Subject: Metallurgical Evaluation of Indications on Steel Sample:

Dear Mr.

Five samples, identified by Item , and one sample, identified by Item and were submitted for scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDS) of regions that showed indications after magnetic particle inspection. Before examination began, it was decided by to reduce the scope of the project to a single, representative sample from Item , which was identified as Sample C and is shown as received in Figure 1. Sample C exhibited three indications, identified in this report as Indications 1 through 3, which were faintly visible as linear features along the longitudinal axis of the original part, and perpendicular to the machining marks. The scope of work was to include SEM, EDS elemental line scans and mapping, metallography, and microhardness testing.

Sample C was rinsed with acetone and marked with black ink the locations of the three indications before EDS elemental line scan analysis, as shown in the scanning electron micrograph presented in Figure 2. Although Indication 2 was faintly visible with an unaided eye, no topographical features were observed when viewed via SEM, as evident in Figure 3. Two line scans, arbitrarily selected at the representative Indication 2, were performed on the surface, perpendicularly crossing Indication 2, to determine changes in relative composition. Initially, a line scan was performed at 75X magnification, but no significant changes in relative composition were observed, as shown in Figures 4 and 5. An additional high-resolution line scan was performed at 200X magnification in the same location, but slightly truncated on either end, as originally shown in Figure 4, as presented in Figure 6. No significant changes in relative composition were observed at the surface through Indication 2. The results of the 200X line scan are presented in Figure 7.

A metallographic cross-section, MC, was excised through the indicated plane in Figure 1. After metallurgical preparation, EDS elemental mapping was performed in the region containing Indication 2, as shown in Figure 8. The EDS elemental map, presented in Figure 9, revealed no large changes in relative composition, suggesting that the magnetic particle indication result for Indication 2 was not due to material inhomogeneity. The individual maps used to construct the initially presented composite elemental map are presented in Figures 10 through 21.

The cross-section was etched with 2% nital to characterize the microstructure. The microstructure was homogenous from surface to core and consisted of tempered martensite. No cracks, laps, folds, or other anomalous features were observed. Photomicrographs of the etched cross-section are presented in Figures 22 through 30.

Near surface 200gf Knoop (HK 0.2) microhardness traverses were performed on the cross-section 0.003” from the surface at and adjacent to Indications 2 and 3, with the results presented in Table 1. Exact hardness locations are indicated in Figures 28 through 30. The hardness readings were generally consistent and did not follow a strong pattern surrounding the indication sites. Five microhardness readings were performed at the core with results summarized in Table 2.

The findings presented herein are given with a reasonable degree of engineering certainty using currently available data. reserves the right to supplement or amend this report should additional information become available.

Table 1 – Near Surface Microhardness Test Results

Test Location[1]	Test Location Description	Knoop Hardness (HK 0.2)
1	0.090” left of Indication 3	392
2	0.075” left of Indication 3	382
3	0.060” left of Indication 3	420
4	0.045” left of Indication 3	402
5	0.030” left of Indication 3	404
6	0.015” left of Indication 3	437
7	Indication 3	418
8	0.015” right of Indication 3	377
9	0.030” right of Indication 3	393
10	0.045” right of Indication 3	395
11	0.060” right of Indication 3	404
12	0.075” right of Indication 3	386
13	0.090” right of Indication 3	382
14	0.090” left of Indication 2	394
15	0.075” left of Indication 2	392
16	0.060” left of Indication 2	396
17	0.045” left of Indication 2	406
18	0.030” left of Indication 2	413
19	0.015” left of Indication 2	379
20	Indication 2	397
21	0.015” right of Indication 2	384
22	0.030” right of Indication 2	386
23	0.045” right of Indication 2	402
24	0.060” right of Indication 2	415
25	0.075” right of Indication 2	384
26	0.090” right of Indication 2	386

Tested in accordance with ASTM E384.

[1] Test Locations 1 through 26 were located 0.003” from the outer diameter surface and indicated in Figure 17 and Figure 18.

Table 2 – Core Microhardness Test Results

Test Location	Test Location Description	Knoop Hardness (HK 0.2)
27	Core	396
28	Core	407
29	Core	397
30	Core	396
31	Core	401
Average Hardness (HK 0.2)	**400**	

Tested in accordance with ASTM E384.

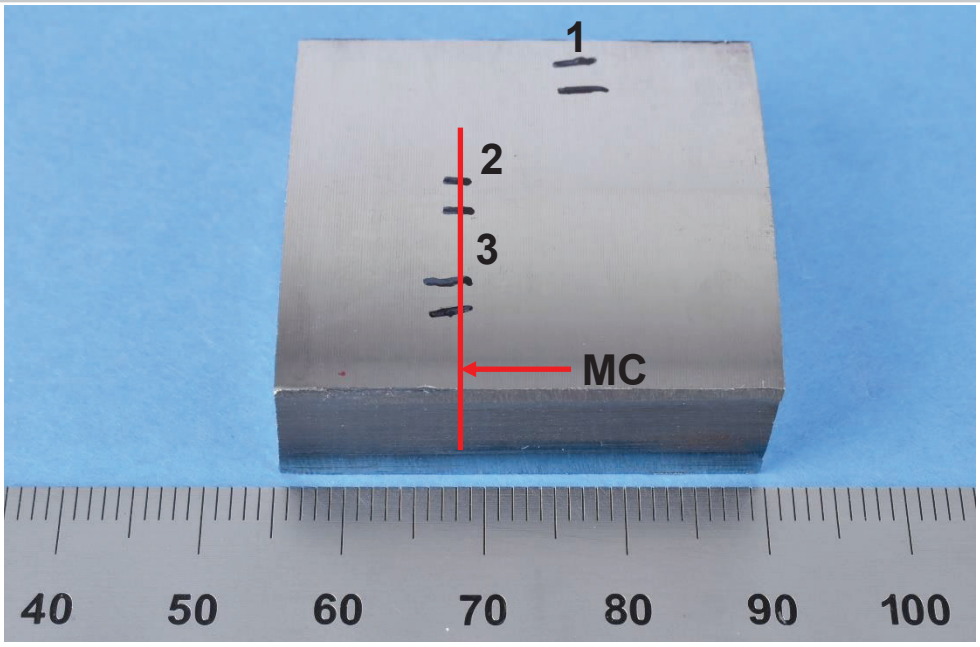

Fig. 1 Sample C, which was excised by [redacted], is shown as received. Between the short, horizontal black ink lines were regions that showed linear indications during magnetic particle inspection, which was performed at a third-party testing laboratory. The red line indicates the plane where the transverse cross-section through Sample C was performed. The scale is in millimeters.

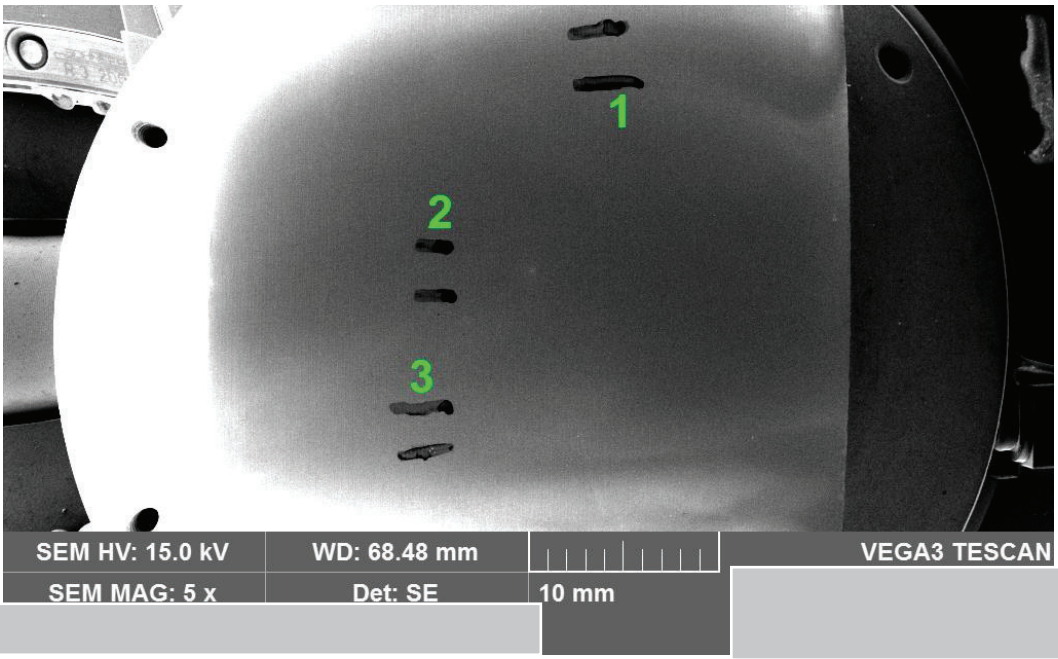

Fig. 2 A scanning electron micrograph of Sample C is presented. Indications 1 through 3 are identified.

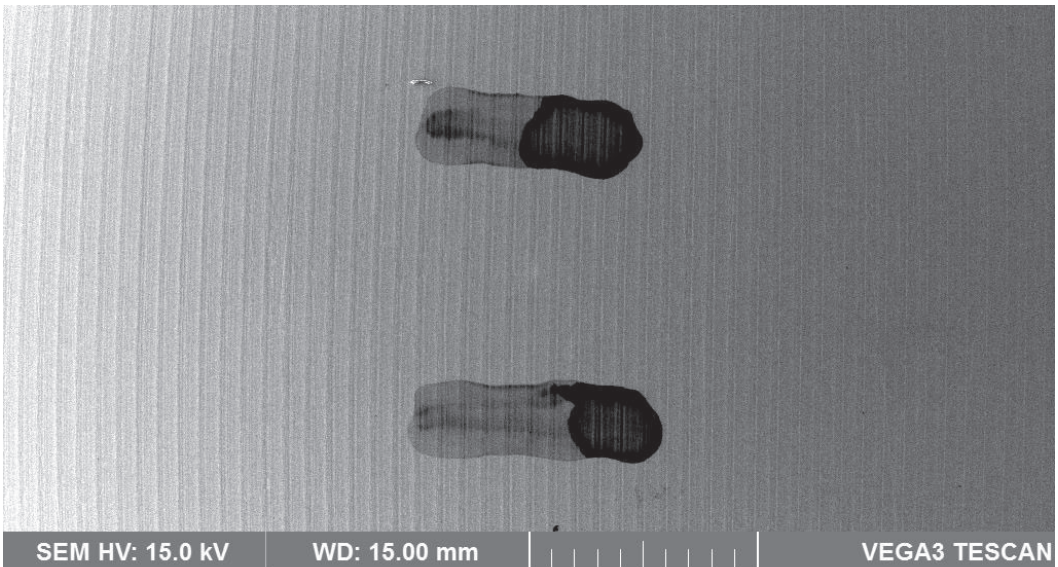

Fig. 3 **A magnified view of Indication 2 from Figure 2 is shown. Machining lines were evident, but no anomalous features were observed.**

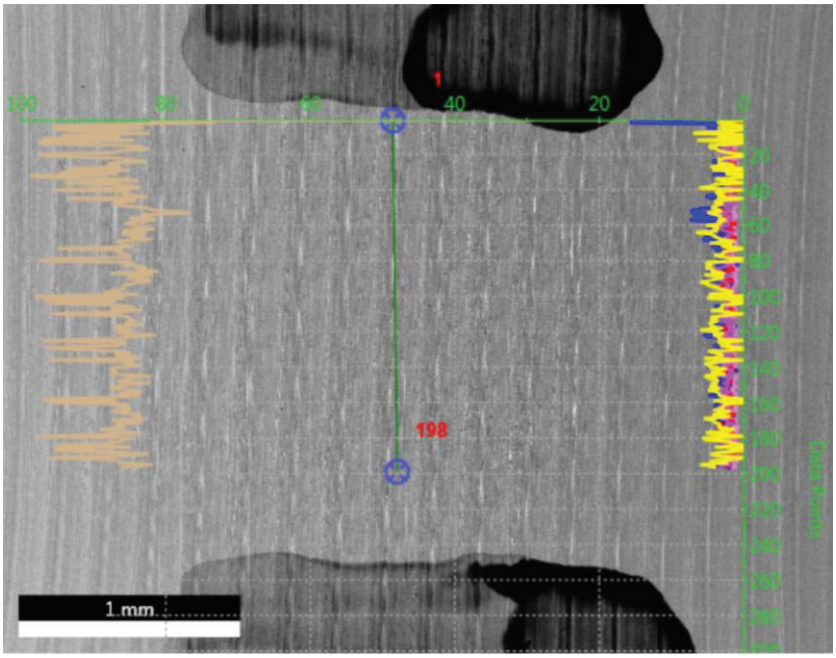

Fig. 4 **A line scan was performed across Indication 2 at a magnification of 75X. A detailed view of the line scan results is shown in Figure 5.**

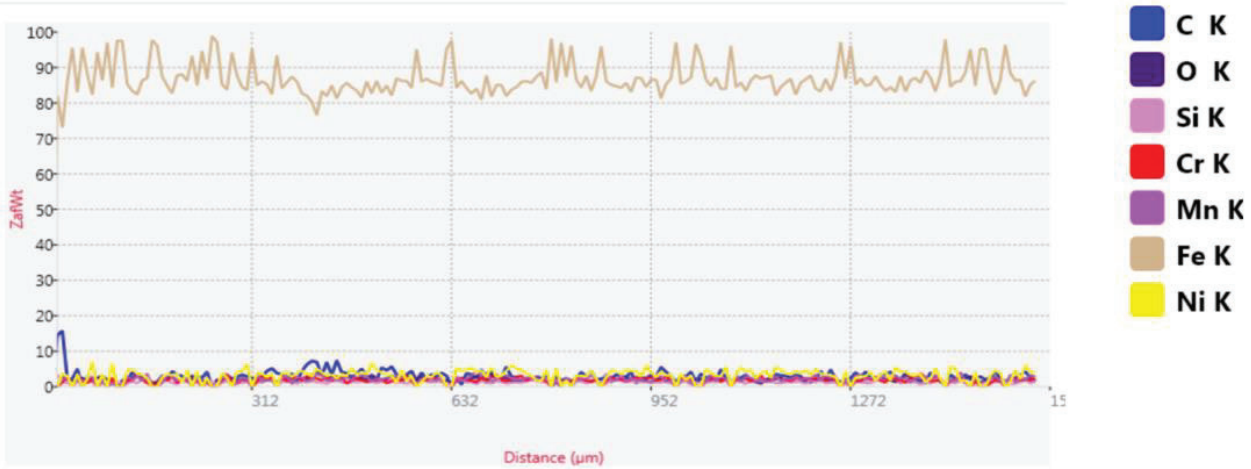

Fig. 5 The line scan results from Figure 4 are presented. No significant change in relative surface composition was observed.

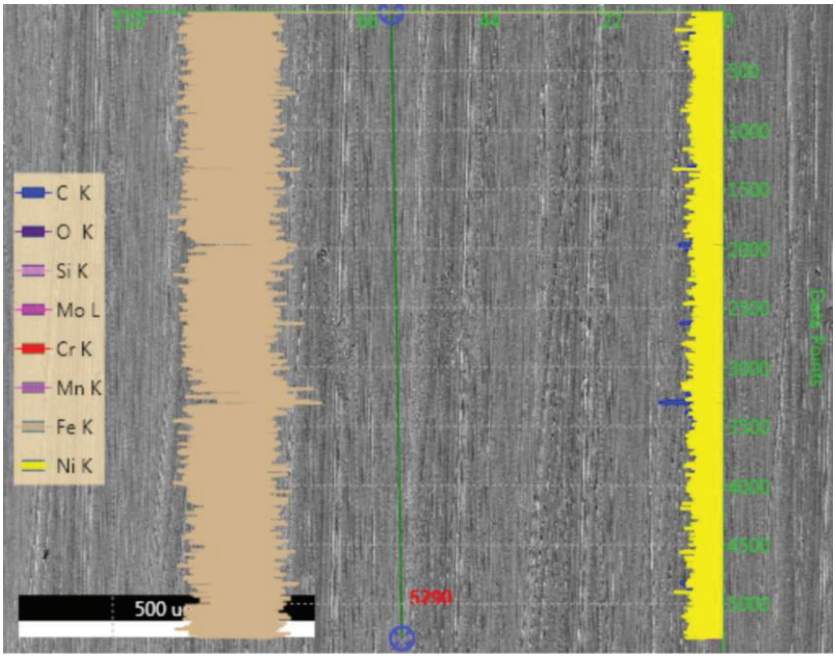

Fig. 6 The center of Figure 4 is shown at higher magnification, where a high-resolution line scan was performed at 200X magnification. A detailed view of the line scan results is shown in Figure 7.

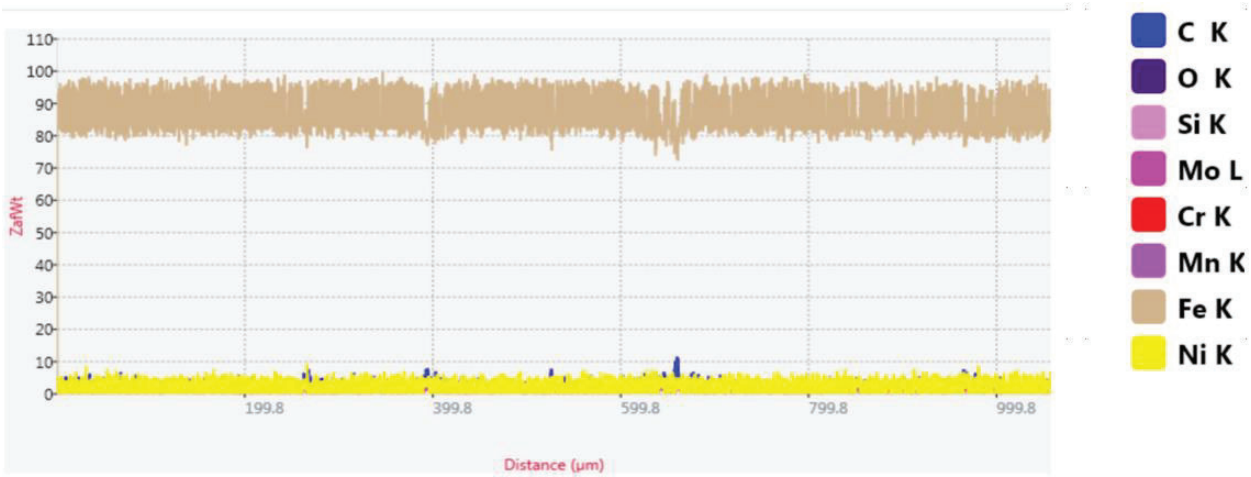

Fig. 7 The line scan results from Figure 6 are presented. No significant change in relative surface composition was observed.

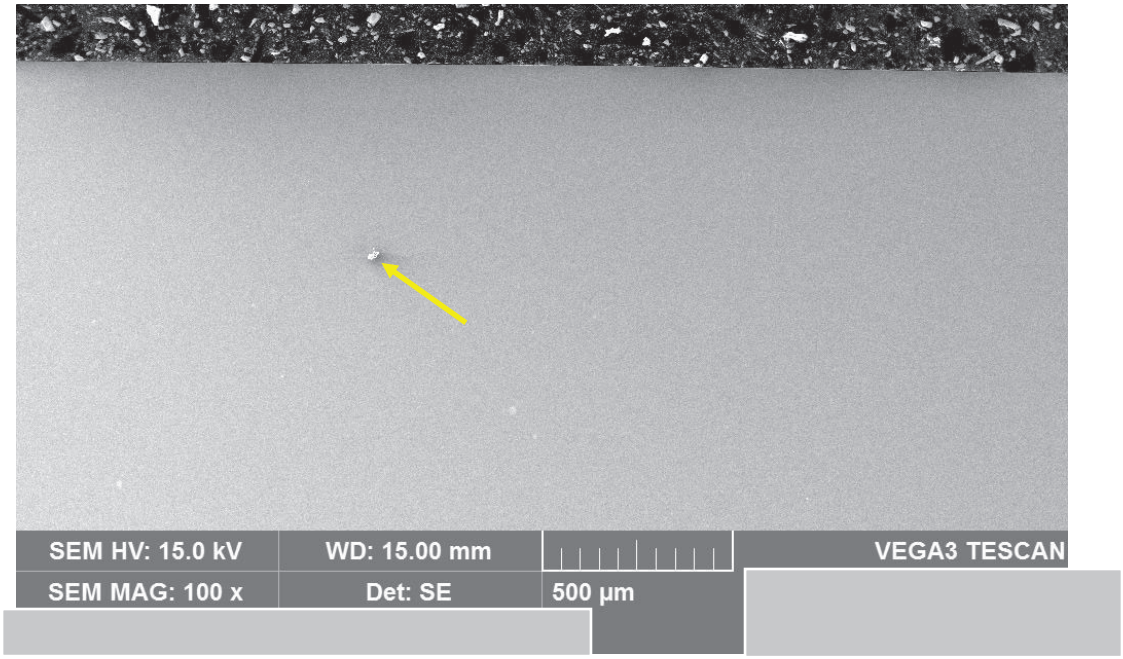

Fig. 8 A scanning electron micrograph of the cross-section at the location of Indication 2 is presented. An EDS elemental map of the field of view was performed and is shown in Figure 9. The location of the elemental map on an overall view of the cross-section is shown in Figure 16. Dust, which had settled on the polished surface, is indicated with the arrow. As Polished.

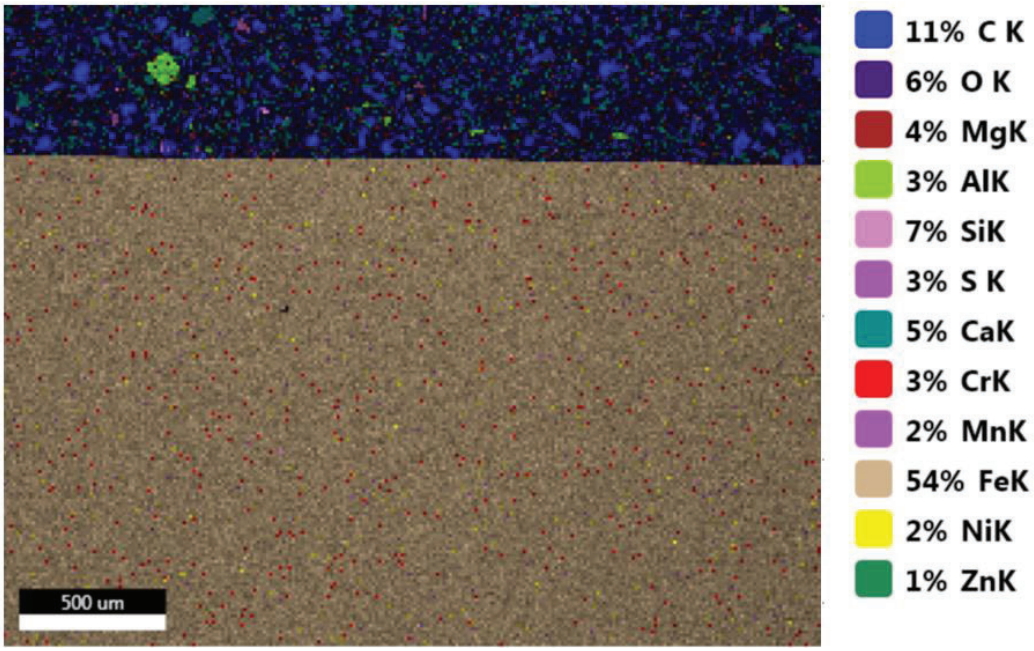

Fig. 9 The EDS elemental map of Figure 8 is presented. The material did not exhibit large variations of relative composition. As Polished.

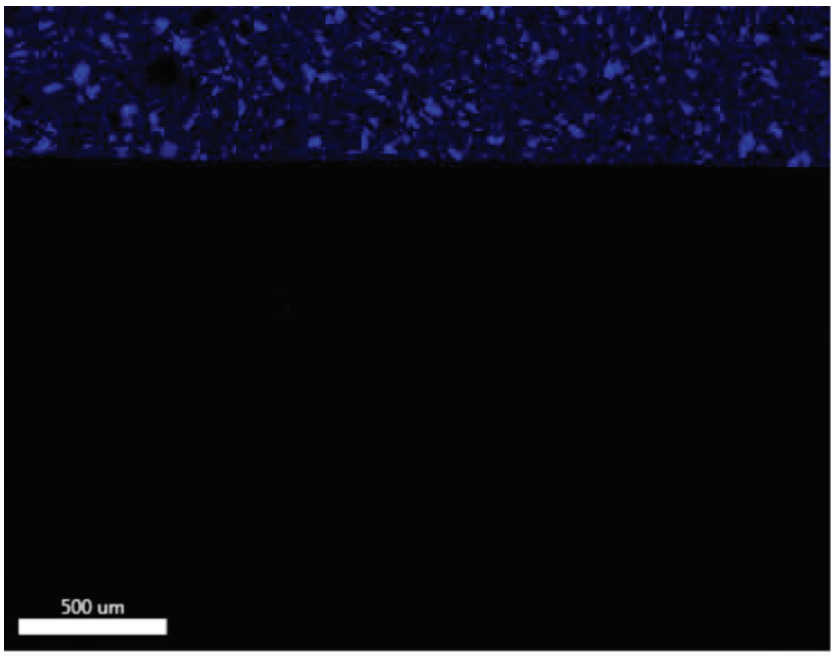

Fig. 10 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where carbon was the predominant element detected.

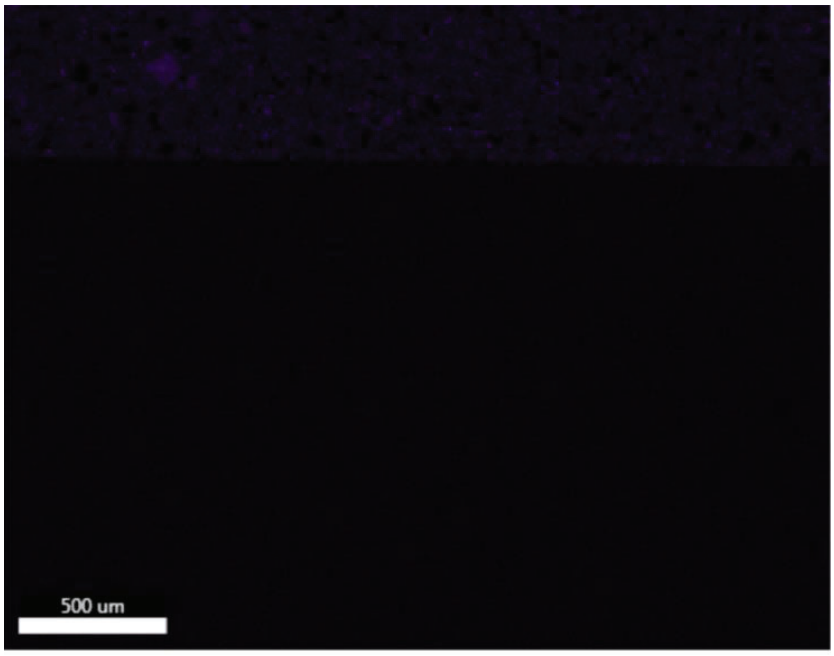

Fig. 11 **The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where oxygen was the predominant element detected.**

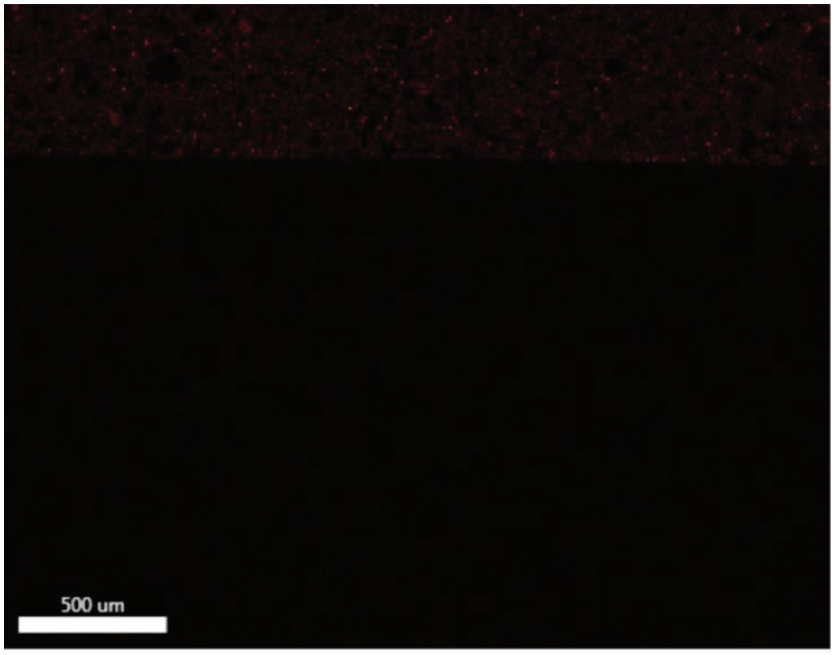

Fig. 12 **The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where magnesium was the predominant element detected.**

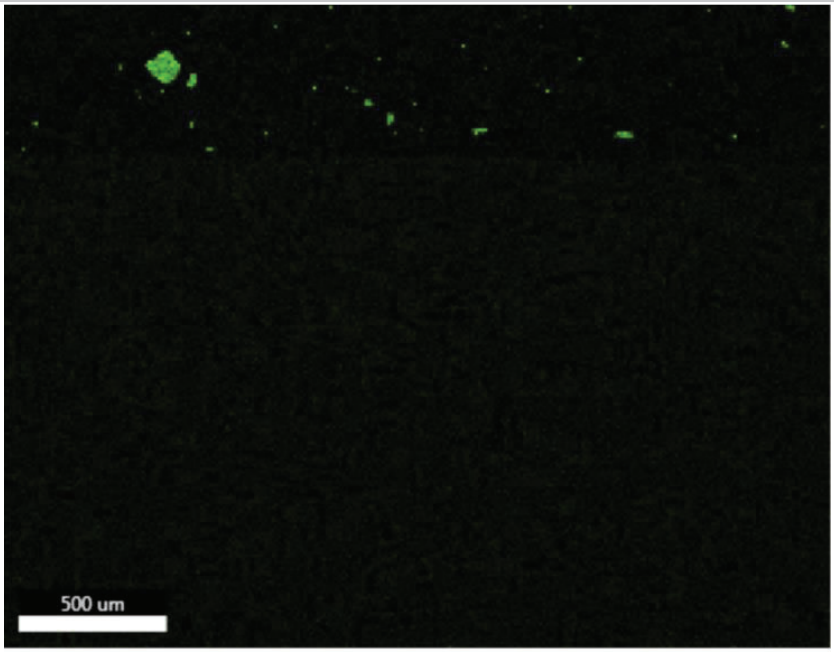

Fig. 13 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where aluminum was the predominant element detected.

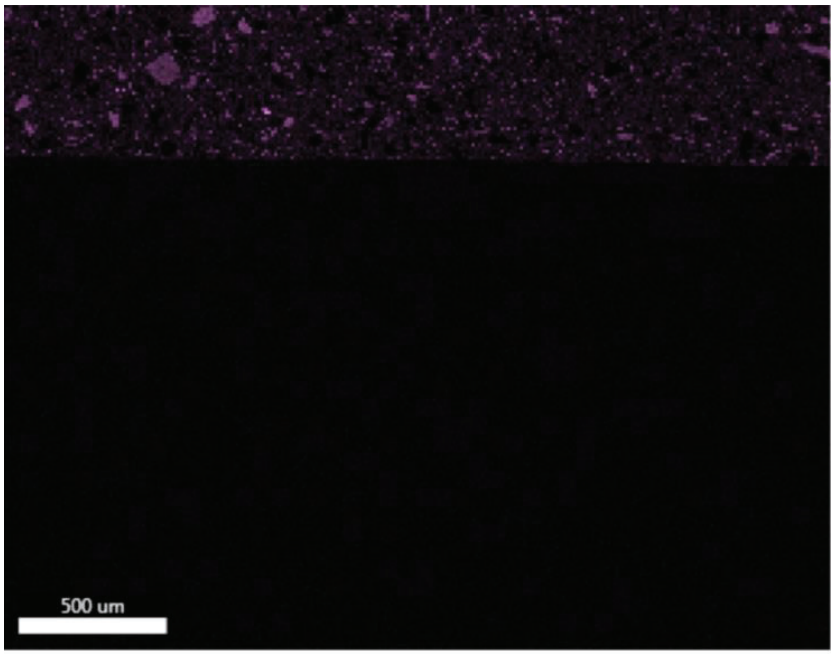

Fig. 14 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where silicon was the predominant element detected.

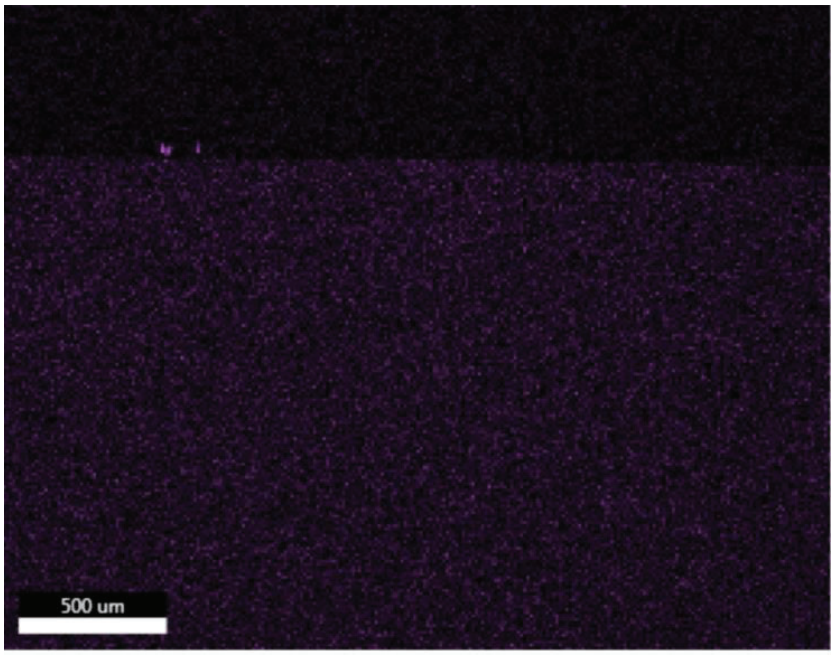

Fig. 15 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where sulfur was the predominant element detected.

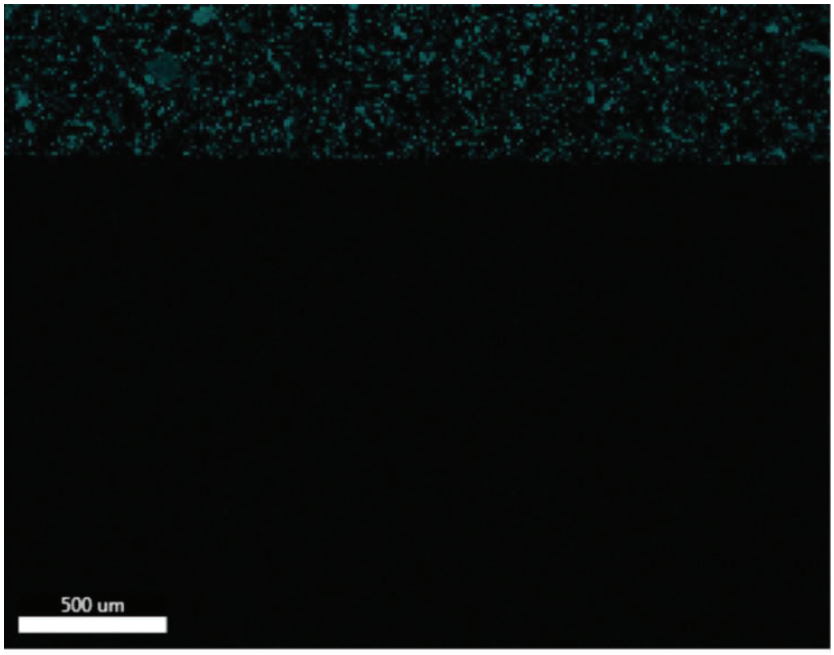

Fig. 16 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where calcium was the predominant element detected.

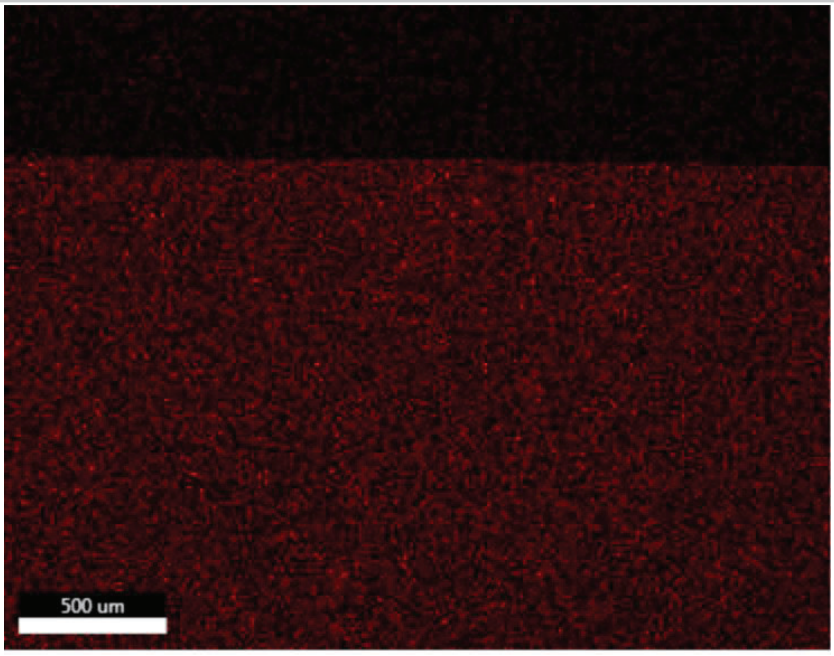

Fig. 17 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where chromium was the predominant element detected.

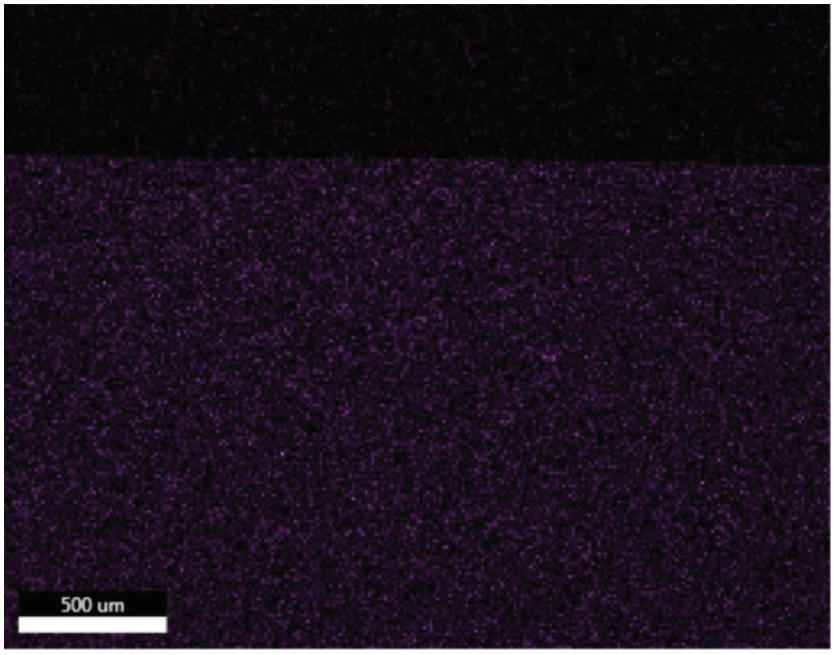

Fig. 18 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where manganese was the predominant element detected.

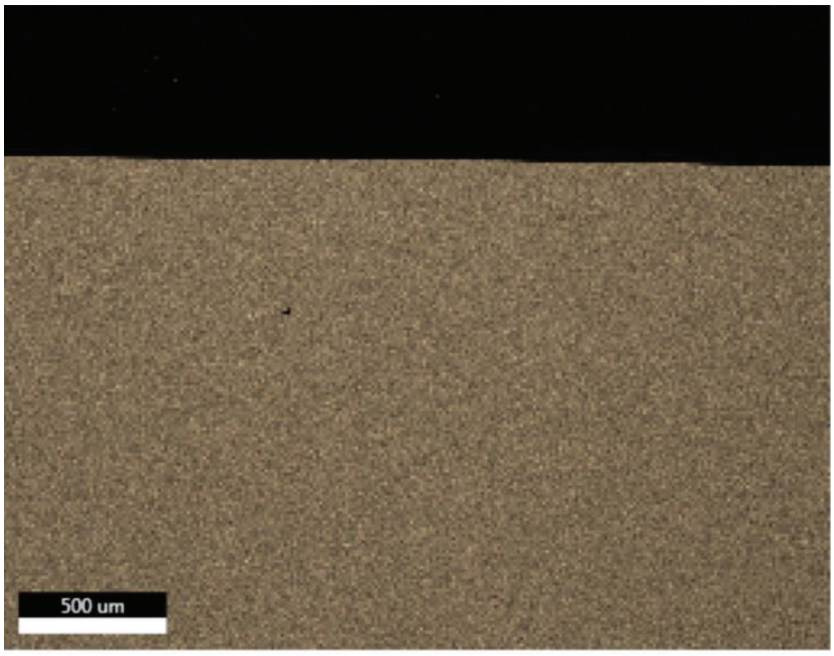

Fig. 19 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where iron was the predominant element detected.

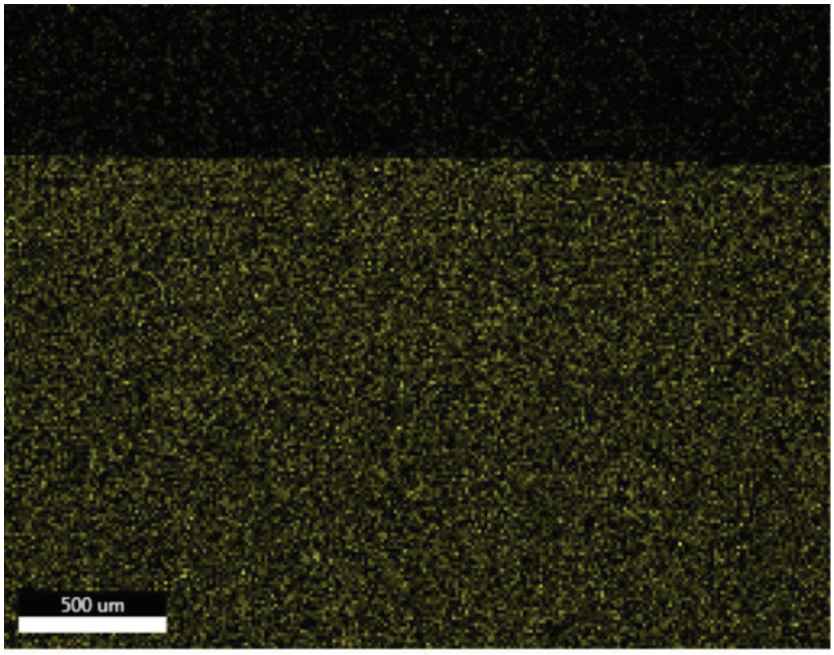

Fig. 20 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where nickel was the predominant element detected.

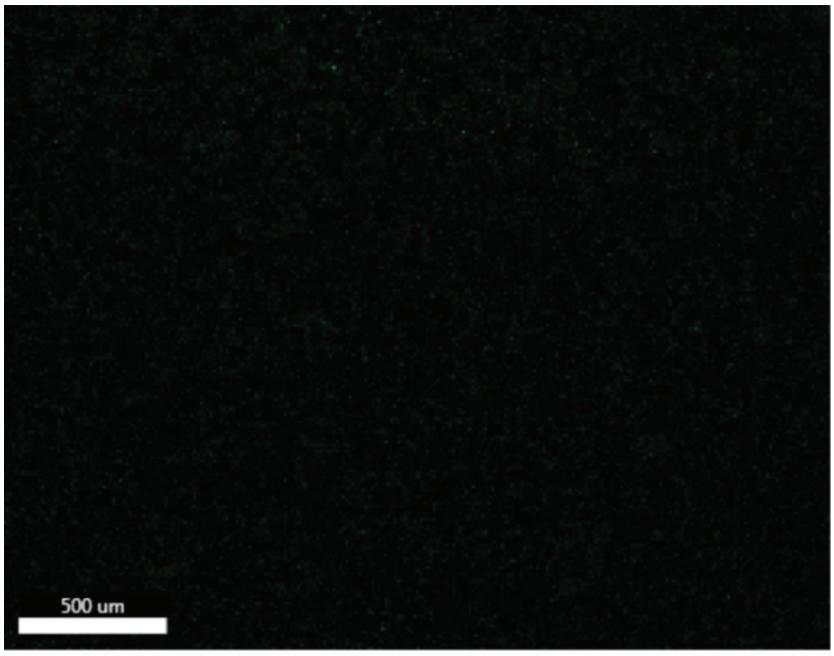

Fig. 21 The EDS elemental map, originally shown in Figure 9, is presented to only reveal the regions where zinc was the predominant element detected.

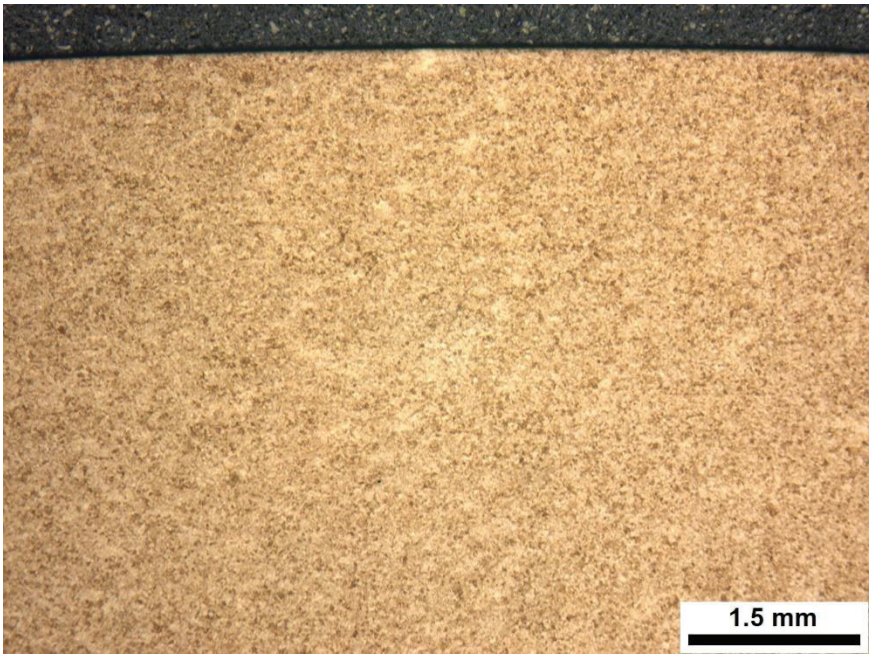

Fig. 22 An overall view of the cross-section is shown at Indication 3 after etching. The microstructure was uniform and contained no anomalous features. 2% Nital.

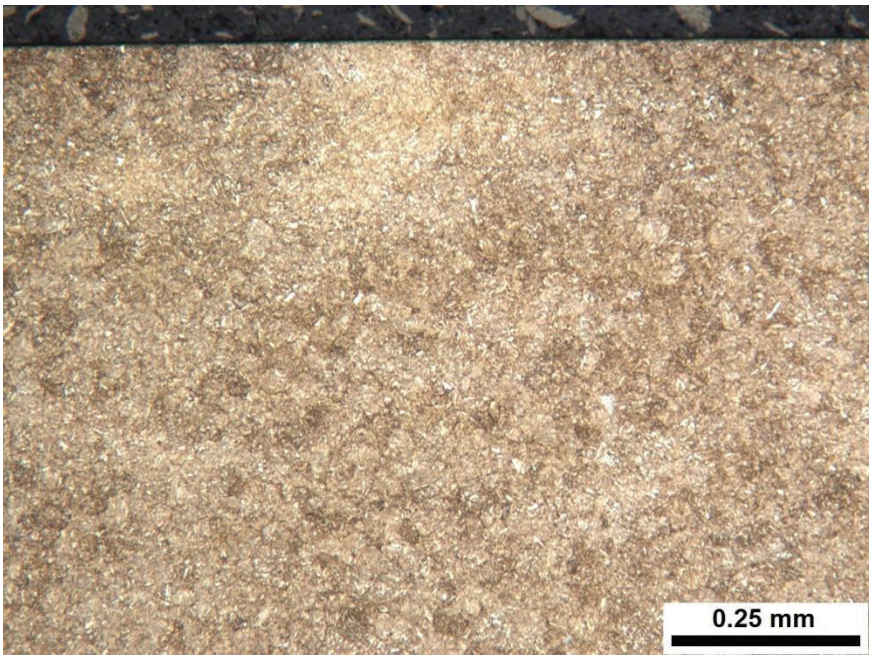

Fig. 23 The top-center of Figure 22 is shown at higher magnification. No decarburization or cracking was observed. 2% Nital.

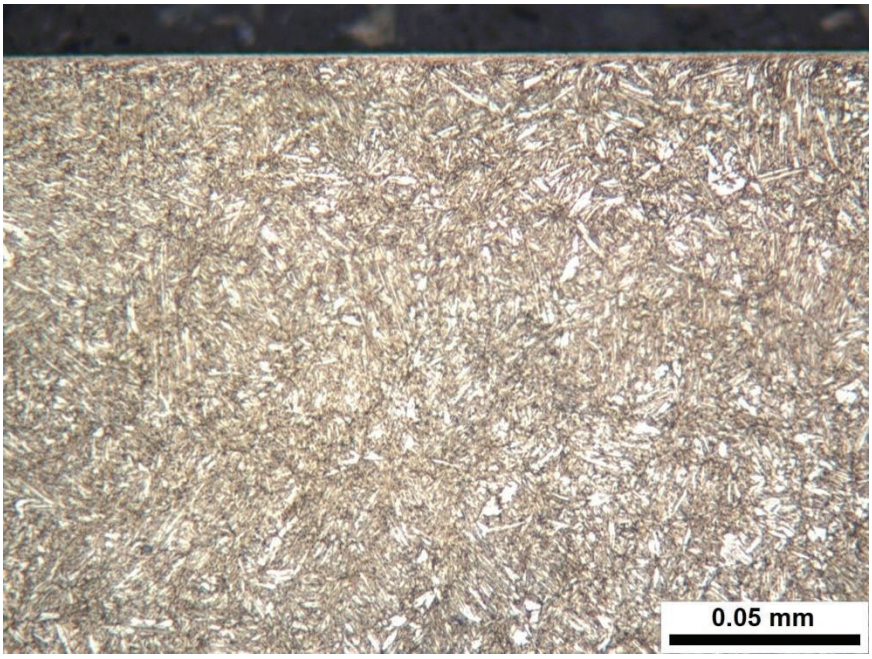

Fig. 24 The top-center of Figure 23 is shown at higher magnification. The microstructure was consistent with tempered martensite. The surface was smooth and uniform and was free of surface cracking, laps, or other forging defects. 2% Nital.

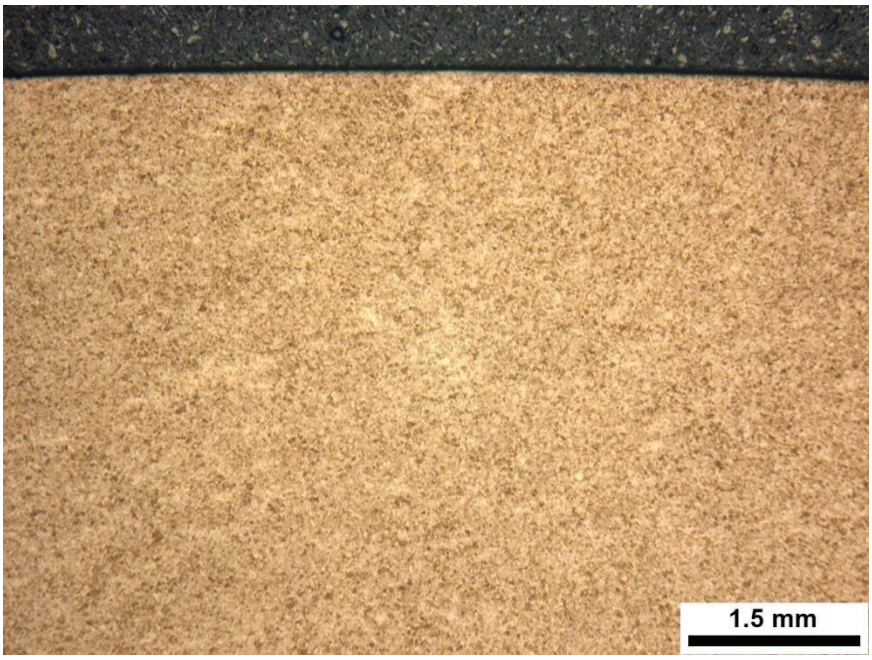

Fig. 25 An overall view of the cross-section is shown at Indication 2 after etching. The microstructure was uniform and contained no anomalous features. 2% Nital.

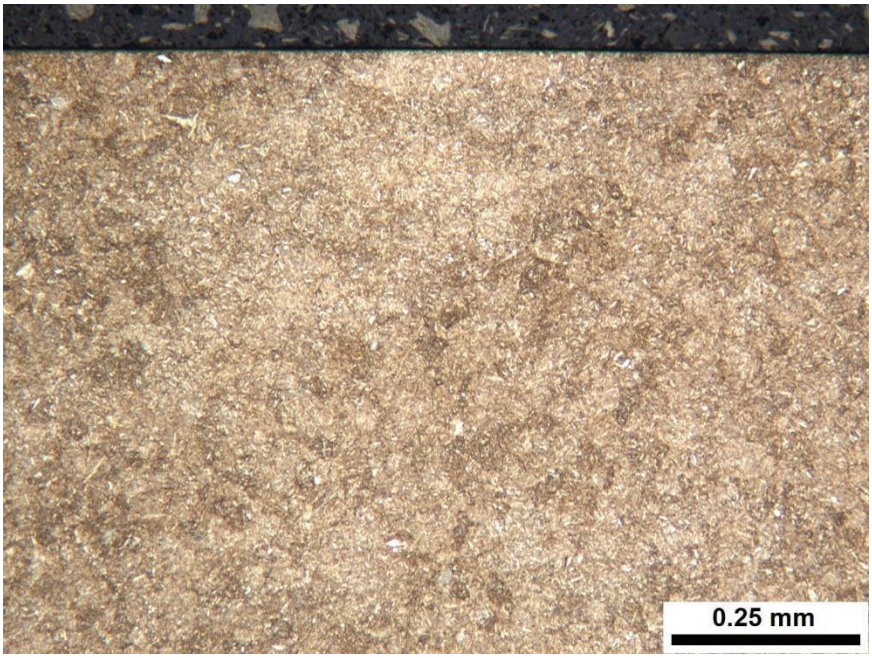

Fig. 26 The top-center of Figure 25 is shown at higher magnification. No decarburization or cracking was observed. 2% Nital.

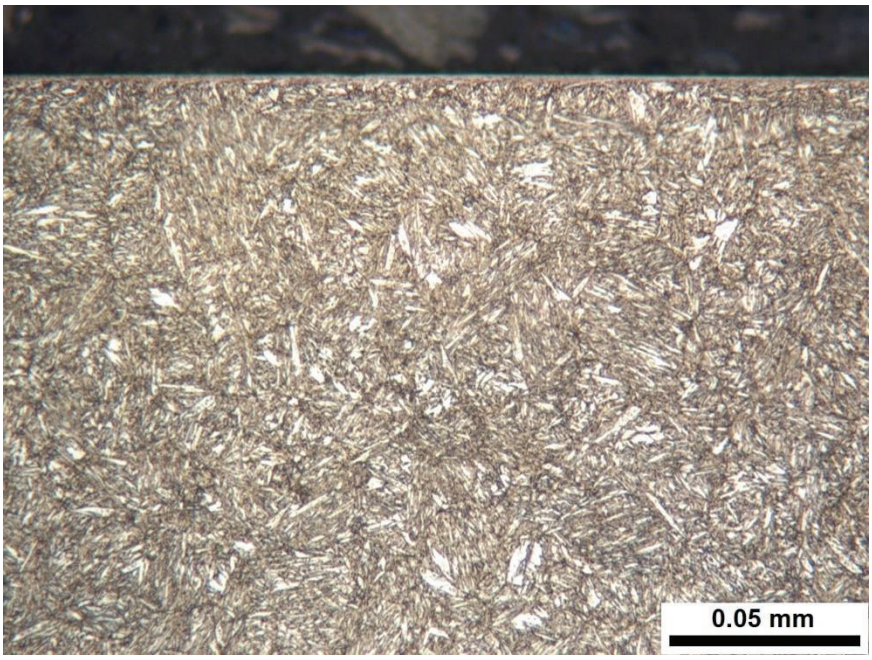

Fig. 27 The top-center of Figure 26 is shown at higher magnification. The microstructure was consistent with tempered martensite. The surface was smooth and uniform and was free of surface cracking, laps, or other forging defects. 2% Nital.

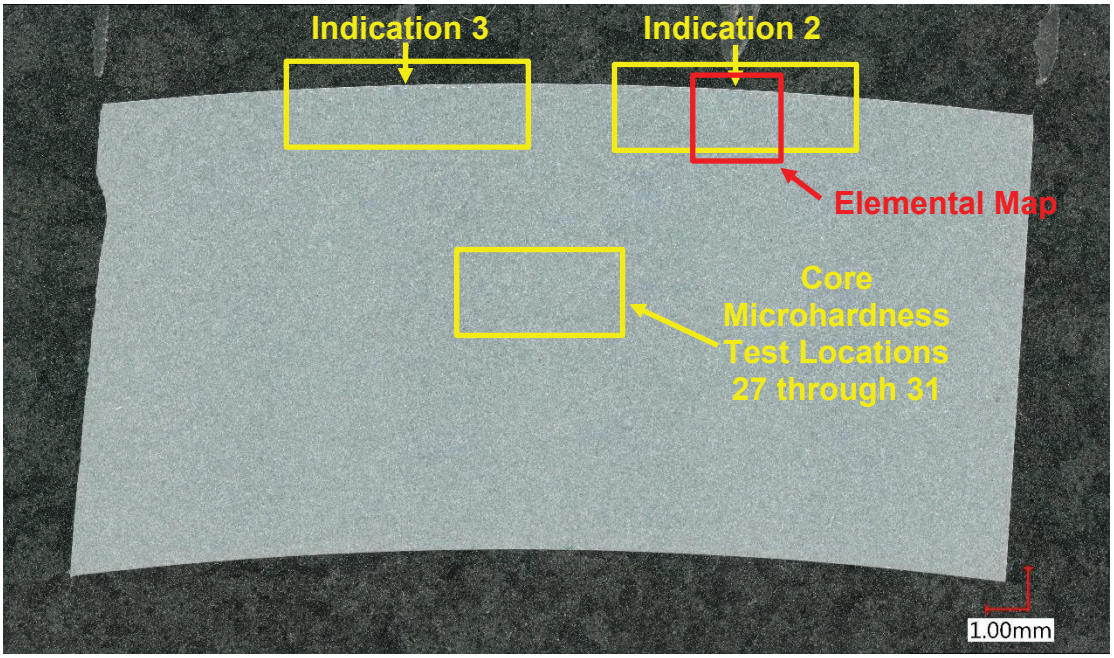

Fig. 28 An overall view of the etched cross-section is shown after microhardness testing. The regions within the yellow boxes were microhardness tested, whereas the red boxed region shows the location of the elemental map in Figure 9. 2% Nital.

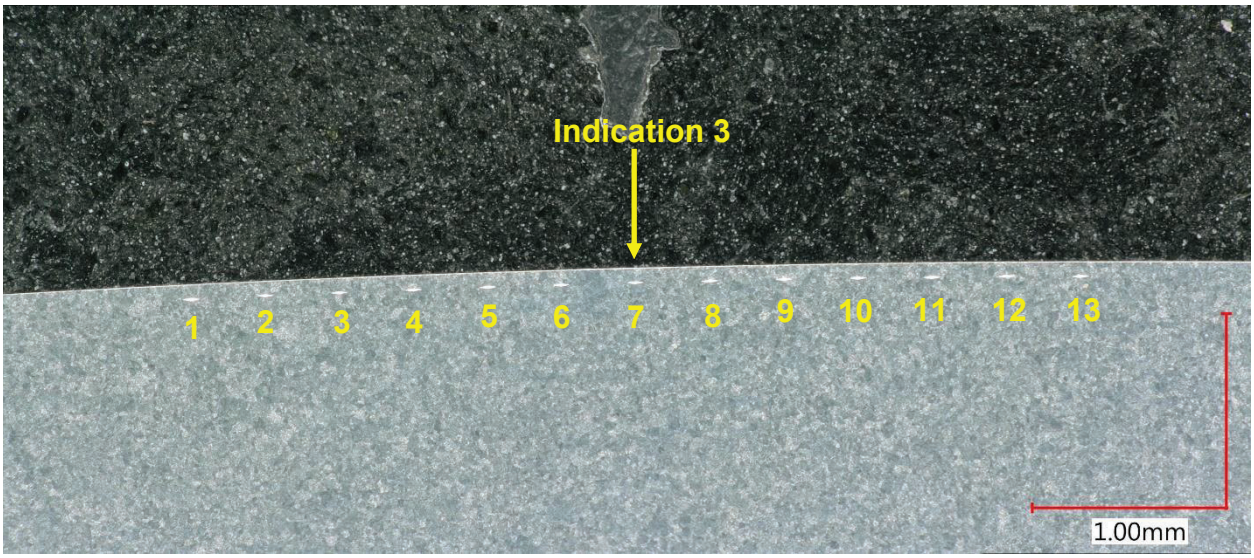

Fig. 29 The boxed region at Indication 3, originally shown in Figure 28, is shown in greater detail. Individual Knoop hardness indentations are visible and numbered, which correlate to their respective hardness results in Table 1. 2% Nital.

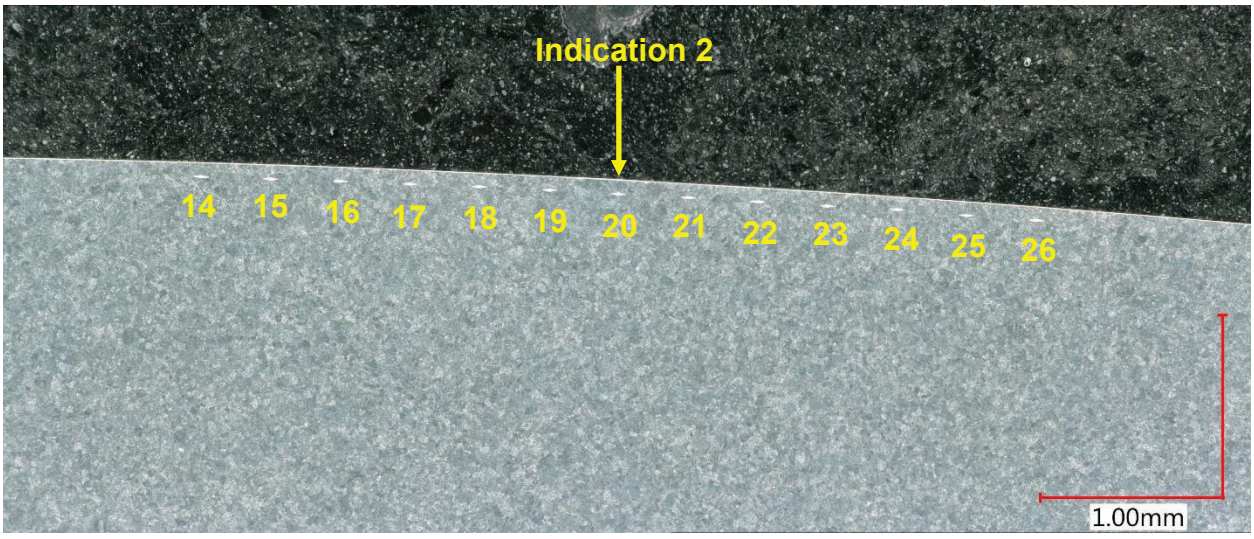

Fig. 30 The boxed region at Indication 2, originally shown in Figure 28, is shown in greater detail. Individual Knoop hardness indentations are visible and numbered, which correlate to their respective hardness results in Table 1. 2% Nital.