MEC-E6007 - Mechanical Testing of Materials

Report: Lab Session 1 – Hardness Mapping

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Introduction

Background

Hardness is a material specific property which defines a material's resistance to localized plastic deformation usually measured through surface indentation or scratch. As the material is subjected to surface indentation the dislocations in the material move and the resulting plastic deformation gives a measure of material hardness. A hard material when in contact with a softer material would cause it to wear. Hardness is generally measured on relative scales, depending on the type of hardness test performed the scale can be Mohs scale, Knoop scale, Brinell scale and Rockwell scale.

Rockwell Test: This test constitutes a combination of various indenters and different loads. The indenters used are typically spherical (1/16, 1/8, ¼ and ½ in. diameter) or conical shaped made of hardened steel and diamond respectively. In this test, initially a minor load is applied on the material followed by a larger major load and hardness is measured as the difference in the penetration depth due to these two loads. Depending on the magnitude of these minor and major loads the test can be categorized as Rockwell or superficial Rockwell test, where the superficial Rockwell test is typically used for thin specimens. The Rockwell scale is designated by symbol HR followed by the scale identification symbol (A, B, C, D, E, F, G, H, K, 15N, 30N, 45N, 15T, 30T, 15W, 30W, 45W etc.) which is defined based on the load and indenter.

Brinell Test: This test also uses a spherical shaped indenter forced into the specimen surface. The diameter of the indenter is usually 10 mm and the indenters are made of hardened steel or tungsten carbide. The test procedure requires load to be maintained for specific time usually between 10 to 30 s. Brinell harness is designated by the symbol HB and it is measured as a function of the load that is applied on the specimen as well as the diameter of the indentation formed on the specimen. The indentation diameter is measured through a microscope or, in modern devices, through a camera.

Knoop and Vickers Tests: Designated by the symbols HK and HV respectively, these tests require small diamond, pyramidal shaped indenters forced into the specimen surface. The size of the indentation is then measured through a microscope, modern test equipment, however, make use of image analyzers coupled with a software package and perform the tests in completely automated way. As the indenter is small, these tests are also called micro-indentation tests. Knoop hardness test is usually utilized for brittle materials. Information on specimen. The hardness scales for Knoop and Vickers hardness are approximately equivalent.

Test case

The test case required the measurement of Vickers Hardness for the weld material in the given specimen in which S355 and S690 grade steel were welded together using submerged arc welding (SAW). As discussed above, HV is measured through a diamond, pyramidal shaped indenter. The geometry of the indenter can be seen in Figure 1:

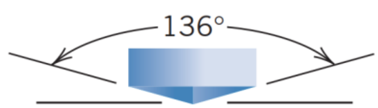

Figure 1. HV indenter geometry. [1]

The base materials on each side of the weld can be distinguished based on their material properties, S355 has minimum yield strength of 355 MPa and hardness values ranging from 146 HB to 187 HB, whereas, S690 has relatively higher minimum yield strength of 690 MPa and hardness values typically in the range of 235 to 295 HB. The weld material composition is unknown and will be estimated based on the hardness test.

Methods

The hardness tester used was a DURAMIN-40 AC2 multipurpose hardness tester. The dwell time was set to 10 s while the indentation force was 1 kgf, corresponding to HV1. Scope magnification was set to 20x. A transversal slice was cut from the parent welded specimen using wired electrical discharge machining to produce the hardness test specimen. The test specimen was ground and then polished using increasingly finer grit sizes, finishing with a fine diamond particle fluid polishing step. Chemical etching was then performed to visually reveal the metallurgical zones present on the surface of the specimen.

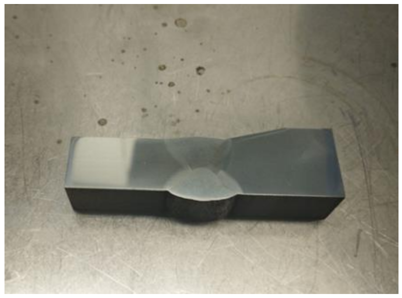

Figure 2. Specimen

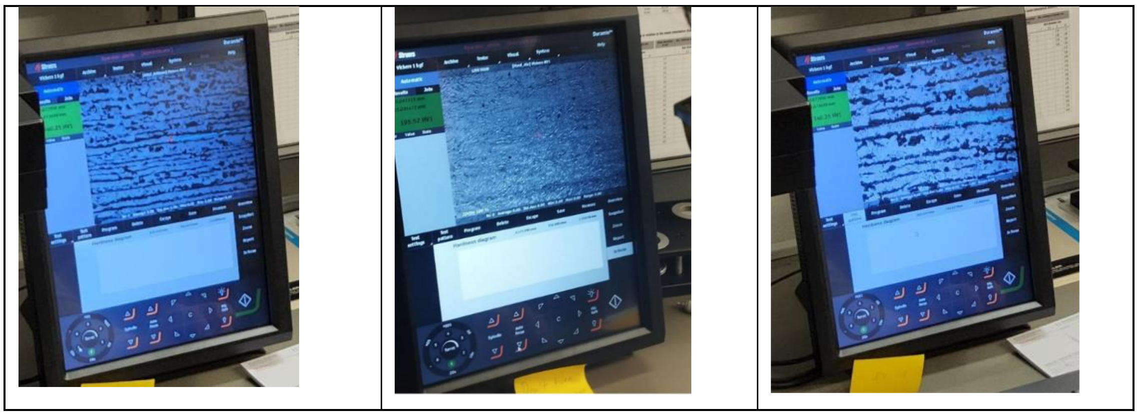

Figure 3. Magnification

Figure 4. DURAMIN-40 AC2

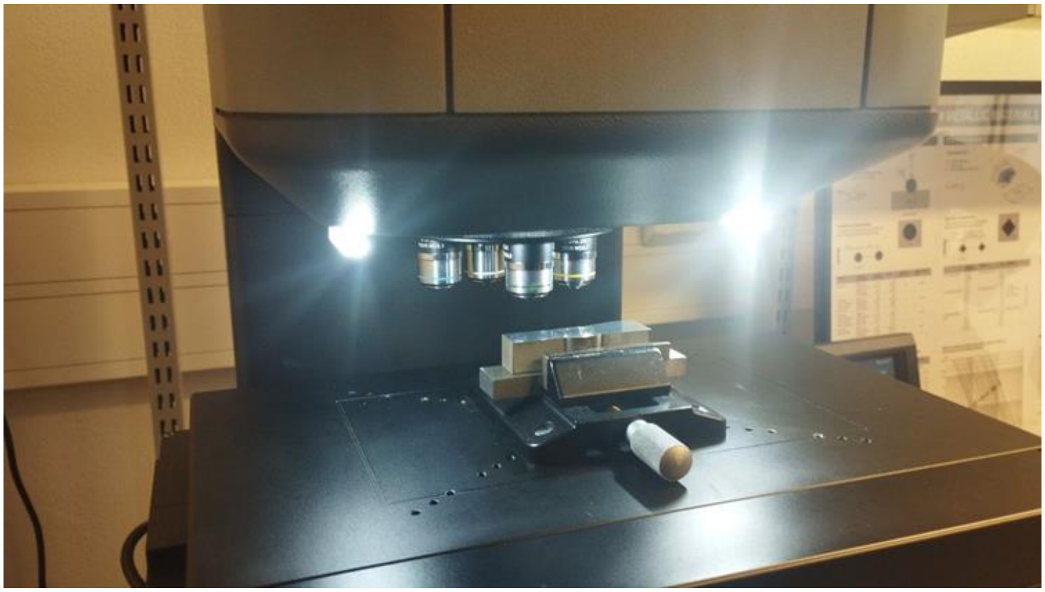

Figure 5. Indentation

Figure 6 shows the prepared specimen under the lens of the hardness tester. A line near the root of one of the weld beads was chosen. The different material zones base metal 1 (BM1), heat-affected zone 1 (HAZ1), weld metal (WM), HAZ2, and BM2 are shown. On both top and bottom weld beads a division of HAZ2 can be seen based on the visible shades. HAZ1 on the other hand remains consistent in shading. For the testing procedure, three indentation points were placed in each material zone while HAZ2 featured 2 x 3 points in an attempt to capture the distinct division present in that zone.

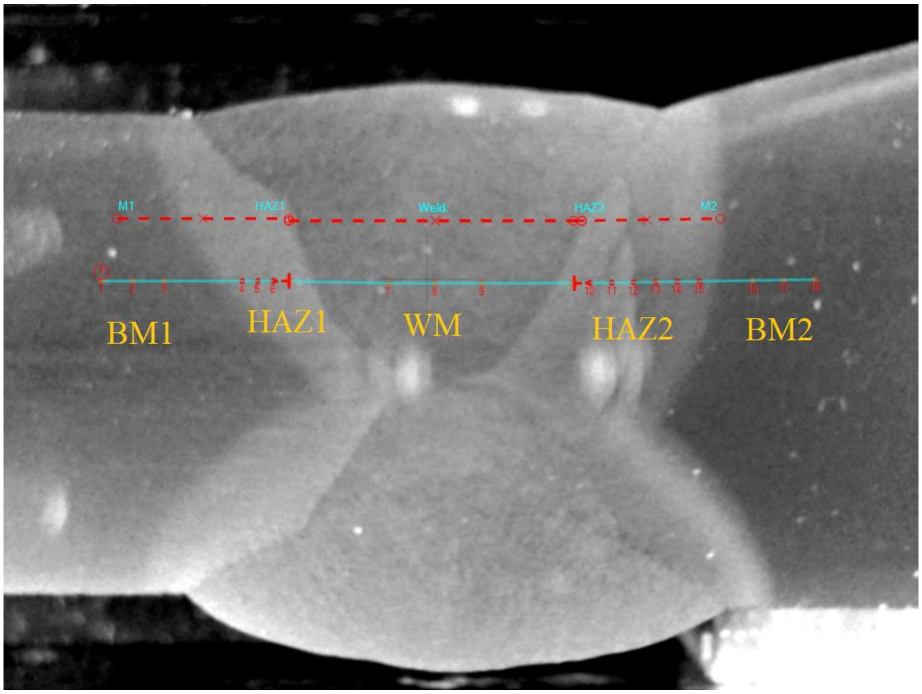

Figure 6 **Overall view of specimen with indentation points.**

Results

Figure 7 shows the measured hardness values, when moving from left to right along the indentation points. Points are grouped into their respective metallurgical zones, with HAZ2 further split into two regions. Table 1 further shows basic statistics corresponding to each zone along with the total statistics of all points. The weld metal displays the lowest mean values. Both heat-affected zones display the greatest variation of measured values with sudden increases or reductions in hardness both in the middle of HAZ1 and at the last point of HAZ2-2. The two base metals and the weld metal feature similar variations in values.

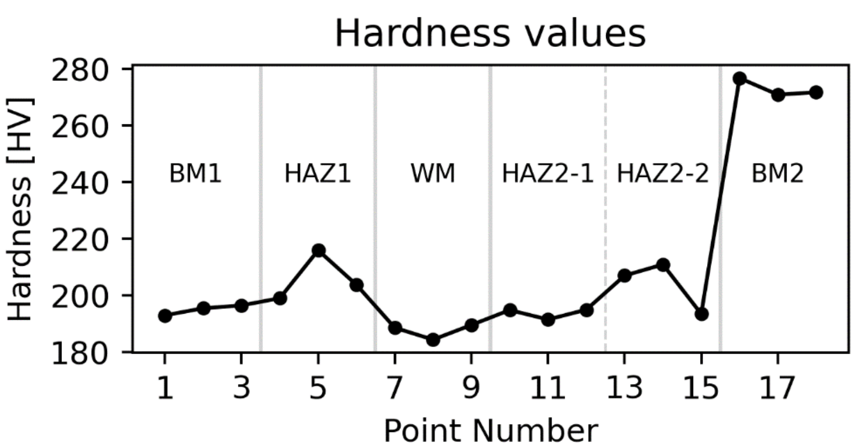

Figure 7. Measured hardness values.

	BM1	HAZ1	WM	HAZ2	BM2	All
Mean	195.0	206.3	187.6	198.8	273.2	209.9
Std. Dev.	1.5	7.1	2.2	7.4	2.6	29.3
Min.	193.0	199.1	184.4	191.6	270.9	184.4
Max.	196.5	216.0	189.6	211.0	276.8	276.8
Range	3.5	16.9	5.2	19.4	5.8	92.3

Table 1. Statistics of each zone [HV].

Figure 8 shows images of microstructures representative of each material zone. While grain boundaries are not distinctly visible, overall, a refinement of carbides can be seen surrounding the weld and a distinct difference in composition between BM1 and BM2. From left to right, coarse layered carbides are visible in BM1, with the carbide distribution becoming finer when moving into HAZ1. No martensite appears to be visible based on the lack of needle-like carbides. HAZ1, WM, and HAZ2-1 appear relatively similar while out of these three, the WM appears to be relatively slightly more coarse. This can also be seen from Figure 3 from the slightly lower hardness values in the WM. Clear change in composition can be seen when moving to HAZ2-2, with its general structure more closely matching BM2 rather than the weld metal. The last two images of HAZ2-2 and BM2 distinctly display a smaller amount of carbides compared to the other zones. Signs of deformation in the form of ‘wakes’ surrounding the indenter are also visible particularly in BM2.

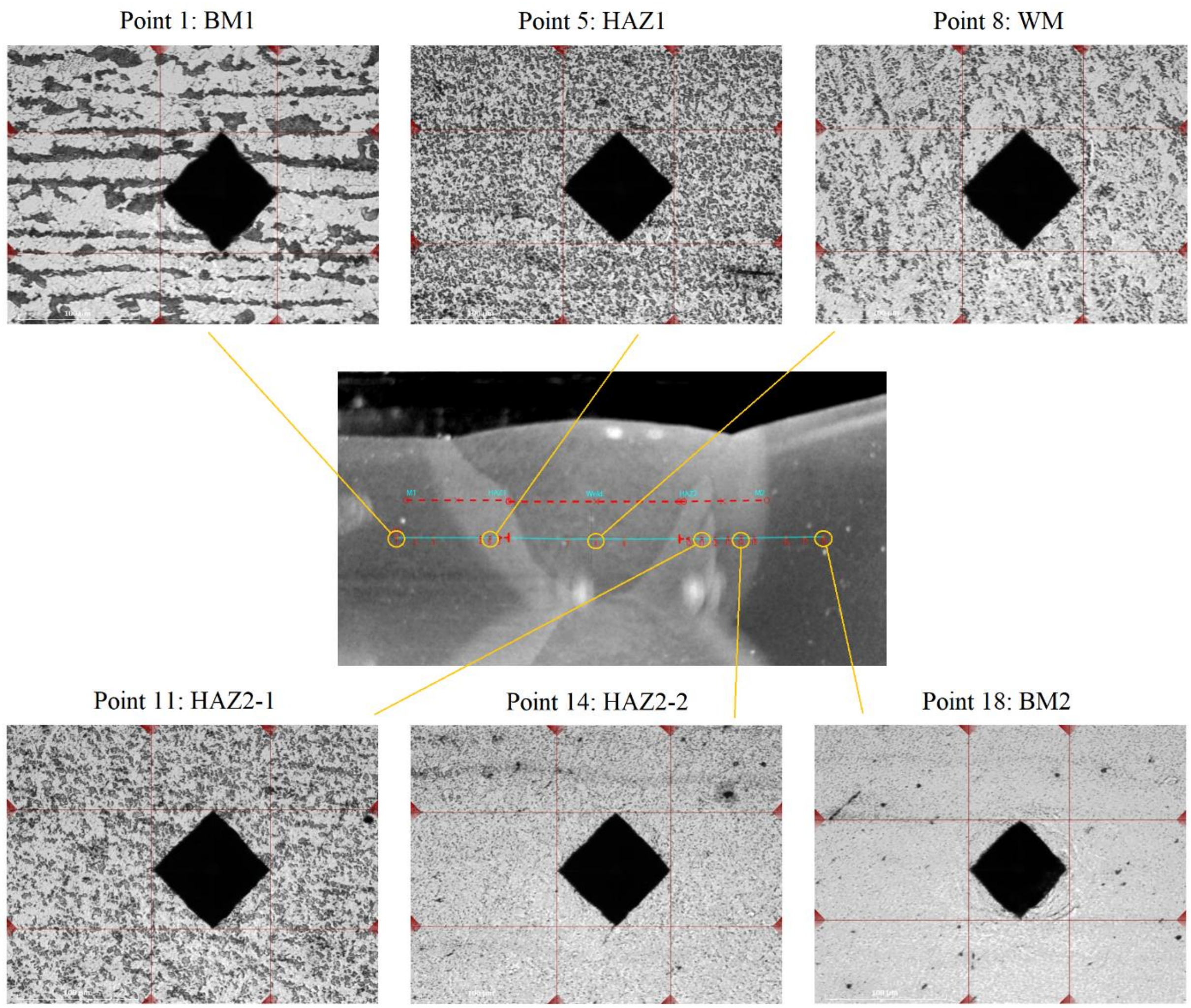

Figure 8. Images of select indentation points showing surrounding microstructures.

Discussion & Conclusions

Based on hardness values and amount of carbides in the microstructure, BM1 likely corresponds to S355 and BM2 to S690 grade steel. Considering potential weak spots in the connection, the connection between the weld and BM2 (see Figure 2) potentially induces a geometrical stress concentration as the right-hand side plate tapers down to the welded connection. The finer carbide distribution of the heat-affected zones can potentially also block dislocation movement and cause more brittle behavior compared to the coarser distribution of the S355 / BM1 zone. The ISO 9015-2 standard [2] on microhardness testing was not exactly followed in certain aspects, which degrades the reliability and reproducibility of the results. The location of the measurement line was not recorded, and additionally the ISO 9015-2 [2] standard specifies the measurement of two additional points in the HAZ vertically along the fusion line for hardening materials. Distance recommendations between points were followed. Additionally, due to the greater variability in hardness values in the heat-affected zones, a sample size of 3 points can potentially be considered insufficient for confident statistics of those zones. It is also difficult to precisely ascertain the reason for the split in both microstructure and hardness values in the middle of the HAZ2 zone without additional information on the welding procedure.

To conclude, a SAW-welded specimen featuring S355 and S690 grade steels was measured for hardness values transversally across a weld bead. The base materials were assumed based on hardness values and microstructures. The heat-affected zones featured the greatest variation in measured values while the two base materials and weld metal were significantly more consistent in measured values. Images of microstructures revealed how carbides became more finely distributed in the heat-affected zones and the weld metal.

References

[1] W. D. Callister, Materials science and engineering: an introduction., New York: John wiley & sons, 2007.

[2] SFS-EN ISO 9015-2: Destructive tests on welds in metallic materials. Hardness testing. Part 2: Microhardness testing of welded joints (ISO 9015-2:2016).