0.38	0.25	0.36	0.28

Table 9 - CMM Dimensional Analysis after 20 Hours Salt Spray

CMM after 40 Hours of Salt Spray

Sample Set N°.	Brand	OE Tolerance (with paint): 153.94 - 154.20 mm Abutment Width [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	154.18	154.18	154.23	154.20
2	Economy grade-2	154.10	154.13	154.10	154.05
3	Premium grade-1	154.13	154.20	154.10	154.13
4	Premium grade with zinc plating	154.08	154.13	154.23	154.20
5	Mid grade-1	154.23	154.13	154.20	154.18
6	OES	154.18	154.18	154.13	154.18
7	Premium grade-2	154.23	154.23	154.23	154.31
8	Mid grade-2	153.92	154.03	154.03	153.95

Sample Set N°.	Brand	OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	17.15	17.25	17.20	17.15	17.25	17.22	17.15	17.17
2	Economy grade-2	17.17	17.15	17.20	17.15	17.07	17.07	17.27	17.09
3	Premium grade-1	16.99	17.45	17.45	17.58	17.07	17.42	17.37	17.35
4	Premium grade with zinc plating	17.20	17.17	17.17	17.35	17.07	17.20	17.25	17.30
5	Mid grade-1	17.22	17.20	17.17	17.12	17.17	17.22	17.15	17.15
6	OES	17.17	17.12	17.09	17.15	17.07	17.17	17.12	17.09
7	Premium grade-2	17.15	17.30	17.30	17.17	17.17	17.20	17.22	17.17
8	Mid grade-2	16.97	17.02	17.07	16.99	16.99	17.04	17.04	17.02

Sample Set N°.	Brand	OE Tolerance: 0.16mm maximum Flatness [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	0.20	0.15	0.30	0.15
2	Economy grade-2	0.25	0.08	0.20	0.28
3	Premium grade-1	NA	NA	NA	NA
4	Premium grade with zinc plating	0.18	0.20	0.25	0.23
5	Mid grade-1	0.18	0.25	0.18	0.10
6	OES	0.20	0.18	0.15	0.20
7	Premium grade-2	0.25	0.18	0.15	0.23
8	Mid grade-2	0.38	0.28	0.36	0.28

Table 10 - CMM Dimensional Analysis after 40 Hours Salt Spray

CMM after 60 Hours of Salt Spray

		OE Tolerance (with paint): 153.94 - 154.20 mm			
		Abutment Width [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	154.20	154.20	154.28	154.20
2	Economy grade-2	154.05	154.00	154.08	154.03
3	Premium grade-1	154.13	154.15	154.33	154.10
4	Premium grade with zinc plating	154.03	154.13	154.28	154.18
5	Mid grade-1	154.25	154.15	154.20	154.18
6	OES	154.20	154.18	154.23	154.18
7	Premium grade-2	154.28	154.20	154.18	154.23
8	Mid grade-2	153.95	154.10	154.03	153.95

		OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	17.20	17.25	17.22	17.17	17.27	17.20	17.15	17.17
2	Economy grade-2	17.22	17.40	17.17	17.27	17.07	17.04	17.15	17.07
3	Premium grade-1	17.09	17.53	17.40	17.48	17.07	17.50	17.35	17.53
4	Premium grade with zinc plating	17.17	17.15	17.17	17.30	17.04	17.22	17.17	17.35
5	Mid grade-1	17.27	17.30	17.12	17.20	17.20	17.17	17.15	17.20
6	OES	17.15	17.22	17.12	17.17	17.12	17.17	17.09	17.09
7	Premium grade-2	17.37	17.30	17.30	17.20	17.22	17.20	17.25	17.20
8	Mid grade-2	17.02	17.04	17.02	16.99	17.04	17.12	17.02	17.02

		OE Tolerance: 0.16mm maximum			
		Flatness [mm]			
Sample Set N°.	Brand	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	0.18	0.13	0.33	0.15
2	Economy grade-2	0.25	0.08	0.20	0.25
3	Premium grade-1	NA	NA	NA	NA
4	Premium grade with zinc plating	0.18	0.20	0.25	0.23
5	Mid grade-1	0.18	0.18	0.18	0.18
6	OES	0.20	0.18	0.15	0.23
7	Premium grade-2	0.25	0.18	0.23	0.23
8	Mid grade-2	0.36	0.28	0.38	0.28

Table 11 - CMM Dimensional Analysis after 60 Hours Salt Spray

CMM after 80 Hours of Salt Spray

Sample Set N°.	Brand	OE Tolerance (with paint): 153.94 - 154.20 mm Abutment Width [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	**Economy grade-1**	154.28	154.20	154.31	154.23
2	**Economy grade-2**	154.10	154.08	154.08	154.10
3	**Premium grade-1**	154.18	154.18	154.31	154.10
4	**Premium grade with zinc plating**	154.03	154.13	154.20	154.18
5	**Mid grade-1**	154.23	154.18	154.20	154.20
6	**OES**	154.20	154.20	154.33	154.33
7	**Premium grade-2**	154.28	154.23	154.20	154.23
8	**Mid grade-2**	153.92	154.10	154.05	153.97

Sample Set N°.	Brand	OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	**Economy grade-1**	17.25	17.27	17.22	17.20	17.27	17.22	17.17	17.20
2	**Economy grade-2**	17.27	17.20	17.17	17.27	17.12	17.04	17.27	17.12
3	**Premium grade-1**	17.20	17.65	17.42	17.53	17.07	17.68	17.45	17.63
4	**Premium grade with zinc plating**	17.20	17.20	17.20	17.30	17.02	17.22	17.20	17.35
5	**Mid grade-1**	17.27	17.30	17.17	17.37	17.25	17.20	17.17	17.27
6	**OES**	17.12	17.20	17.15	17.30	17.12	17.20	17.12	17.15
7	**Premium grade-2**	17.35	17.30	17.35	17.27	17.25	17.20	17.25	17.22
8	**Mid grade-2**	17.07	17.04	17.02	17.02	17.09	17.07	17.12	17.09

Sample Set N°.	Brand	OE Tolerance: 0.16mm maximum Flatness [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	**Economy grade-1**	0.20	0.13	0.30	0.15
2	**Economy grade-2**	0.33	0.10	0.20	0.25
3	**Premium grade-1**	NA	NA	NA	NA
4	**Premium grade with zinc plating**	0.18	0.20	0.20	0.25
5	**Mid grade-1**	0.18	0.20	0.23	0.18
6	**OES**	0.20	0.20	0.15	0.20
7	**Premium grade-2**	0.23	0.18	0.18	0.23
8	**Mid grade-2**	0.41	0.28	0.36	0.28

Table 12 - CMM Dimensional Analysis after 80 Hours Salt Spray

CMM after 96 Hours of Salt Spray

Sample Set N°.	Brand	OE Tolerance (with paint): 153.94 - 154.20 mm			
		Abutment Width [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	154.33	154.28	154.33	154.28
2	Economy grade-2	154.13	154.13	154.18	154.13
3	Premium grade-1	154.18	154.20	154.33	154.10
4	Premium grade with zinc plating	154.03	154.05	154.23	154.20
5	Mid grade-1	154.28	154.15	154.25	154.28
6	OES	154.25	154.20	154.33	154.23
7	Premium grade-2	154.33	154.23	154.23	154.23
8	Mid grade-2	153.95	154.13	154.08	153.97

Sample Set N°.	Brand	OE Tolerance (with paint): 16.94 - 17.20 mm							
		Abutment Height LEFT-SIDE [mm]				Abutment Height RIGHT-SIDE [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4	Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	17.25	17.32	17.37	17.27	17.25	17.22	17.20	17.20
2	Economy grade-2	17.37	17.22	17.20	17.27	17.25	17.12	17.37	17.15
3	Premium grade-1	17.30	17.73	17.48	17.78	17.07	17.68	17.55	17.65
4	Premium grade with zinc plating	17.20	17.20	17.27	17.30	17.02	17.22	17.17	17.37
5	Mid grade-1	17.37	17.30	17.25	17.37	17.25	17.22	17.35	17.32
6	OES	17.15	17.20	17.15	17.20	17.12	17.20	17.15	17.15
7	Premium grade-2	17.37	17.45	17.45	17.40	17.27	17.27	17.30	17.22
8	Mid grade-2	17.15	17.17	16.99	17.07	17.12	17.12	17.09	17.17

Sample Set N°.	Brand	OE Tolerance: 0.16mm maximum			
		Flatness [mm]			
		Pad 1	Pad 2	Pad 3	Pad 4
1	Economy grade-1	0.25	0.18	0.28	0.20
2	Economy grade-2	0.25	0.10	0.20	0.25
3	Premium grade-1	NA	NA	NA	NA
4	Premium grade with zinc plating	0.18	0.23	0.25	0.23
5	Mid grade-1	0.18	0.20	0.18	0.15
6	OES	0.08	0.20	0.15	0.13
7	Premium grade-2	0.25	0.18	0.18	0.25
8	Mid grade-2	0.38	0.28	0.36	0.28

Table 13 - CMM Dimensional Analysis after 96 Hours Salt Spray

Appendix E

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SURFACE ANALYSIS OF VARIOUS METAL SAMPLES USED IN BRAKE SYSTEMS

PO#: PH58316
Laboratory Ref. #G550223
January 28, 2015

EXOVA - CAMBRIDGE

Per: **Mario Arenas, PEng.**
Metallurgist

Per: **Carl Fleck, CET**
Metallurgical Dept. Manager

(Samples will be retained for a period of six months prior to disposal)

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SURFACE ANALYSIS OF VARIOUS METAL SAMPLES USED IN BRAKE SYSTEMS

1. INTRODUCTION

Global Brake Safety Council submitted a number of metal samples to Exova-Cambridge with a request for surface analysis. The samples are used in the assembly of brake systems. The purpose was to investigate the presence of oxides particles or oxide layers at the surface. The matrix of the samples received is shown in the Appendix of this report.

The analysis incorporated scanning electron microscopy and metallographic evaluation. This report summarizes the findings.

2. METHODOLOGY

The SEM examination was performed utilizing a JEOL JSM-5600 scanning electron microscope (MII No B05028) equipped with a PGT Avalon energy dispersive x-ray spectrometer (EDS) *(EDS analysis is a method to semi-quantitatively determine the approximate chemical composition. Hence, the relative concentrations of the identified elements should be taken only as approximations of the real values).*

Cross sections of the surface were cut at random locations or at locations specified by Global Brake Safety Council. The specimens were prepared for metallographic analysis in accordance with ASTM E3-11. The samples were examined in the etched condition with an Olympus PMG3 metallographic microscope (MII No B05034). The microstructural features were exposed using a 3% Nital solution applied under the guidelines of ASTM E407-07.

3. RESULTS

The results for the aforementioned samples are summarized in Table 1 and images or features of interest are presented in Figures 1 to 28.

Exova

Table 1: Results

Sample	Test Object	Surface Condition	Special Notes	SEM Analysis	Metallography
"1"	Black "mill scale" steel Q235B (5"x2")	As-received		A continuous oxide layer was observed. The oxide layer was approximately 10 microns thick (Fig. 1)	The microstructure was composed of ferrite and pearlite. No grain deformation was observed at the surface (Fig. 2)
"2"	Black "mill scale" steel Q235B (5"x2")	Shot Blasted		Embedded particles were found at some subsurface locations (Fig. 3)	The oxide particles had a maximum length of approximately 30 microns. The microstructure was composed of ferrite and pearlite. The grains were deformed at the surface (Fig. 4).
"3"	Black "mill scale" steel Q235B (5"x2")	Shot Blasted with glue		Several embedded particles were found at some subsurface locations (Fig. 5)	The oxide particles had a maximum length of approximately 55 microns. The microstructure was composed of ferrite and pearlite. The grains were deformed at the surface (Fig 6).
"4"	SAE 1010 HRPO steel (5"x2")	Oily (as-received)		No oxides were found (Fig. 7)	The microstructure was composed of ferrite and pearlite. No grain deformation was observed at the surface (Fig. 8)
"5"	SAE 1010 HRPO steel (5"x2")	Shot Blasted		No oxides were found (Fig. 9)	The microstructure was composed of ferrite and pearlite. Grain deformation was observed at the surface (Fig. 10)
"6"	SAE 1010 HRPO steel (5"x2")	Shot Blasted with glue		No oxides were found (Fig. 11)	The microstructure was composed of ferrite and pearlite. A shallow region with a deformed microstructure was observed at the surface (Fig. 12)

Table 1: Results (cont'd)

Sample	Test Object	Surface Condition	Special Notes	SEM Analysis	Metallography
"7"	D833 (SAE 1010 HRPO)	painted	Cross section through blind hole on centerline	No oxides were found (Fig. 13)	The microstructure was composed of ferrite and pearlite. No grain deformation was observed (Fig. 14).
"7.1"	D833 (SAE 1010 HRPO)	painted	Cross section through Ø 4 mm extruded lug	No oxides were found (Fig. 15)	The microstructure was composed of ferrite and pearlite. No grain deformation was observed (Fig. 16).
"8"	D833 (suspected black "mill scale" steel)	painted	Cross section through blind hole on centerline	An oxide layer of approximately 10 microns thick was observed inside the lock hole (Fig. 17 top) The surface at the interface exhibited embedded oxides layer was observed (Fig. 17 bottom).	The oxide layer inside the hole is shown in Fig. 18 top. The microstructure was composed of ferrite and pearlite. The grains were deformed at the surface interface (Fig 18 bottom).
"8.1"	D833 (suspected black "mill scale" steel)	painted	Cross section through Ø 4mm extruded lug	Isolated embedded oxide particles were found (Fig. 19)	The microstructure was composed of ferrite and pearlite. The grains were deformed at the surface (Fig. 20).
"9"	D833 (suspected black "mill scale" steel)	painted	Cross section through blind hole on centerline	An oxide layer was found at the corners of the blind hole (Fig. 21 top and middle). Outside the hole, embedded oxides were found (Fig. 21 bottom)	The microstructure was composed of ferrite and pearlite. The grains were deformed at the surface outside the hole (Fig. 22).
"9.1"	D833 (suspected black "mill scale" steel)	painted	Cross section through Ø 4mm extruded lug	Isolated embedded oxides were found inside (Fig. 23 top) and outside (Fig. 23 bottom) the hole	The microstructure was composed of ferrite and pearlite. The grains were deformed at the surface (Fig. 24).

Table 1: Results (cont'd)

Sample	Test Object	Surface Condition	Special Notes	SEM Analysis	Metallography
"10"	D1282 (suspected black "mill scale" steel)	Oily (as-received)		Few oxide particles were observed at the surface (Fig. 25). EDS analysis revealed that the oxides contained aluminum in addition to iron.	The microstructure was composed of ferrite and pearlite. No grain deformation was observed (Fig. 26).
"11"	D1283 (suspected black "mill scale" steel)	Oily (as-received)		Few oxide particles were observed at the surface (Fig. 27). EDS analysis revealed that the oxides contained aluminum in addition to iron.	The microstructure was composed of ferrite and pearlite. No grain deformation was observed (Fig. 28).

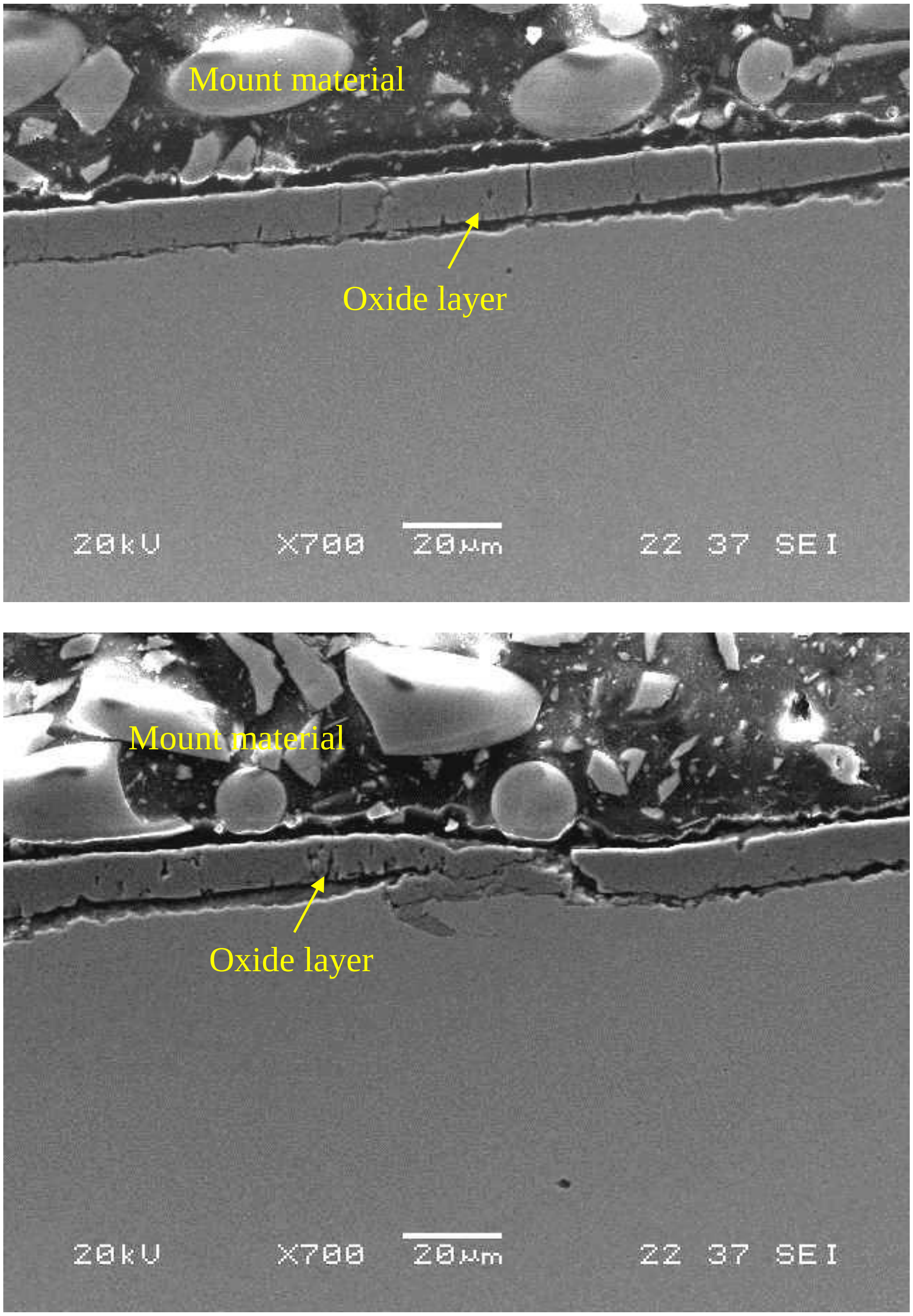
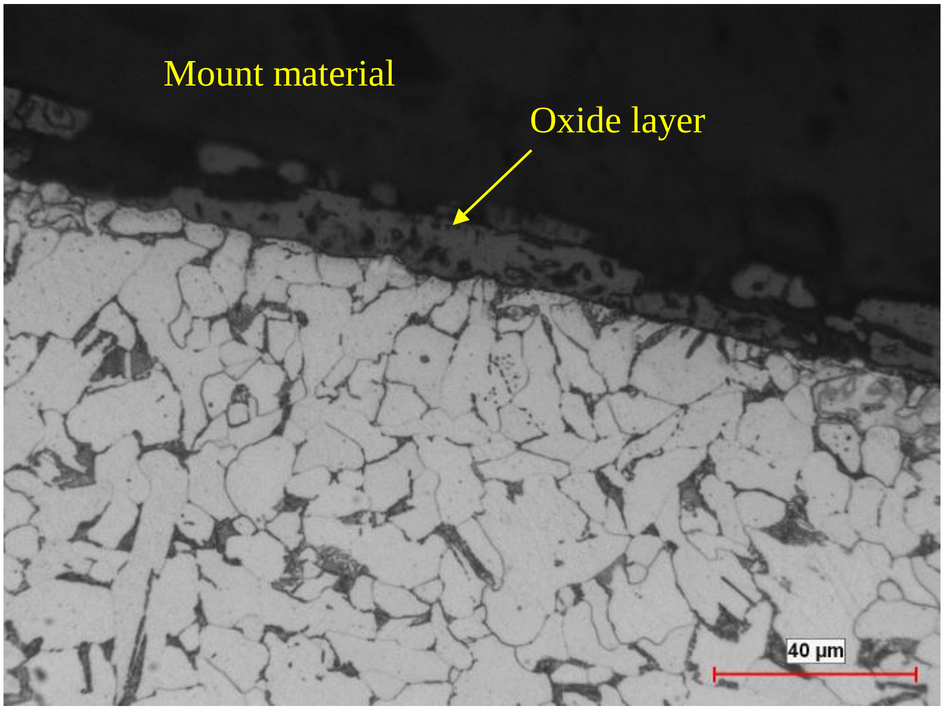


Figure 1: Selected SEM images of the surface of sample "1" black mill scale steel Q235B (5"x2") illustrating the presence of a continuous oxide layer on the surface.



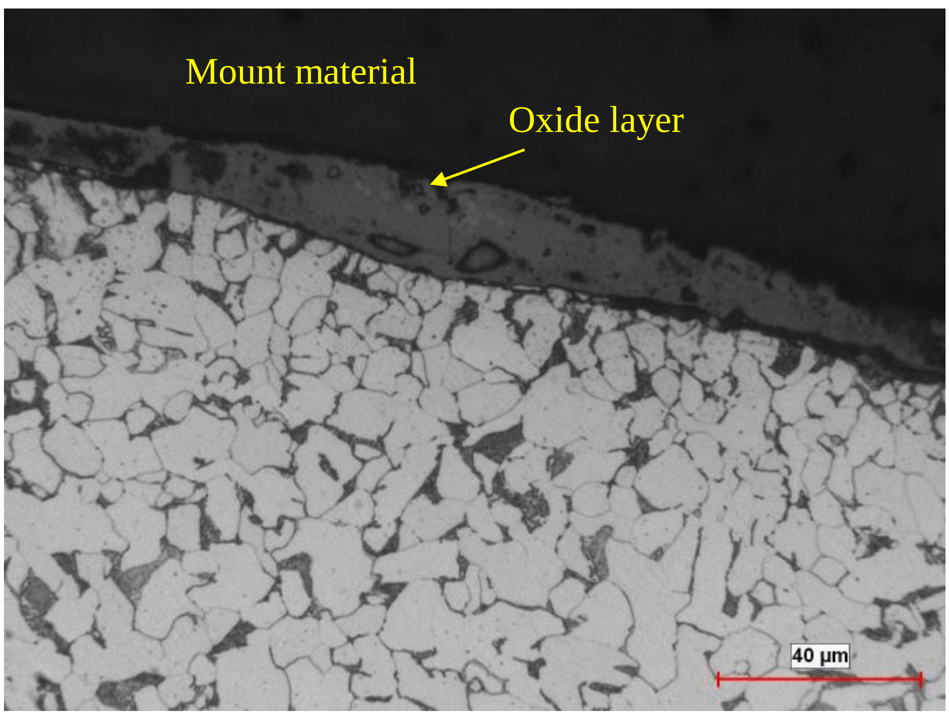


Figure 2: Optical micrographs showing the microstructure of sample "1", black mill scale steel Q235B (5"x2") at the surface. A superficial oxide layer is noted. The microstructure was composed of ferrite (light) and pearlite (dark). No grain deformation was observed (etched with 3% Nital, original magnification: 500X).

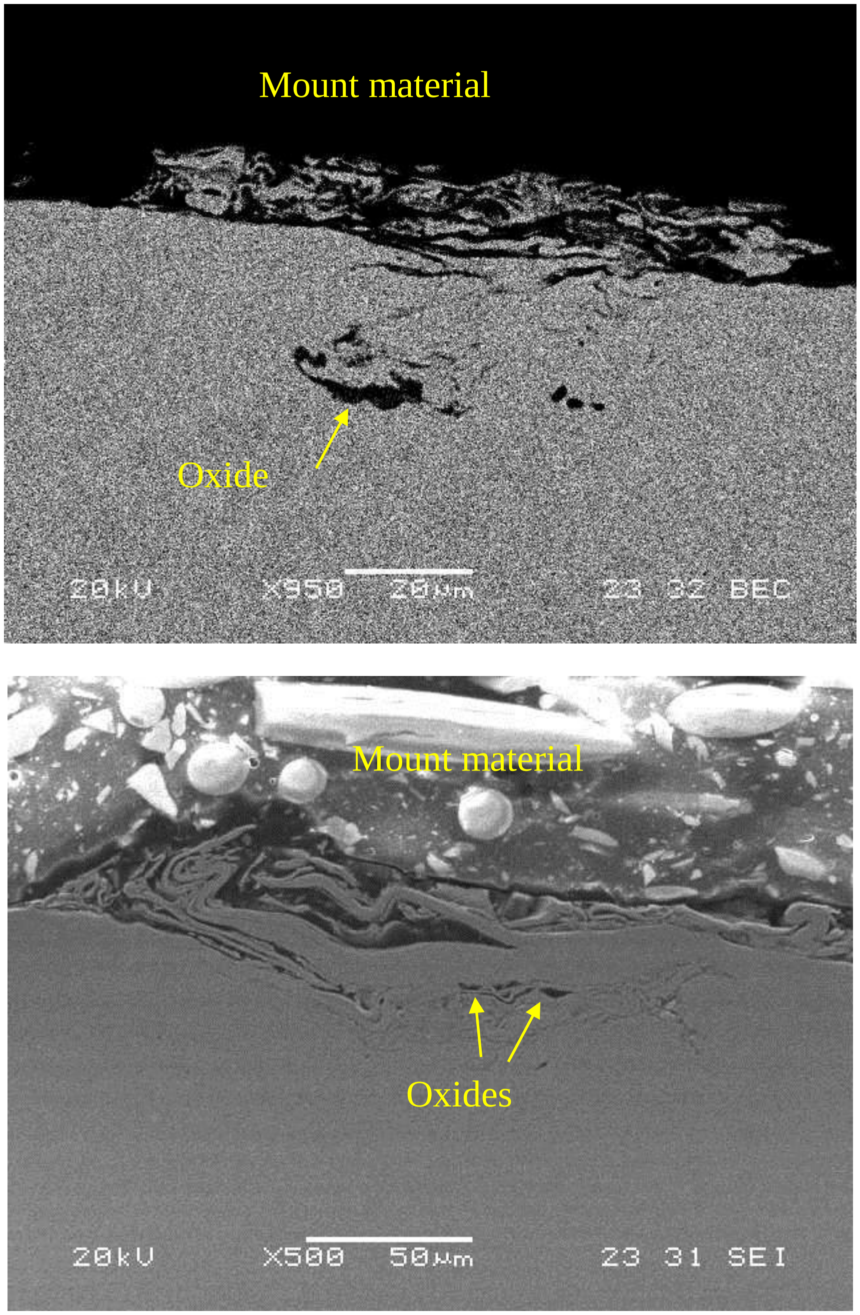
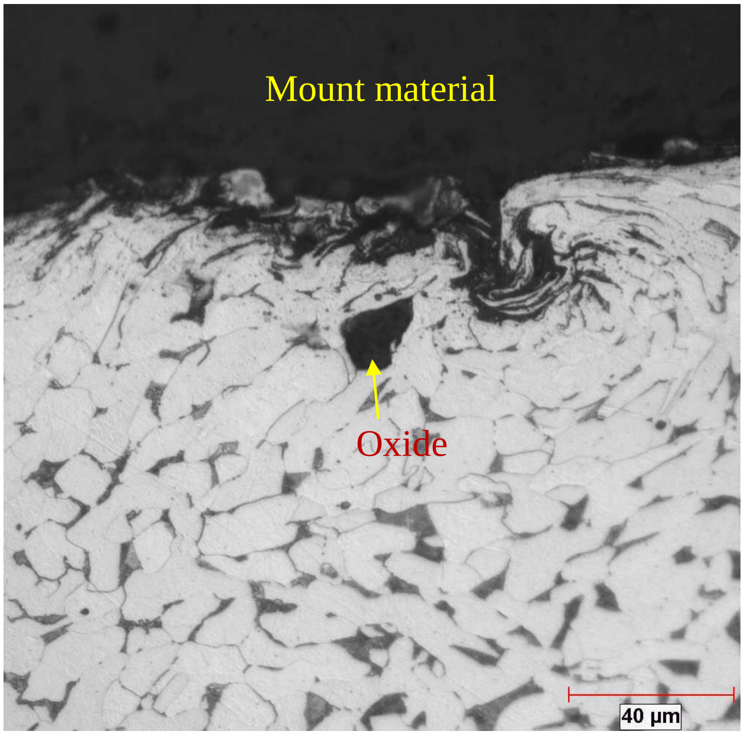


Figure 3: Selected SEM images of the surface of sample "2" black mill scale steel Q235B (5"x2") illustrating embedded oxide particles.



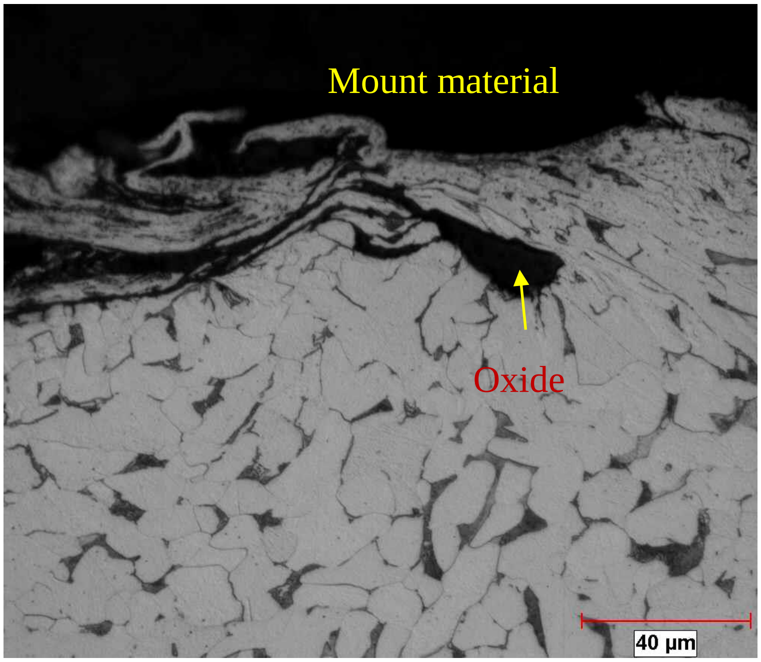
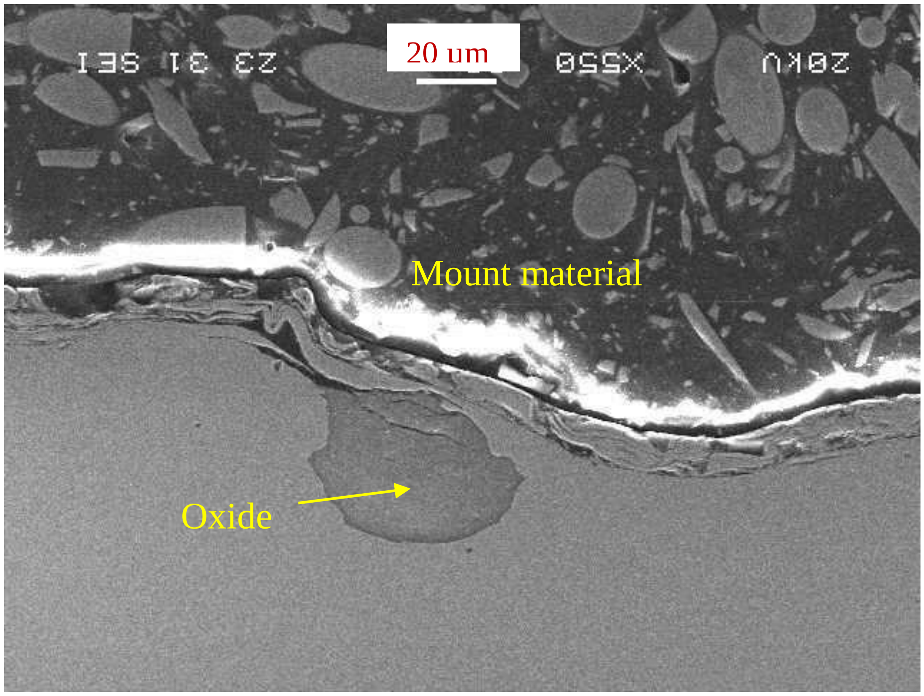


Figure 4: Optical micrographs showing the microstructure of sample "2", black mill scale steel Q235B (5"x2") at the surface. Embedded oxides are noted (arrows). The microstructure was composed of ferrite (light) and pearlite (dark). The grains appeared deformed at the surface (etched with 3% Nital, original magnification: 500X).



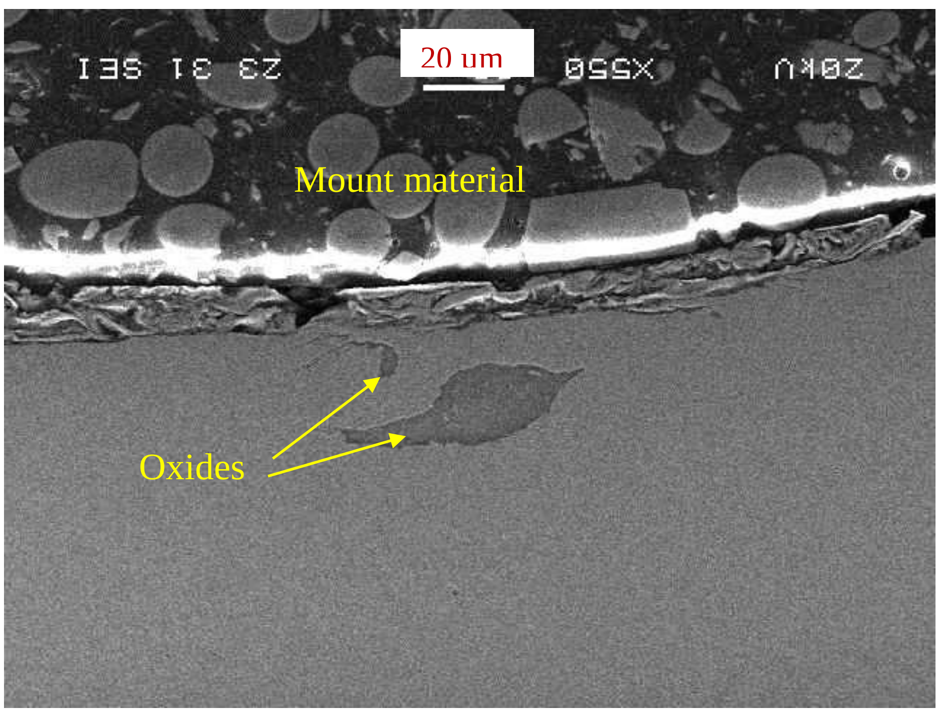
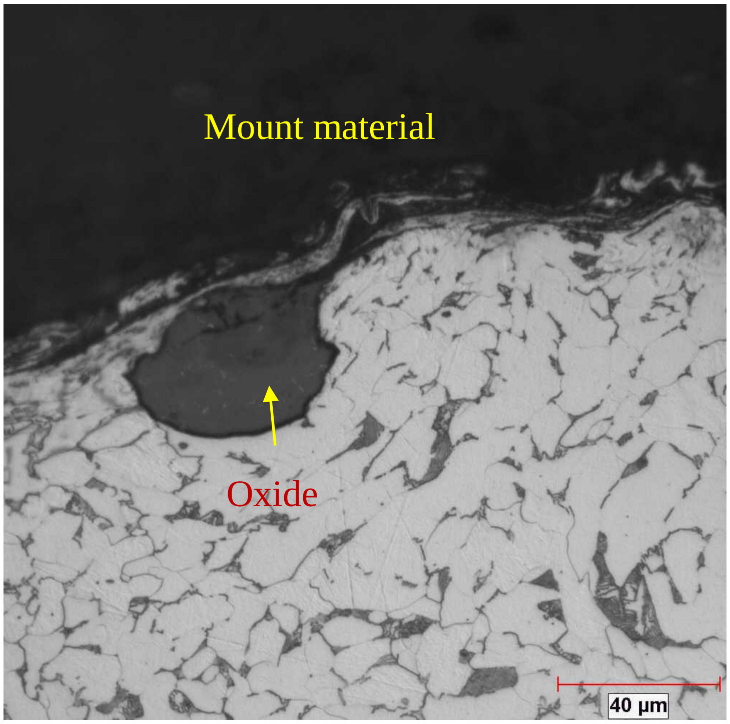


Figure 5: Selected SEM images of the surface of sample "3", black mill scale steel Q235B (5"x2") illustrating embedded oxide particles.



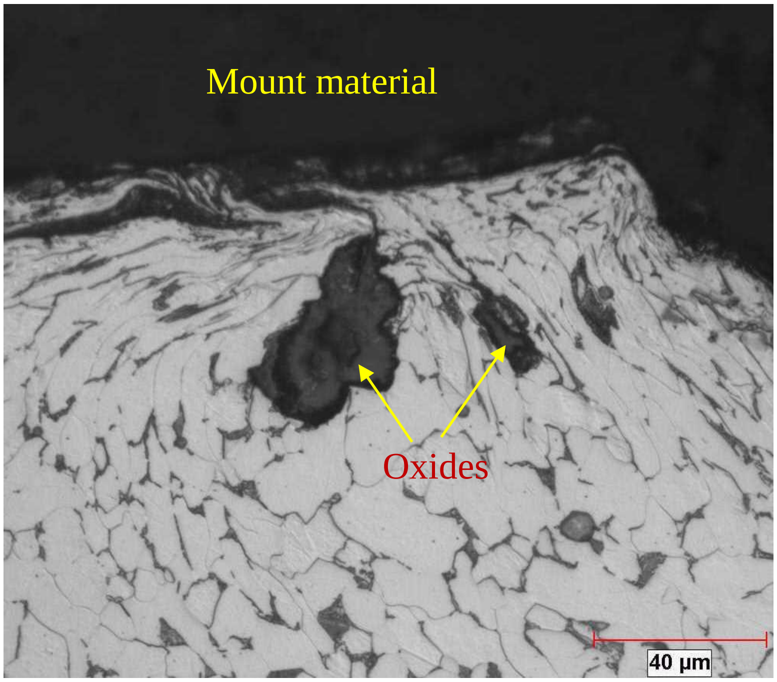
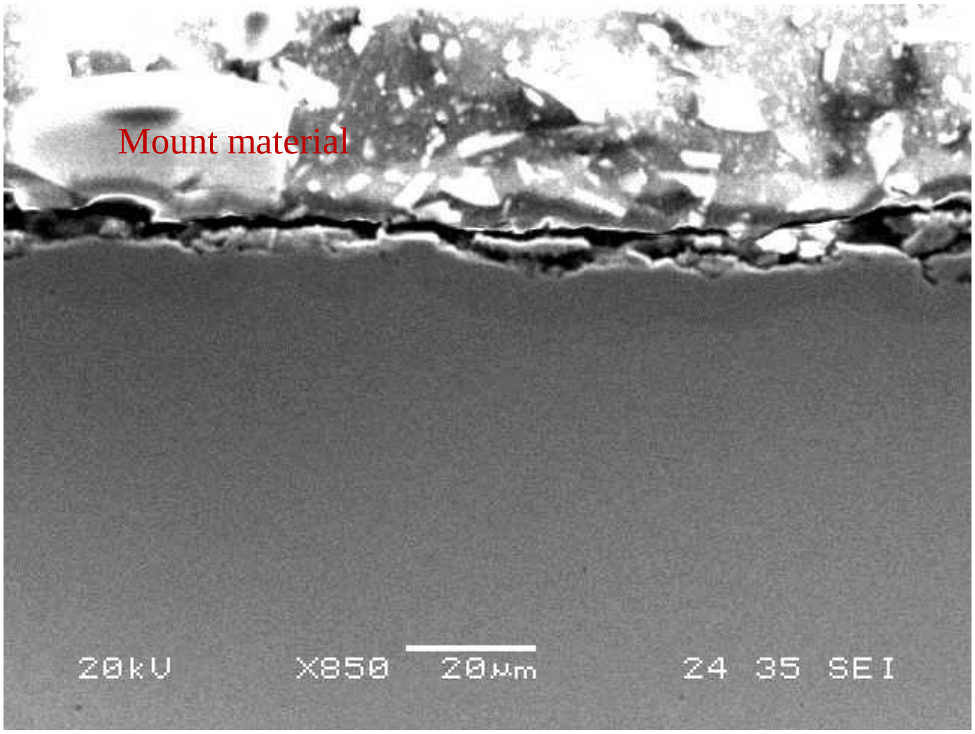


Figure 6: Optical micrographs showing the microstructure of sample “3”, black mill scale steel Q235B (5”x2”) at the surface. Embedded oxides are noted (arrows). The microstructure was composed of ferrite (light) and pearlite (dark). The grains appeared deformed at the surface (etched with 3% Nital, original magnification: 500X).



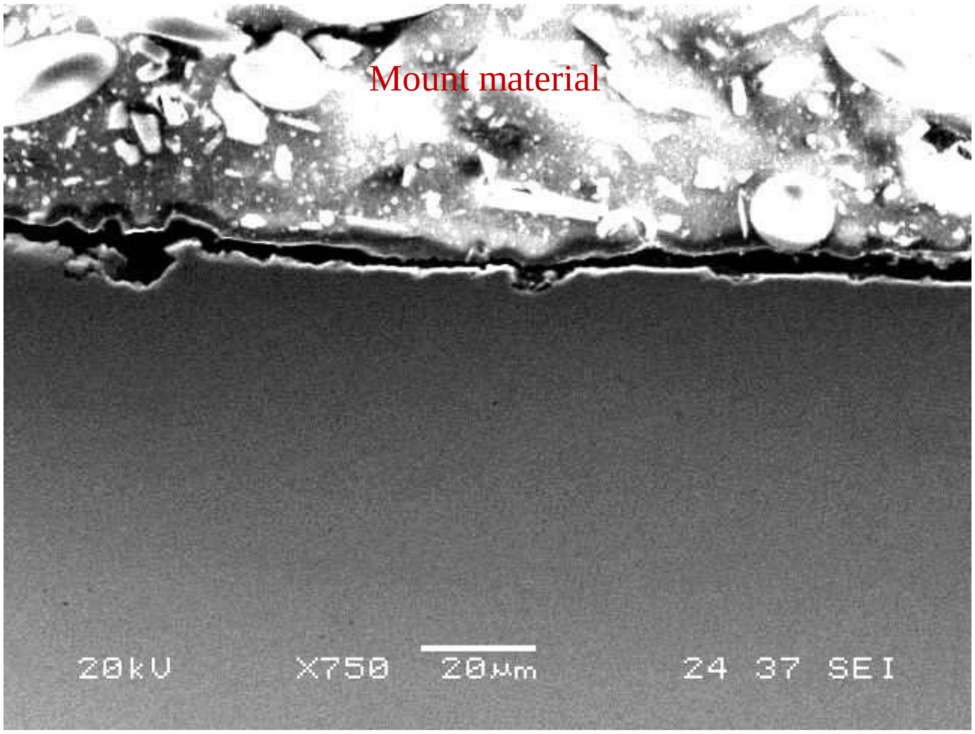
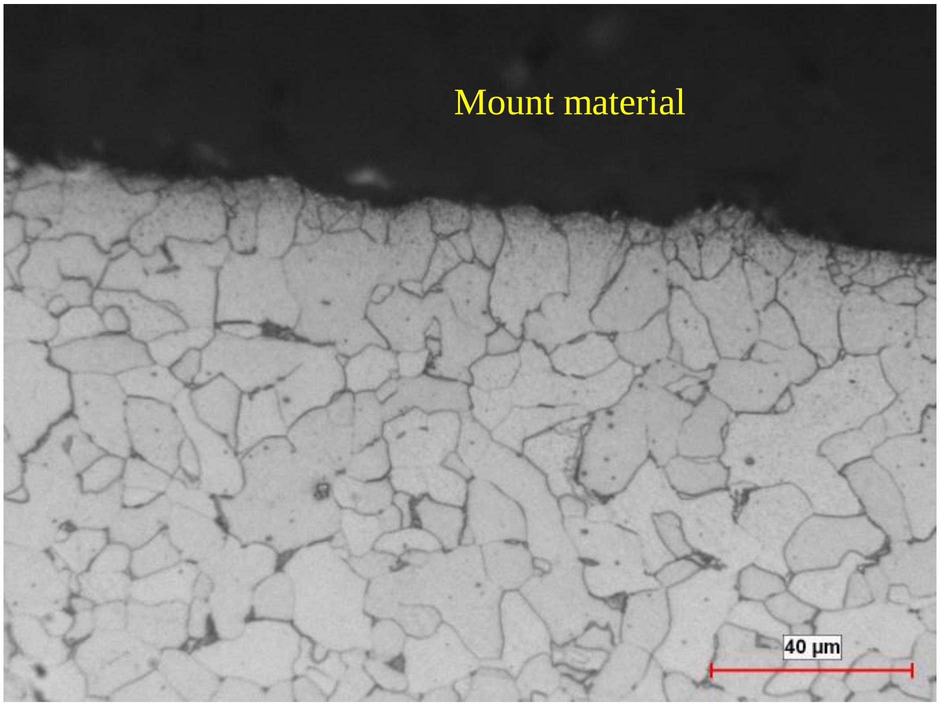


Figure 7: Selected SEM images of the surface of sample “4”, SAE 1010 HRPO steel (5”x2”). No oxide particles were observed.



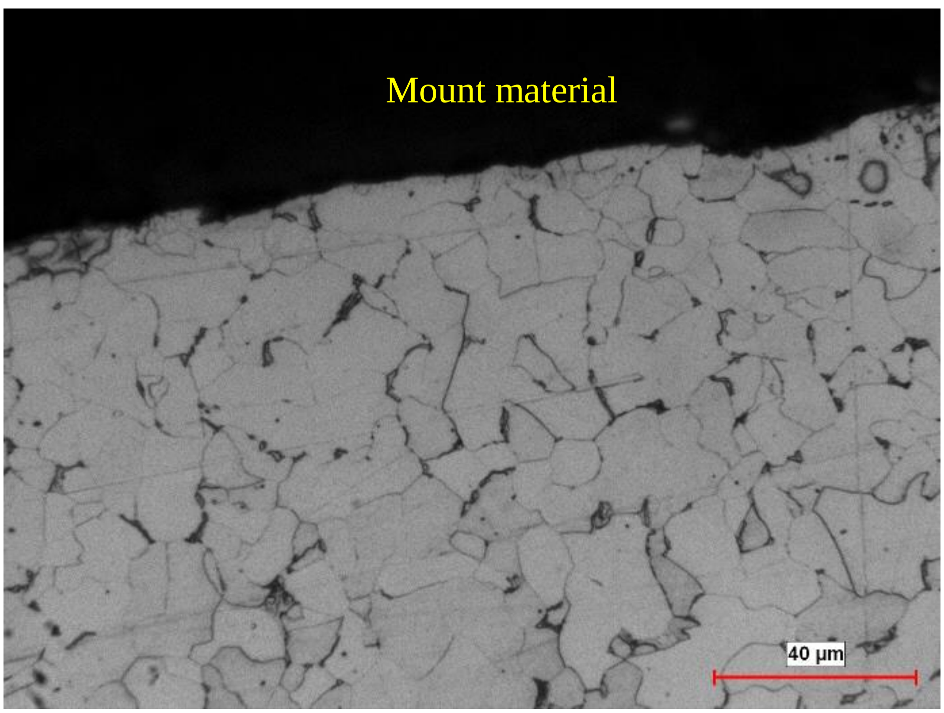
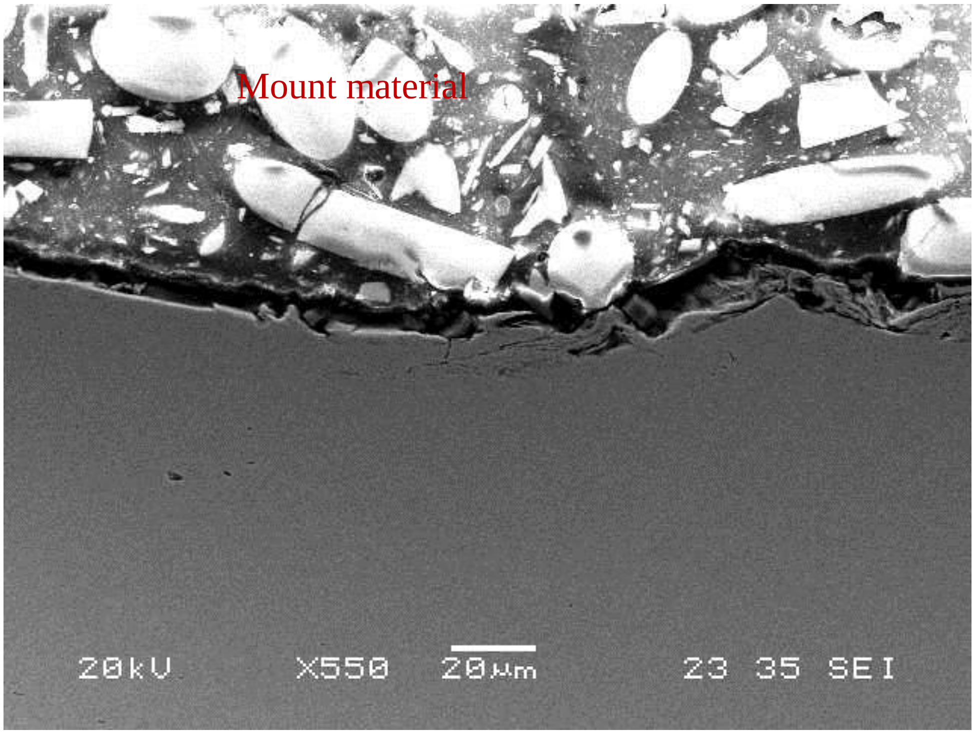


Figure 8: Optical micrographs illustrating the microstructure of sample “4”, SAE 1010 HRPO steel (5”x2”) at the surface. The microstructure was composed of ferrite (light) and pearlite (dark). No oxides were observed. The microstructure was not deformed at the surface (etched with 3% Nital, original magnification: 500X).



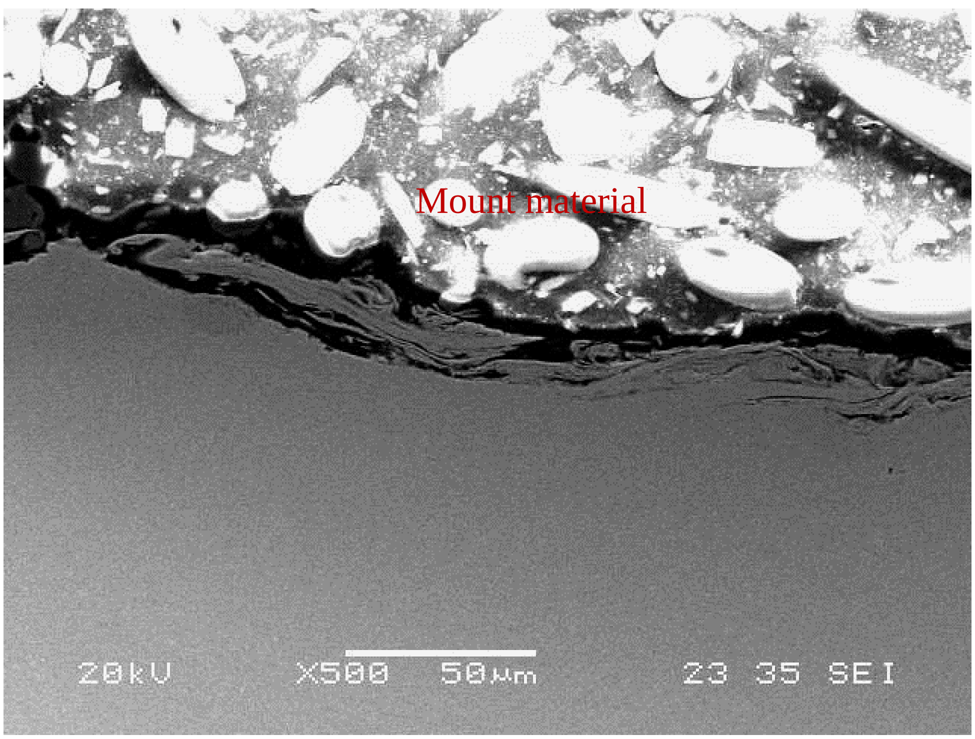
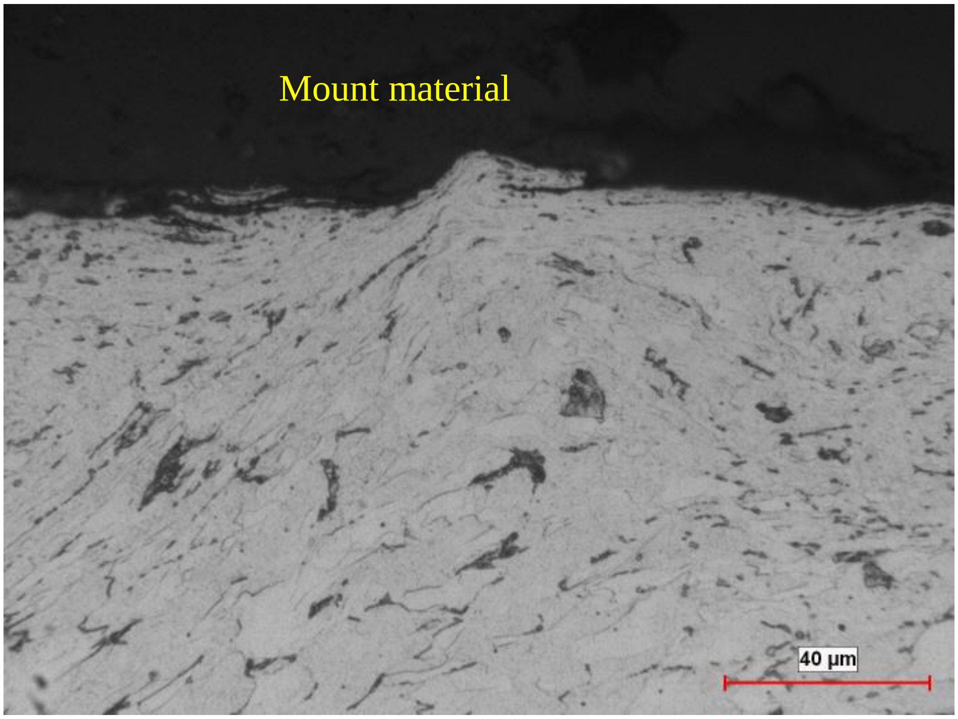


Figure 9: Selected SEM images taken from the surface of sample “5”, SAE 1010 HRPO steel (5”x2”). No oxide particles were observed.



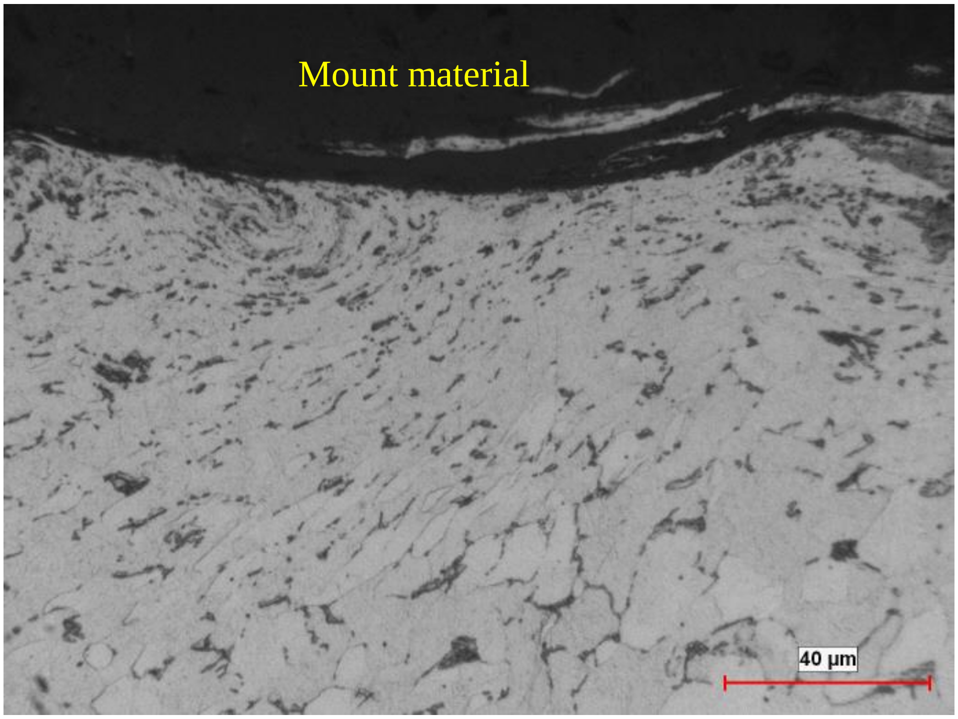
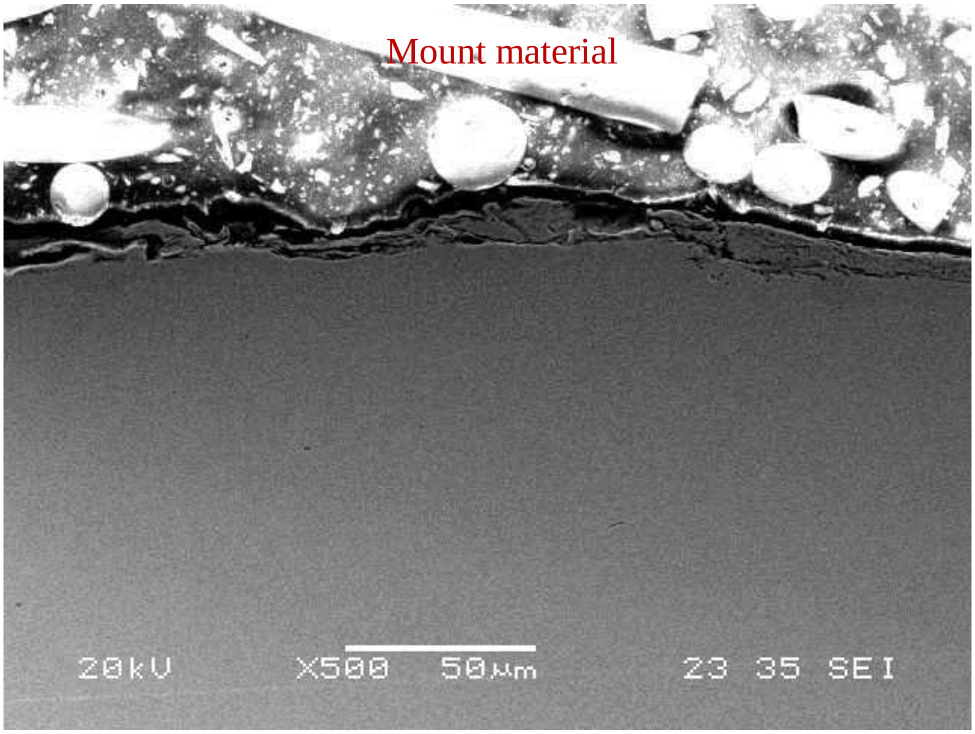


Figure 10: Optical micrographs illustrating the microstructure of sample “5”, SAE 1010 HRPO steel (5”x2”) at the surface. The microstructure was composed of ferrite (light) and pearlite (dark). The microstructure was deformed at the surface. No oxides were observed (etched with 3% Nital, original magnification: 500X).



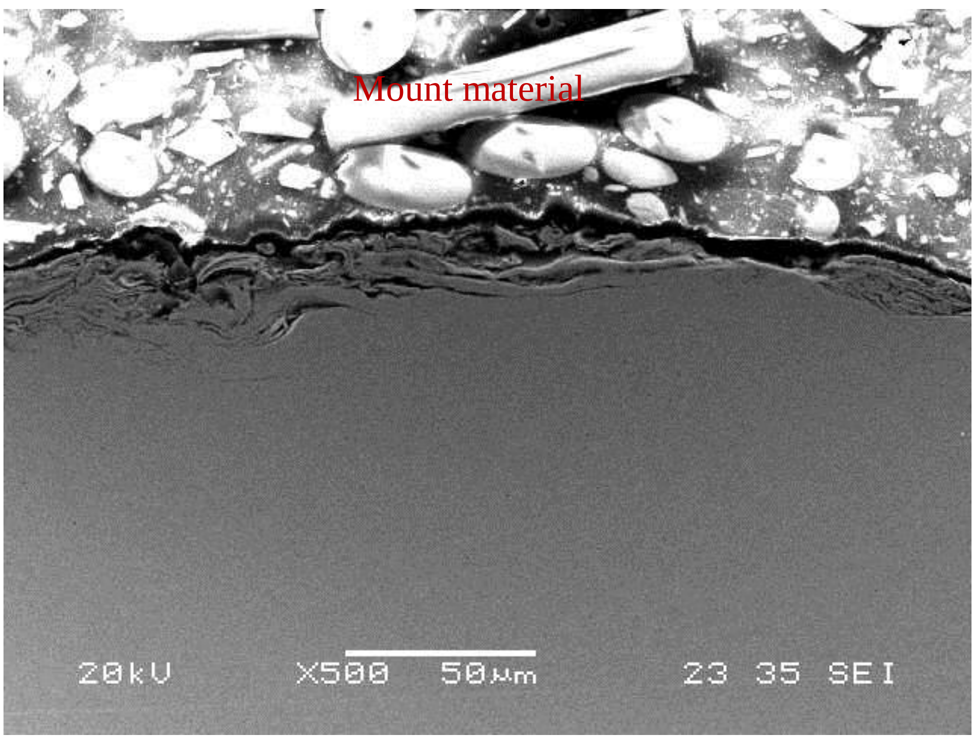
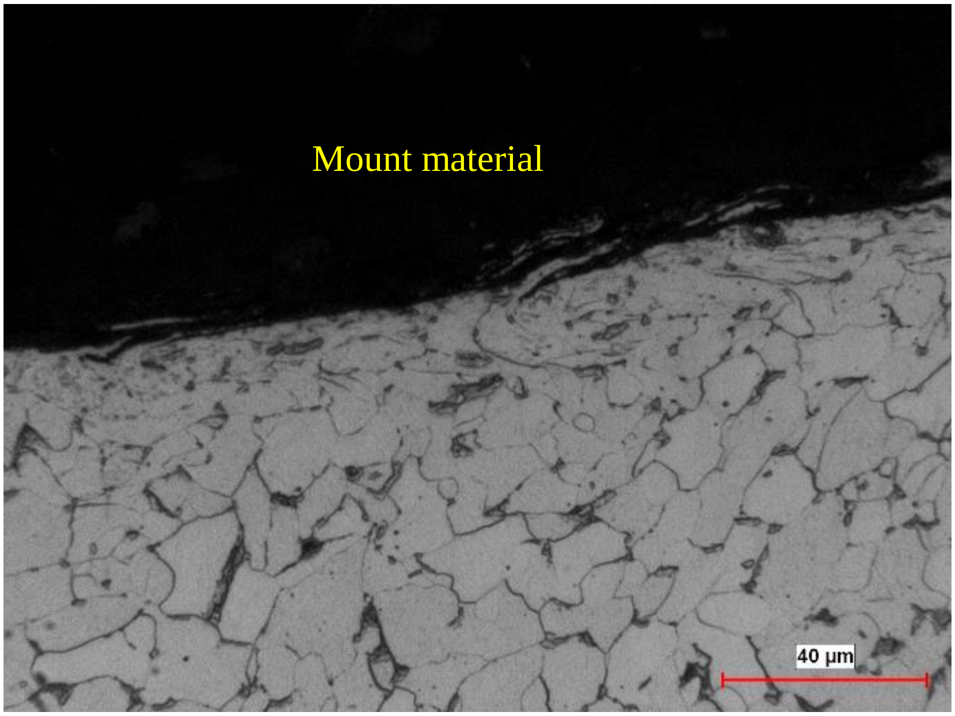


Figure 11: Selected SEM images taken from the surface of sample "6", SAE 1010 HRPO steel (5"x2"). No oxide particles were observed.



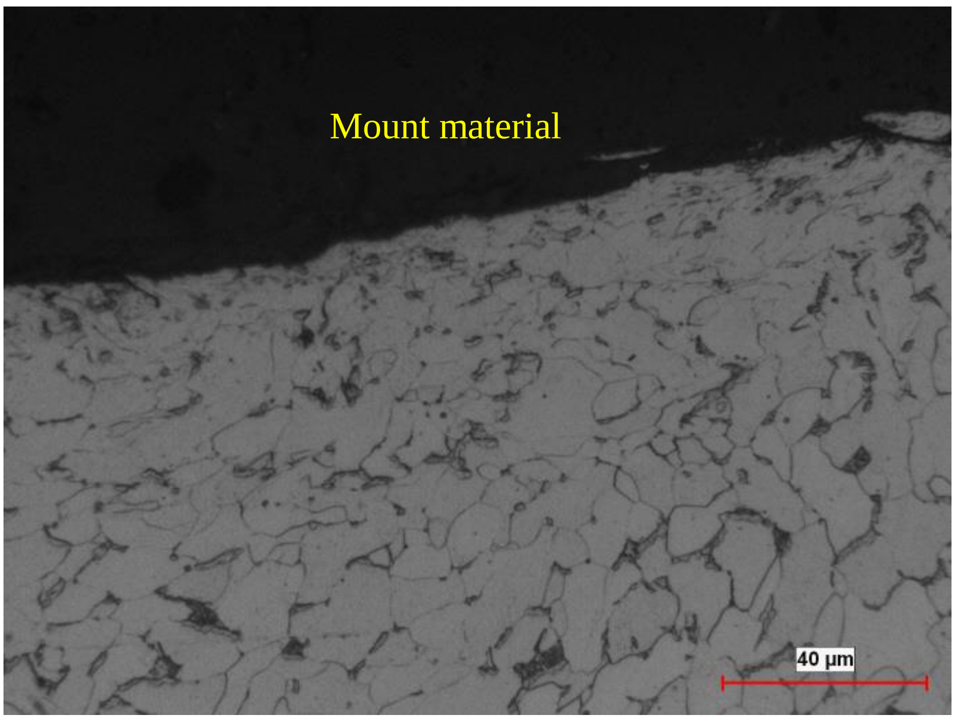


Figure 12: Optical micrographs illustrating the microstructure of sample "6", SAE 1010 HRPO steel (5"x2") at the surface. The microstructure was composed of ferrite (light) and pearlite (dark). A shallow region with a deformed microstructure was observed at the surface. No oxides were found (etched with 3% Nital, original magnification: 500X).

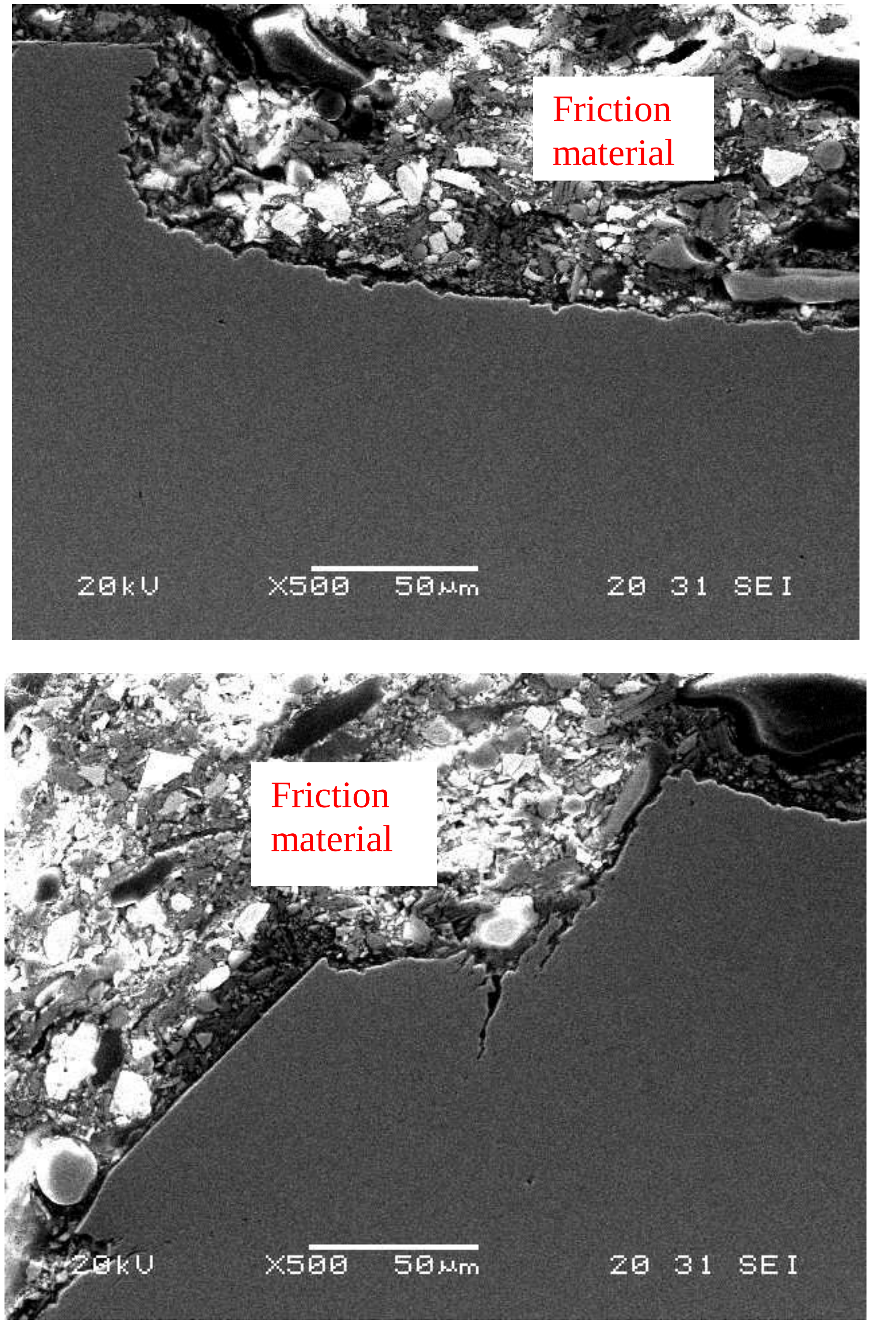


Figure 13: Selected SEM images of the surface of sample "7", D833 (SAE 1010 HRPO). No oxide particles were observed.

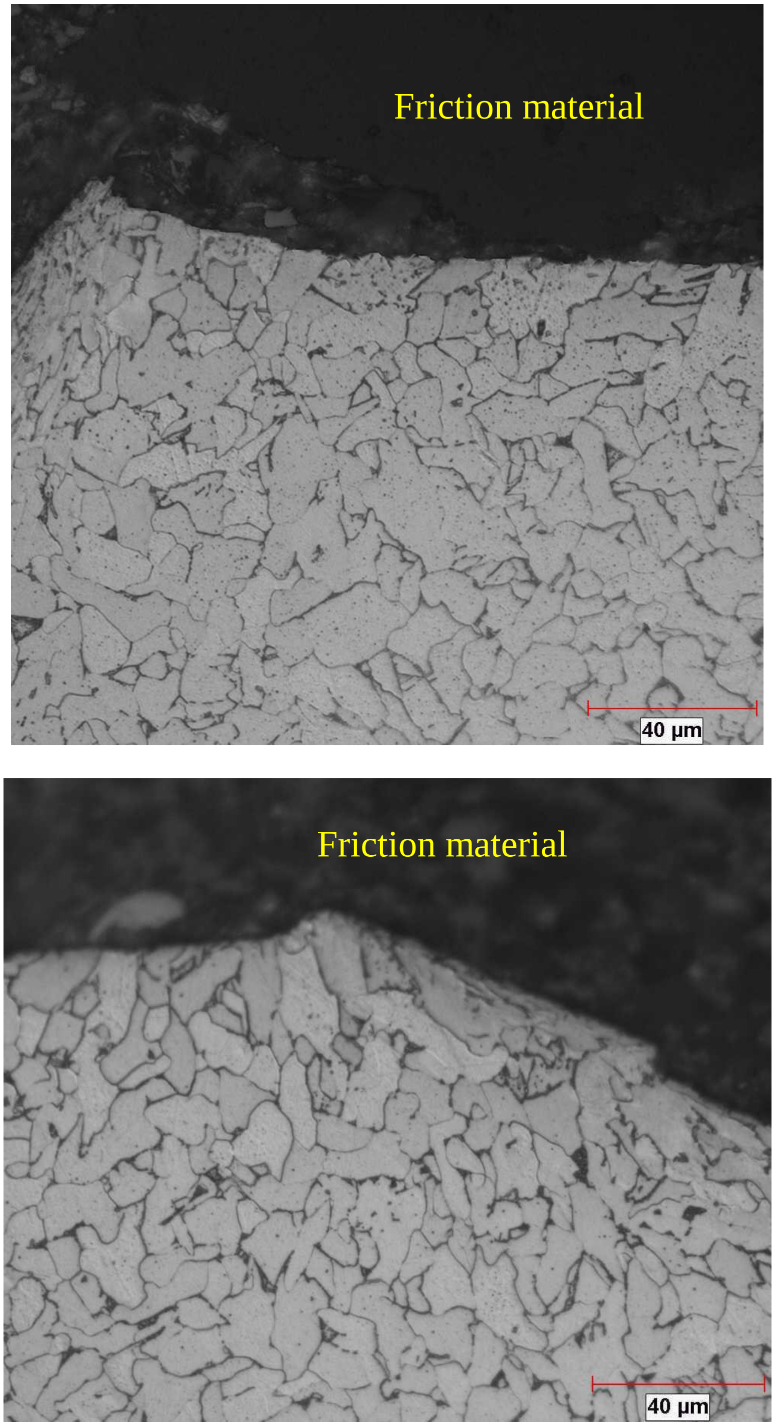
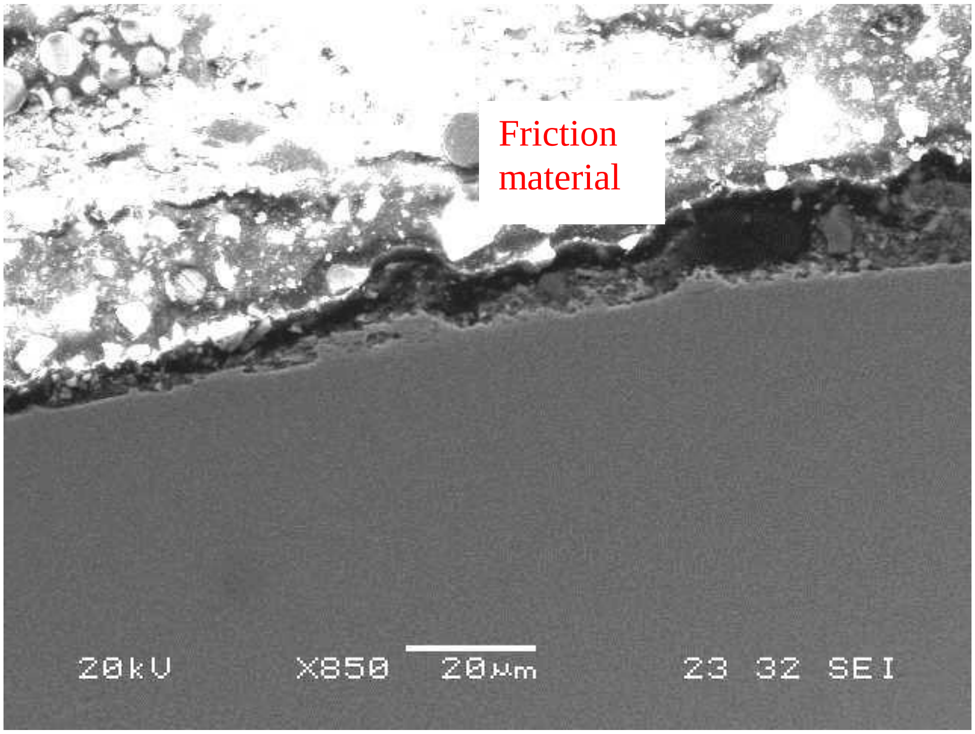


Figure 14: Optical micrographs showing the microstructure at the surface of sample "7" D833 (SAE 1010 HRPO). The microstructure was composed of ferrite (light) and pearlite (dark). No grain deformation was observed (etched with 3% Nital, original magnification: 500X).



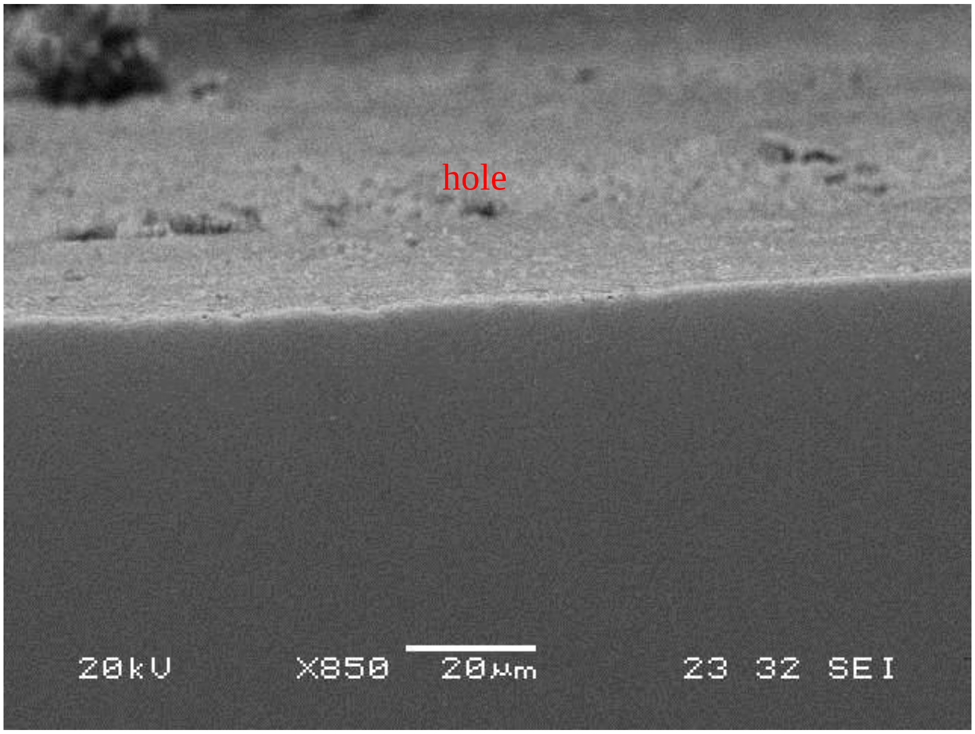


Figure 15: Selected SEM images of the surface of sample "7.1", D833 (SAE 1010 HRPO). The bottom image was taken from the hole at the lug location. No oxide particles were observed.

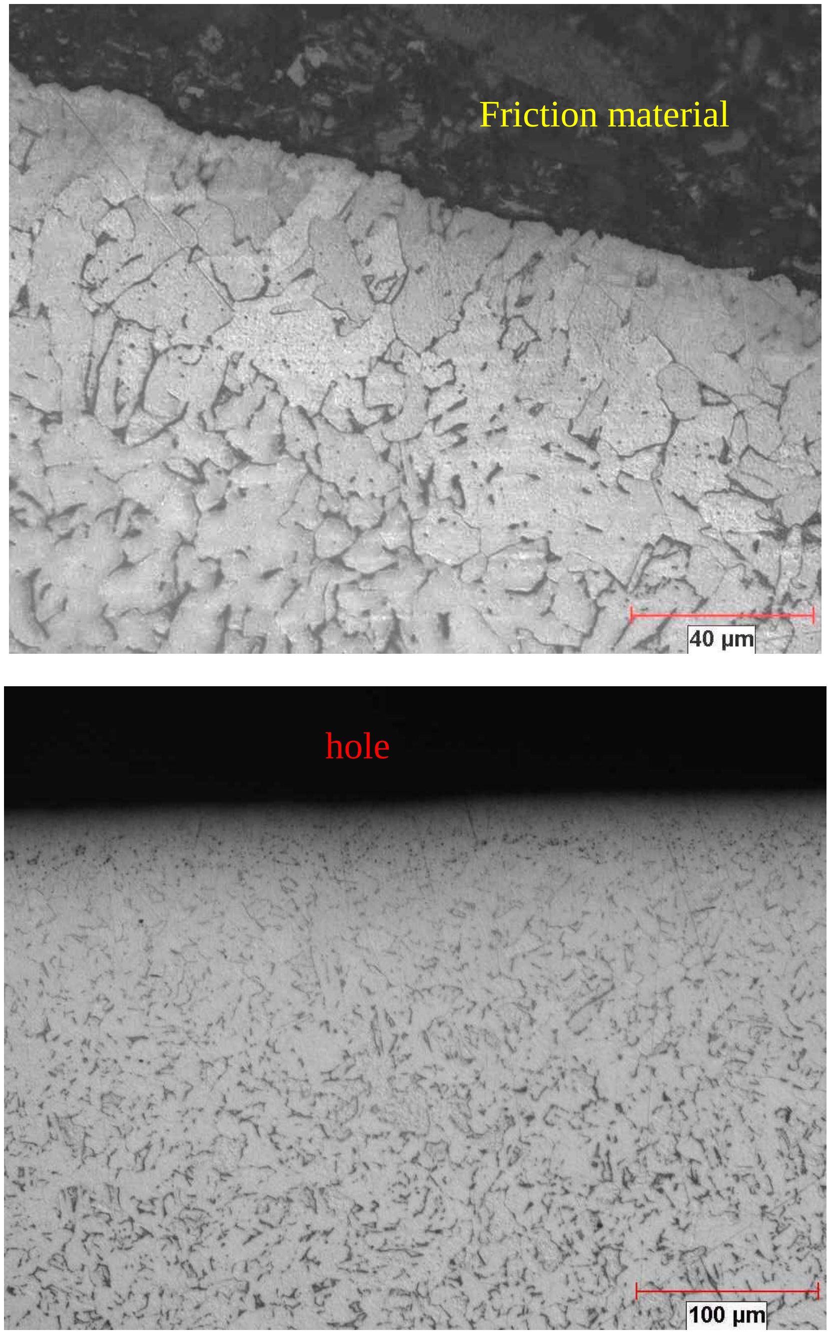


Figure 16: Optical micrographs showing the microstructure at the surface of sample "7.1" D833 (SAE 1010 HRPO). The bottom image was taken from the hole at the lug location. The microstructure was composed of equiaxed ferrite (light) and pearlite (dark). No grain deformation was observed (etched with 3% Nital, original magnification: top: 500X, bottom 200X).

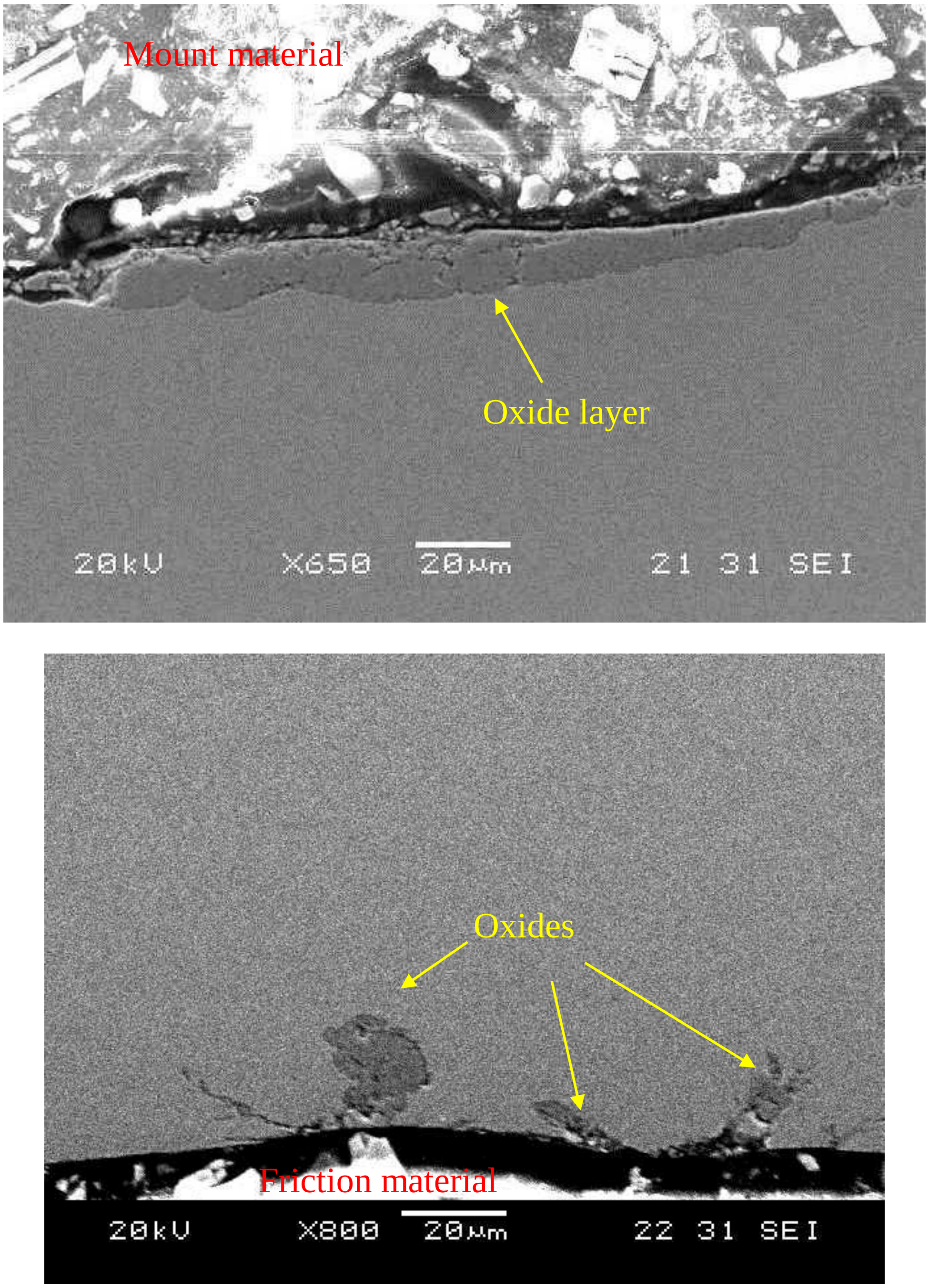


Figure 17: Selected SEM images of the surface of sample "8", D833 (suspected black mill scale steel). The top image shows the presence of an oxide layer at the hole's bottom surface. Embedded oxide particles were observed at the interface with the friction material (bottom).

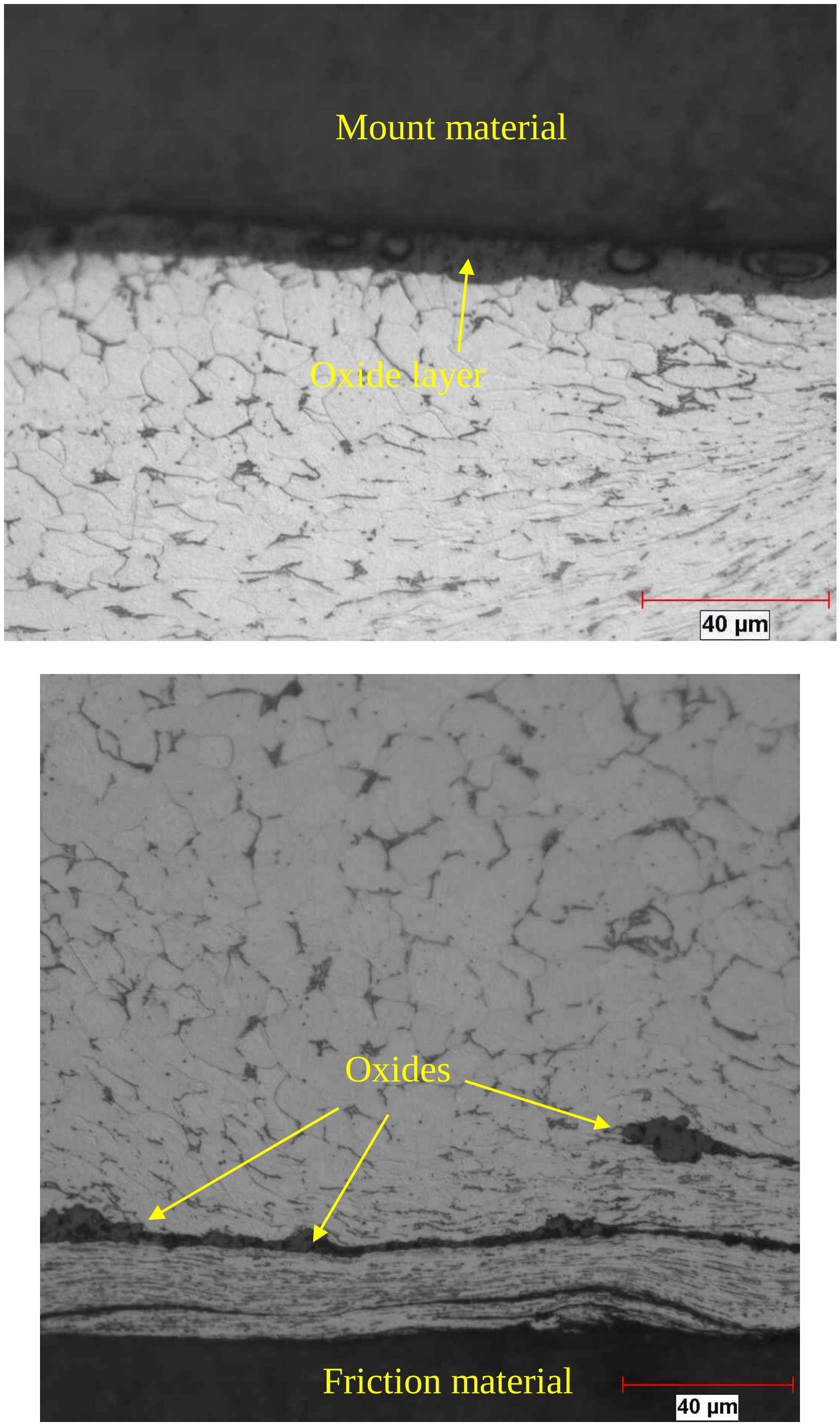
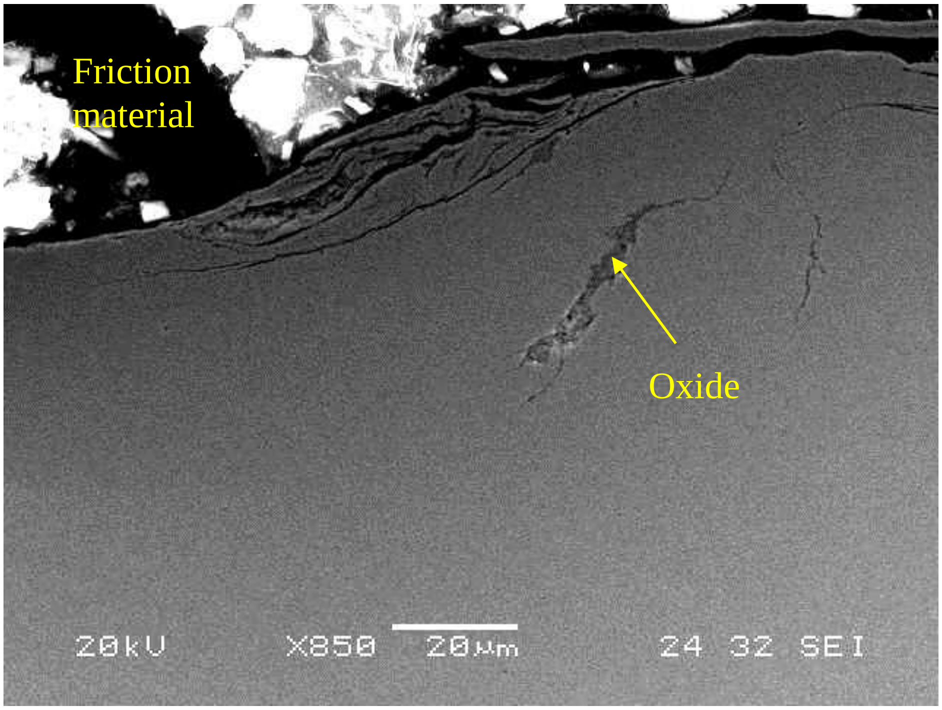


Figure 18: Optical micrographs showing the microstructure at the surface of sample "8", D833 (suspected black mill scale steel). The top images illustrates the oxide layer. The bottom image shows embedded oxides and a deformed microstructure. The microstructure was composed of ferrite (light) and pearlite (dark) (etched with 3% Nital, original magnification: 500X).



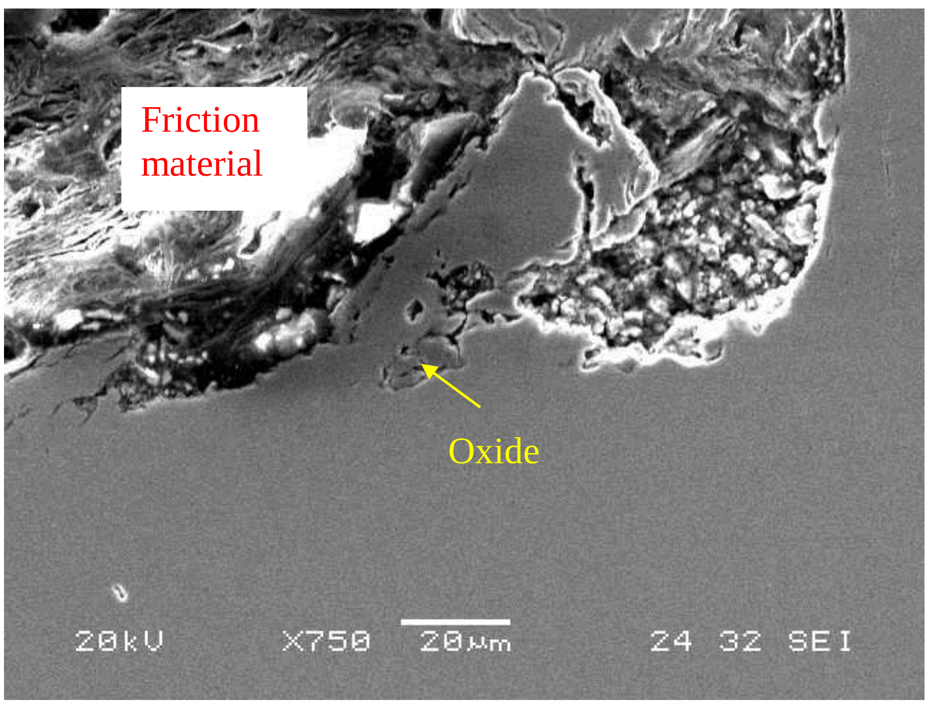


Figure 19: Selected SEM images taken from the surface of sample “8.1”, D833 (suspected black mill scale steel) illustrating isolated embedded oxide particles. The bottom image was taken from the hole at the lug location.

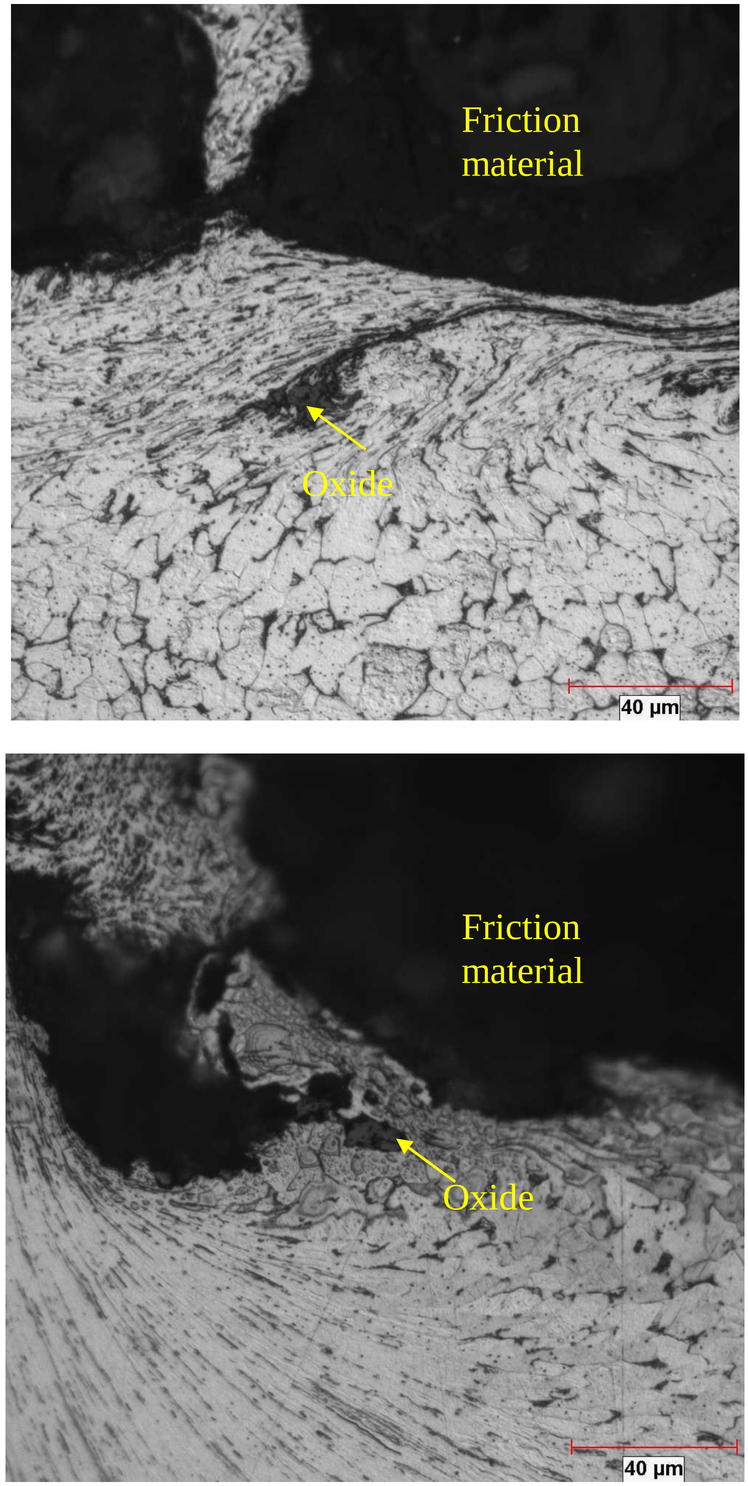


Figure 20: Optical micrographs showing the microstructure at the surface of sample "8.1", D833 (suspected black mill scale steel). The images presented illustrate the presence of oxide particles observed. The bottom image was taken from the hole at the lug location. The microstructure was composed of ferrite (light) and pearlite (dark). A deformed microstructure is noted at the surface (etched with 3% Nital, original magnification: 500X).

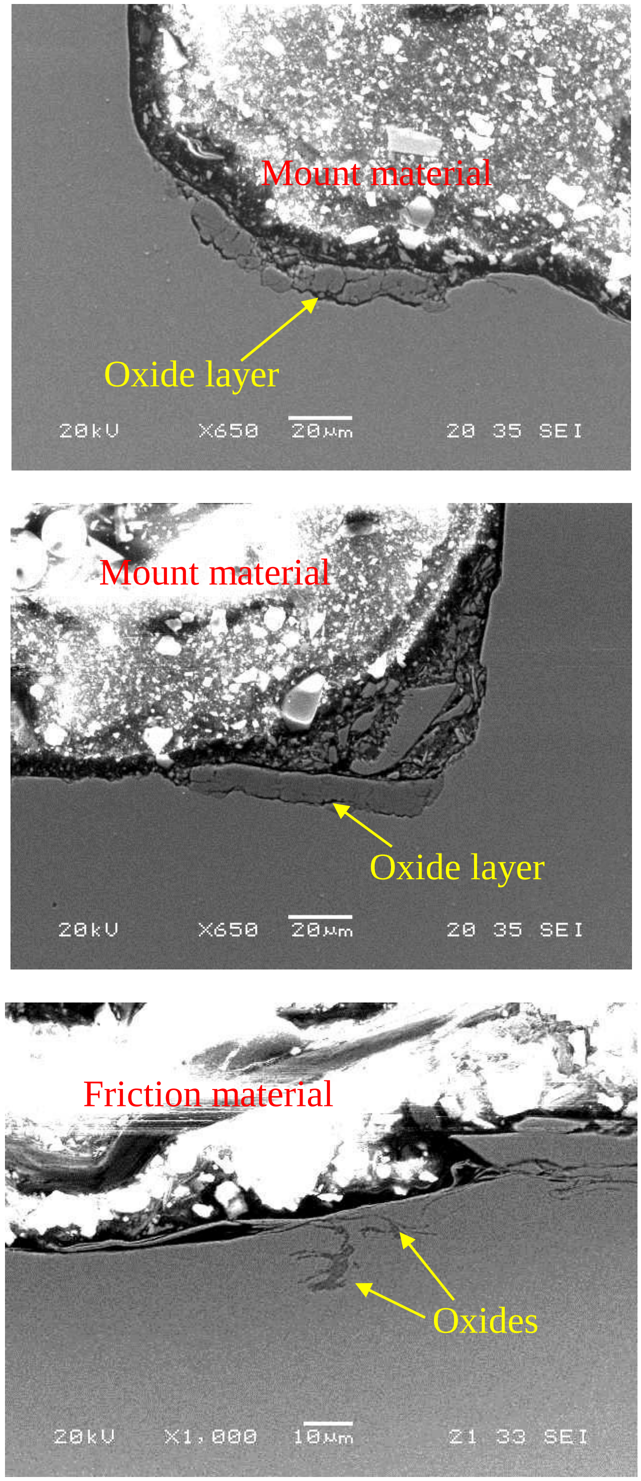
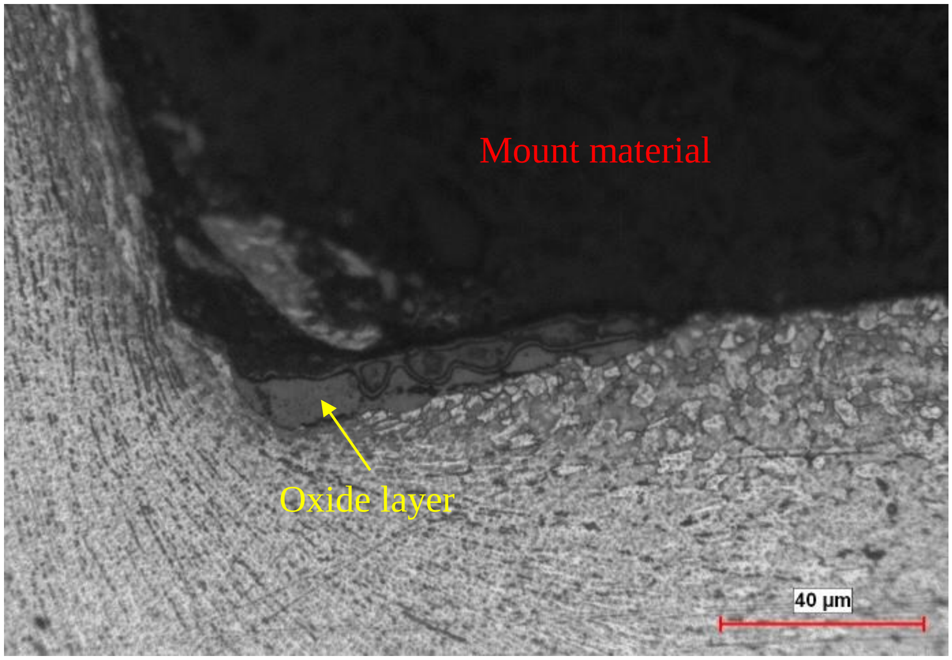


Figure 21: Selected SEM images taken from the surface of sample “9”, D833 (suspected black “mill scale” steel). The top and middle images show an oxide layer at the corners of the blind hole. The bottom image depicts embedded oxide particles.



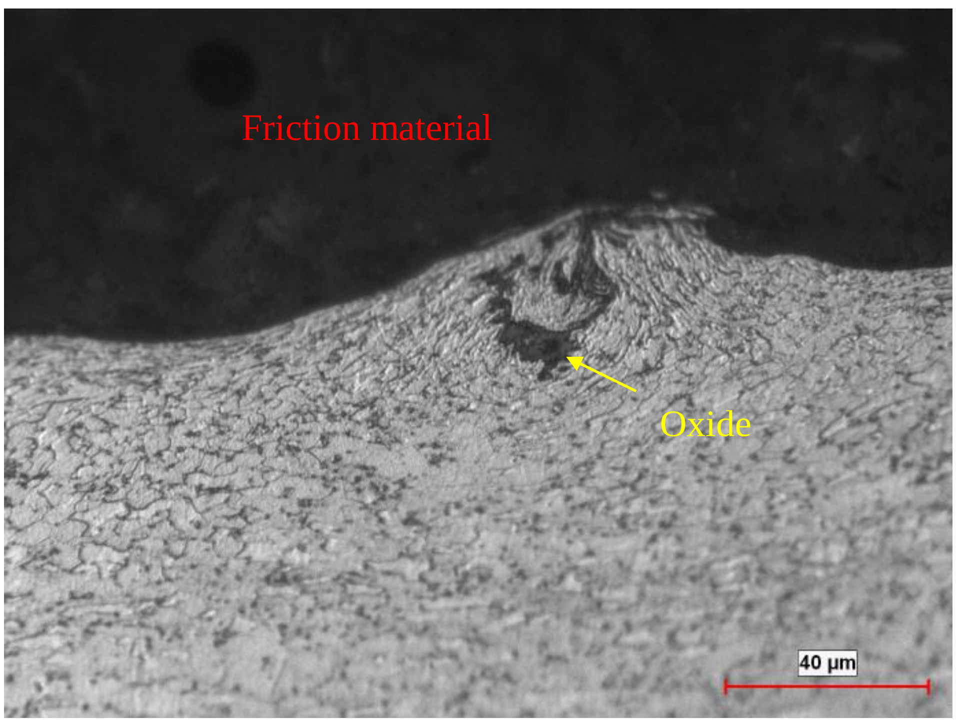
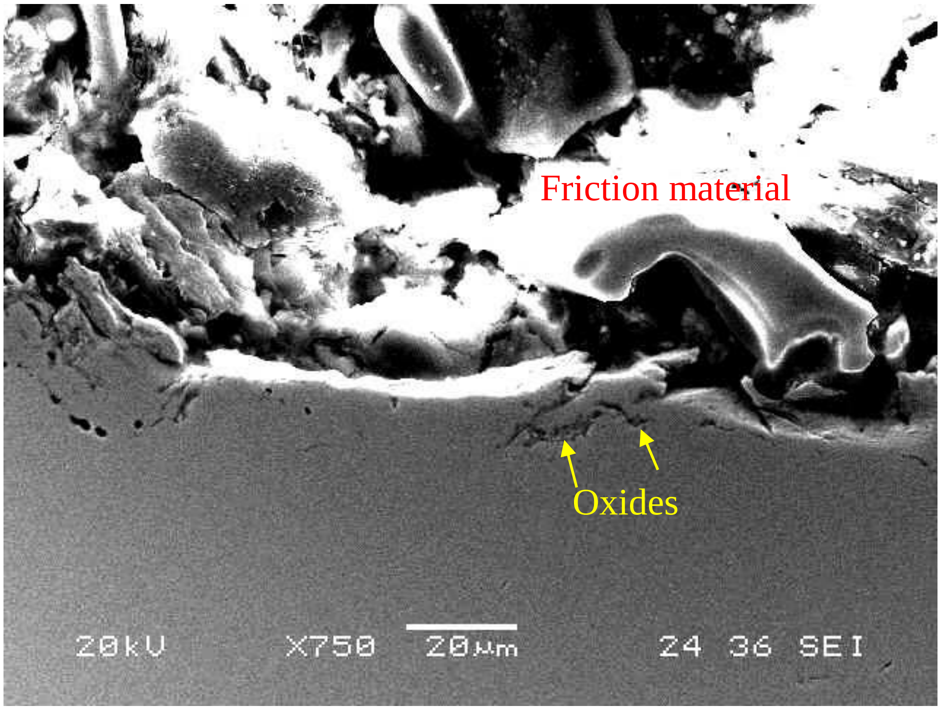


Figure 22: Optical micrographs illustrating the microstructure at the surface of sample “9”, D833 (suspected black mill scale steel). The top image shows the oxide layer at the hole’s corner. The microstructure was deformed at the edges of the hole and at the surface in contact with the friction material. The microstructure was composed of ferrite (light) and pearlite (dark) (etched with 3% Nital, original magnification: 500X).



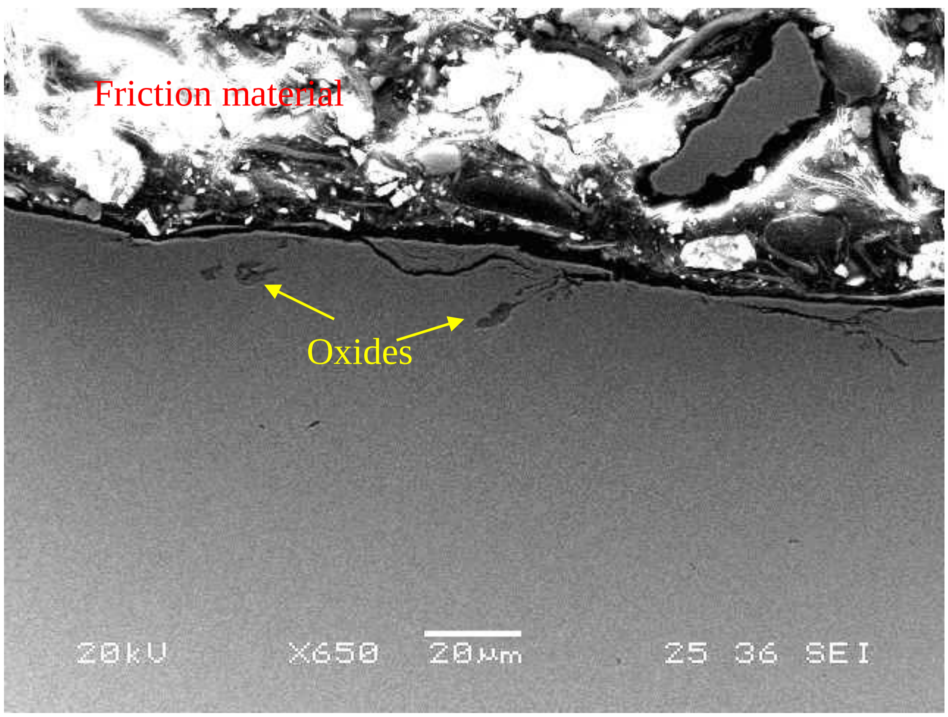


Figure 23: Selected SEM images taken from the surface of sample “9.1”, D833 (suspected black “mill scale” steel). The top image shows oxides inside the hole associated with the lug. The bottom image depicts embedded oxide particles at the interface with the friction material outside the hole.

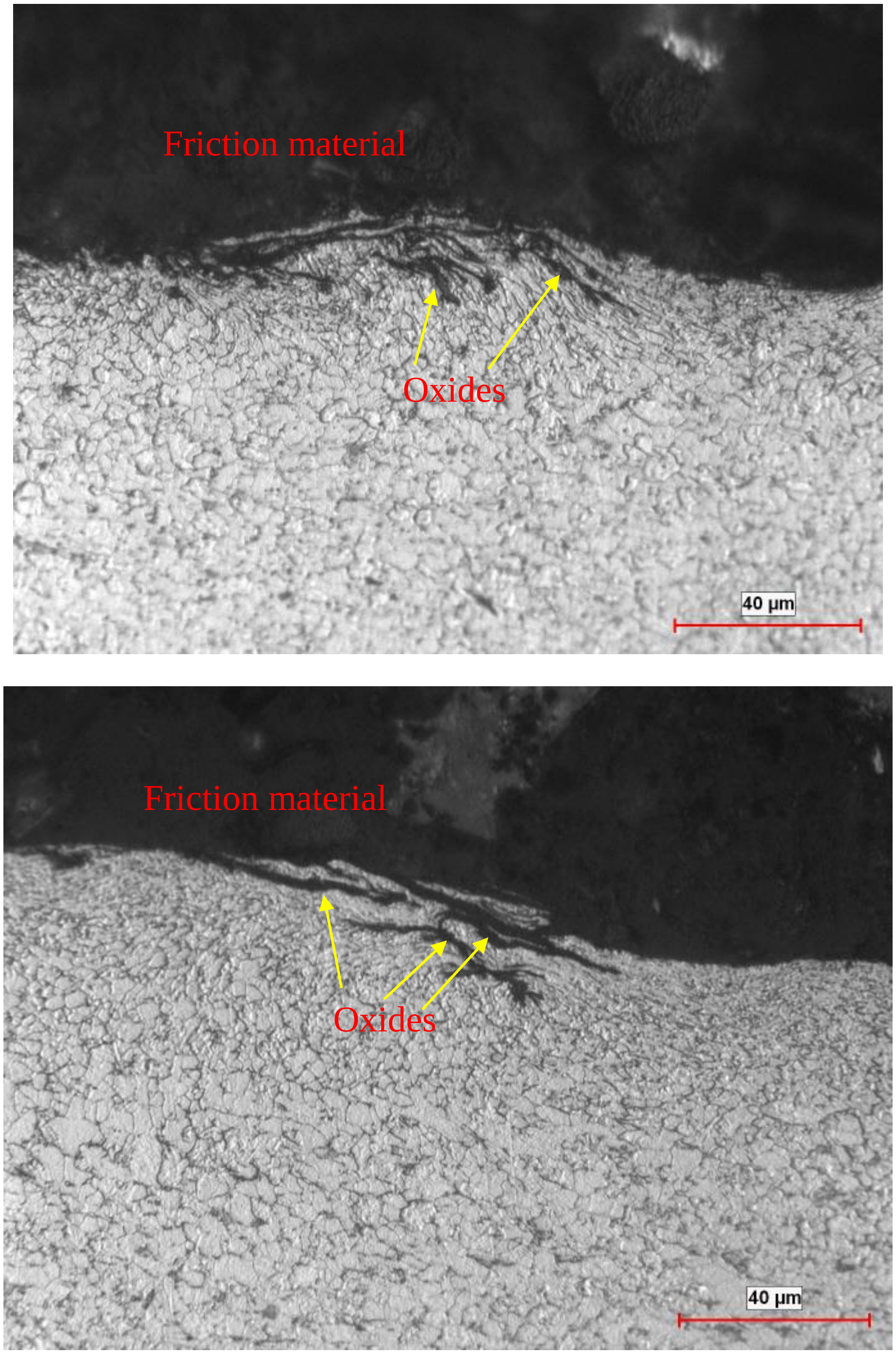


Figure 24: Optical micrographs illustrating the microstructure at the surface of sample "9.1", D833 (suspected black mill scale steel). The top image was taken from the hole associated with the lug and the bottom image was taken outside the hole. Embedded oxide particles are depicted. The microstructure was composed of ferrite (light) and pearlite (dark). Deformed grains are observed adjacent to the surface (etched with 3% Nital, original magnification: 500X).

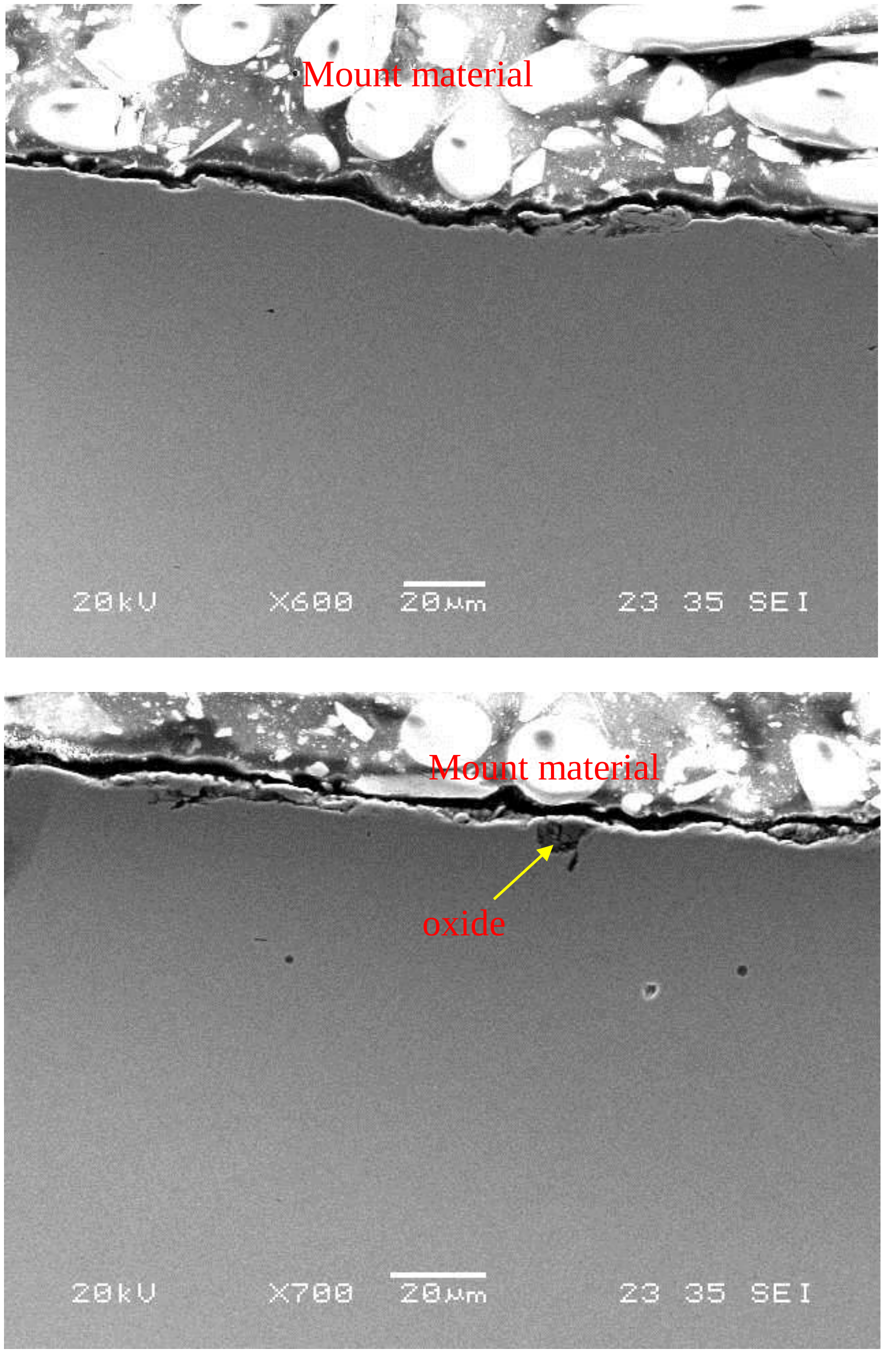
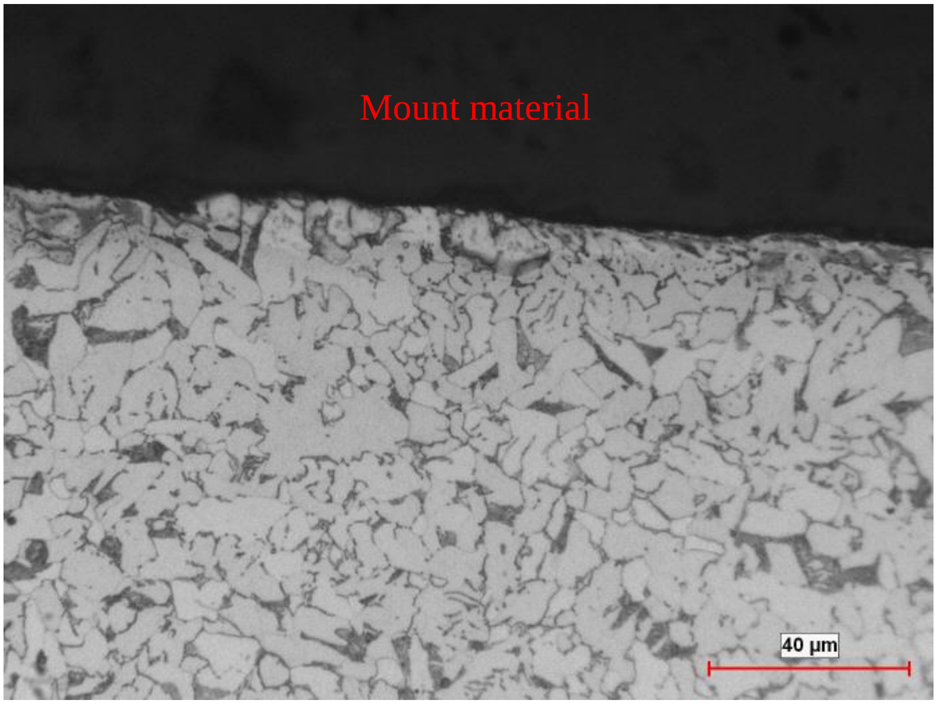


Figure 25: Selected SEM images taken from the surface of sample "10", D1282 (suspected black "mill scale" steel). Few isolated oxide particles rich in iron and aluminum were detected (bottom image).



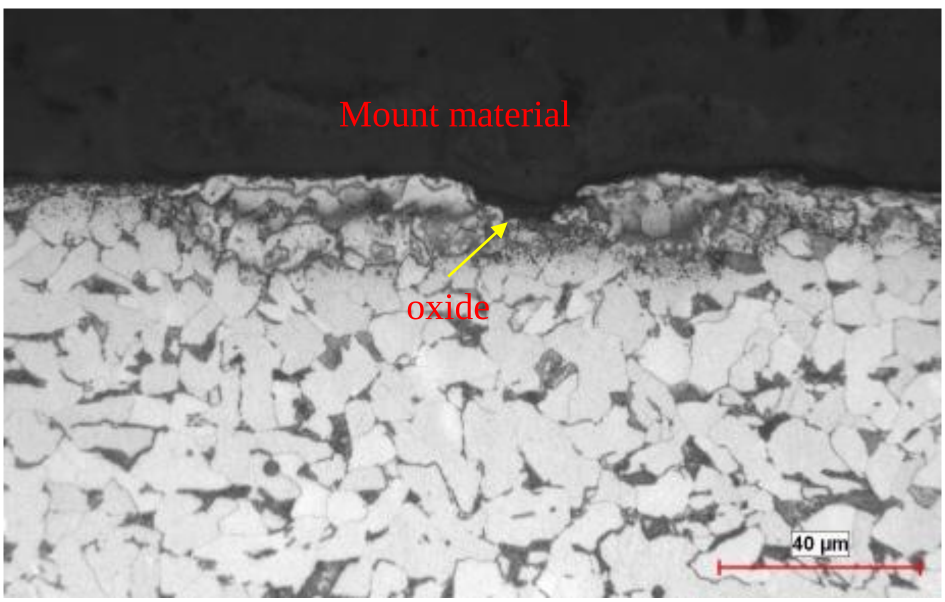
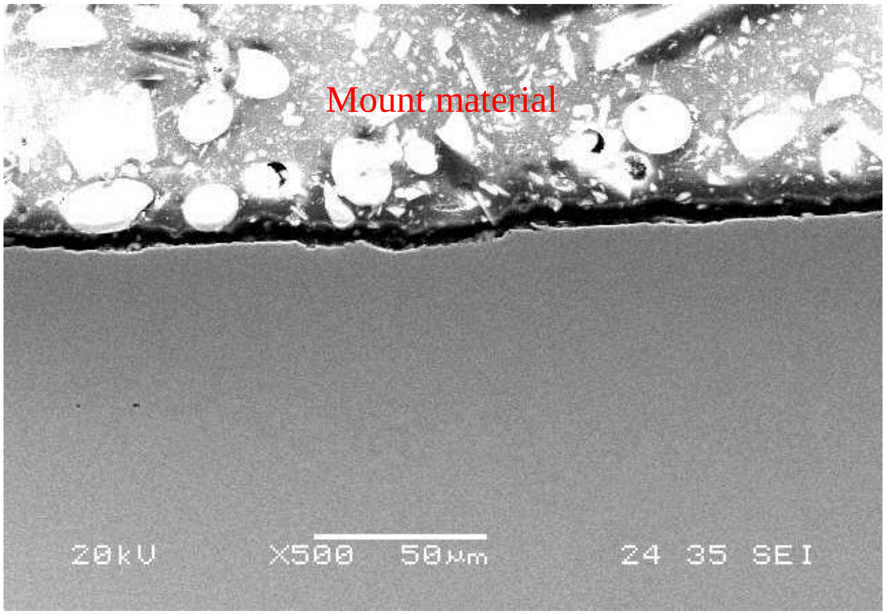


Figure 26: Optical micrographs illustrating the microstructure at the surface of sample "10", D1282 (suspected black mill scale steel). The microstructure was composed of ferrite (light) and pearlite (dark). No deformed grains were observed (etched with 3% Nital, original magnification: 500X).



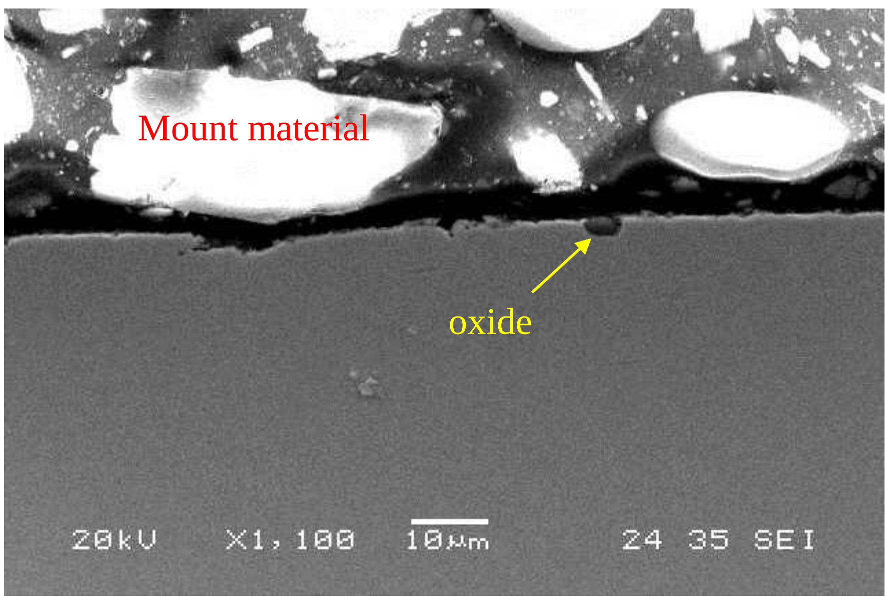
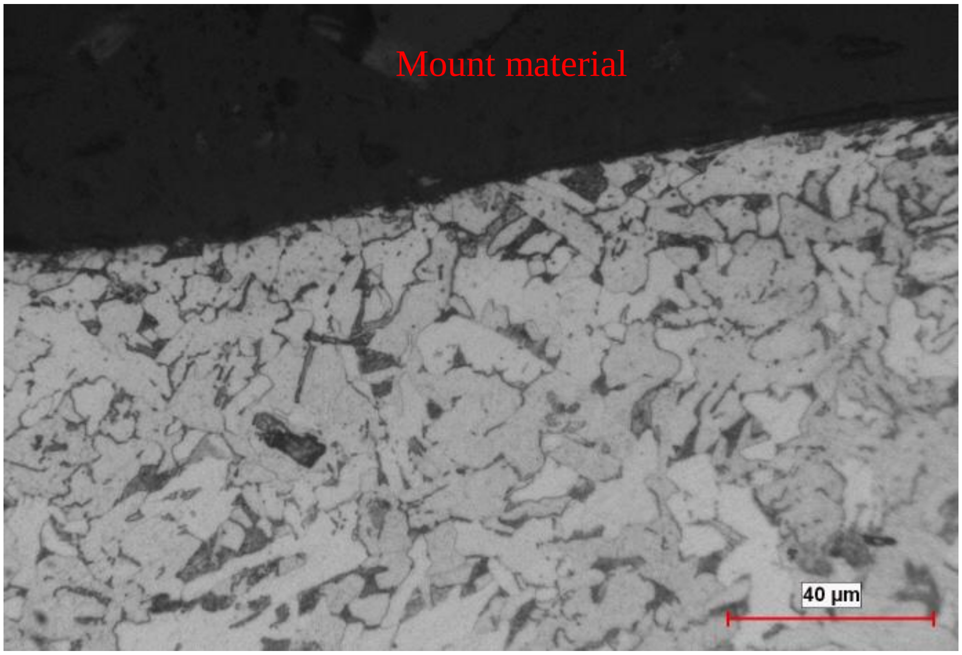


Figure 27: Selected SEM images taken from the surface of sample "11", D1283 (suspected black "mill scale" steel). Few isolated oxide particles rich in iron and aluminum were detected (bottom image).



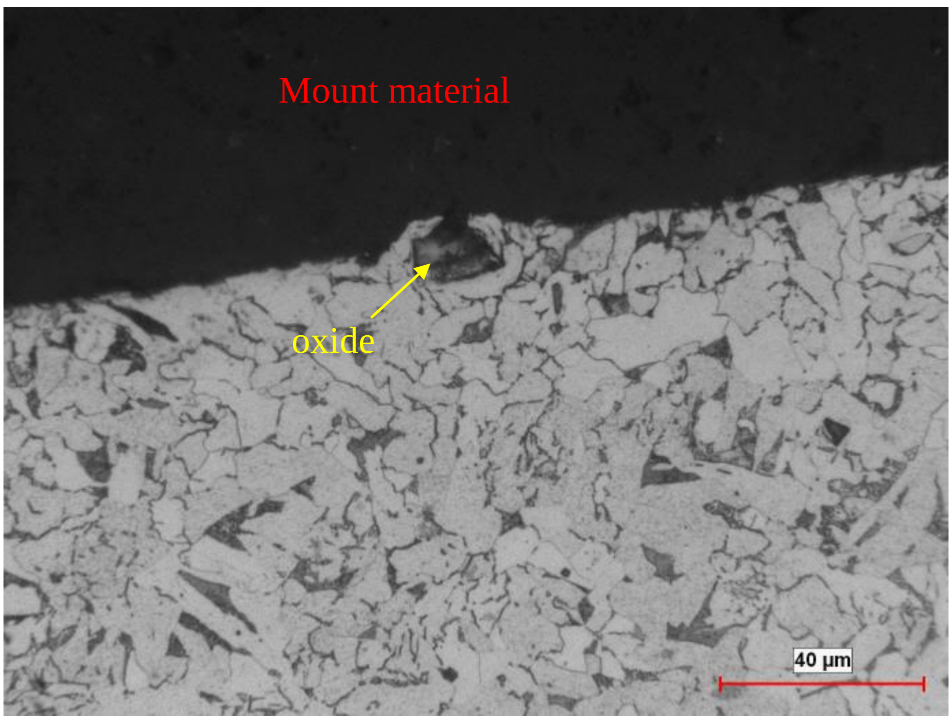
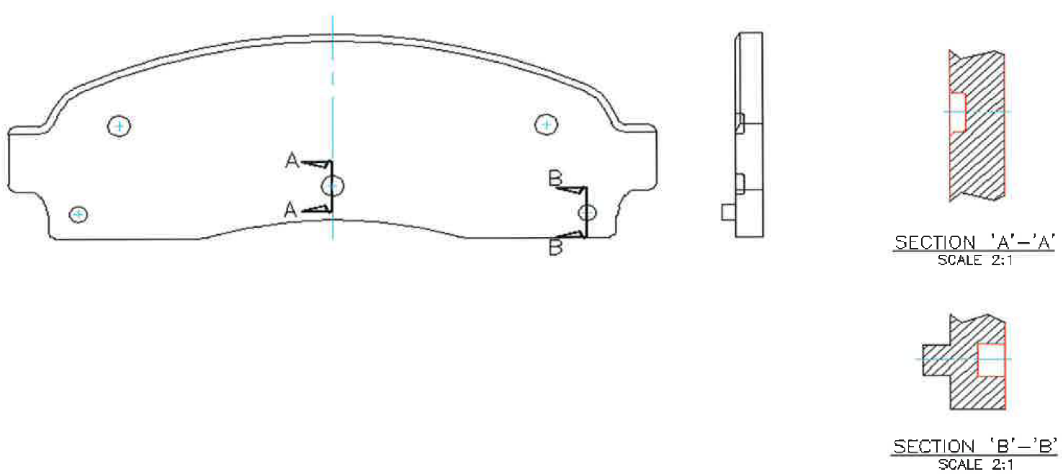


Figure 28: Optical micrographs illustrating the microstructure at the surface of sample “11”, D1283 (suspected black mill scale steel). The microstructure was composed of ferrite (light) and pearlite (dark). No deformed grains were observed (etched with 3% Nital, original magnification: 500X).

Appendix 1: Matrix of samples

Surface Analysis Test Matrix					
Sample Number	**Test Object Description**	**Surface condition**	**Special Notes**	**Surface Analysis (Scanning Electron Microscope)**	**Metallographic Cross-section (Oxide Thickness)**
1	**Black "Mill Scale" Steel Q235B (5"x2")**	As received		Yes	Yes
2	**Black "Mill Scale" Steel Q235B (5"x2")**	Shot blasted		Yes	Yes
3	**Black "Mill Scale" Steel Q235B (5"x2")**	Shot blasted with glue		Yes	Yes
4	**SAE 1010 HRPO Steel (5"x2")**	oily (as received)		Yes	Yes
5	**SAE 1010 HRPO Steel (5"x2")**	Shot blasted		Yes	Yes
6	**SAE 1010 HRPO Steel (5"x2")**	Shot blasted with glue		Yes	Yes
7	**D833 (SAE 1010 HRPO)**	painted	Cross-section ('A'-'A') through blind hole on centerline of disc brake shoe	Yes	Yes
7.1	**D833 (SAE 1010 HRPO)**	painted	Cross-section ('B'-'B') through Ø4 mm extruded lug	Yes	Yes
8	**D833 (Suspected black "mill scale "steel)**	painted	Cross-section ('A'-'A') through blind hole on centerline of disc brake shoe	Yes	Yes
8.1	**D833 (Suspected black "mill scale "steel)**	painted	Cross-section ('B'-'B') through Ø4 mm extruded lug	Yes	Yes
9	**D833 (Suspected black "mill scale "steel)**	painted	Cross-section ('A'-'A') through blind hole on centerline of disc brake shoe	Yes	Yes
9.1	**D833 (Suspected black "mill scale "steel)**	painted	Cross-section ('B'-'B') through Ø4 mm extruded lug	Yes	Yes
10	**D1282 (Suspected black "mill scale" steel)**	oily (as received)		Yes	Yes
11	**D1283 (Suspected black "mill scale" steel)**	oily (as received)		Yes	Yes
Notes: When performning metallographic cross-section of brake pads, check oxide layer thickness on both the outer surface and interface between the steel and friction liner.					



Red lines depict the areas on D833 in which we are interested for the microscopic analysis.