Aalto University
School of Engineering

MEC-E6007 Mechanical Testing of Materials
Laboratory Exercise 1: Hardness Mapping

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1. Introduction

Objective was to perform hardness test to a part of a welded connection extracted from a joint in cruise ship, determine the base materials on each side of the weld, and determine possible locations of weaknesses within the welded joint. The method used for welding was submerged arc welding (SAW), and the base materials used for manufacturing were S690 and S355. The former is a special alloy steel having high strength and impact properties having its application in structural members. The latter is also from the structural steel class with a lower yield strength than the former one. A difference in yield strength meant that the behavior of material in the weld zone and heat affected zone (HAZ) needs to be examined to properly draft the behavior of weld joint. In this experiment the hardness of the joint will be mapped and discussed for increase or decrease in the hardness and eventually the strength of the joint. The comparison of chemical composition and mechanical properties of base metals S690 and S355 are listed in Table 1 and Table 2 respectively.

Table 1. Comparison of chemical compositions.

Chemical Composition	C	Si	Mn	Ni	Cr	Cu	Fe
S690	0.2	0.8	1.7	2	1.5	-	Balance
S355	0.2	0.5	1.6	-	-	0.5	Balance

Table 2. Comparison of mechanical properties.

Mechanical properties	**Vicker's Hardness (HV)**	**Tensile Strength (MPa)**	**Yield Strength (MPa)**	**Impact (J) @ -20Deg**	**Reference**
S690	240 - 300	770 - 940	690	40	(Metinvest, ei pvm)
S355	160 - 200	490 - 630	355	27	(MatWeb, ei pvm)

2. Method

The hardness measurements were performed on a Stuers Duramin-40 AC2 automatic hardness tester, as presented in Figure 1. The specimen consisted of two base materials welded together with a fully penetrated double V-butt joint. The concerned joint was sectioned, and the sectioned surface was etched to study the hardness behavior in the base metal, HAZ and the weld zone. This report discusses the result of hardness mapping close to the surface of the weld which primarily means that the hardness values can be predicted to be on the higher side as this could be the last pass of the joint and would have been exposed to the still air resulting in higher hardness and strength. The measurements were executed according to the SFS-EN ISO 6507-1:2023 standard (Finnish Standards Association, SFS-EN ISO 6507-1:2023:en. Metallic materials. Vickers hardness test. Part 1: Test method (ISO 6507-1:2023), 2023). The test pattern used for the hardness testing is illustrated in Figure 2, and was inspired by standards SFS-EN ISO 9015-1 and SFS-EN ISO 9015-2 (Finnish Standards Association, SFS_EN ISO 9015-1:en. Destructive test on welds in metallic materials. Hardness testing. Part 1: Hardness test on arc welded joints (ISO 9015-1:2001), 2012; Finnish Standards Association, SFS_EN ISO 9015-2:en, Destructive tests on welds in metallic materials. Hardness testing. Part 2: Microhardness testing of welded joints (ISO 9015-2:2016)., 2016). The test setup is summarized below:

- Performed test: Vickers Hardness test, HV 1 (1 kgf / 9.807 N)
- Base materials: S690 and S355
- Weld type: SAW
- Test equipment: Duramin-40 AC2
- Test date: 12th of March 2023
- Dwell time: 10 seconds
- Indentations were approximately 0.4 mm off the edge on the left side of the weld, which agrees with below 2 mm specification from the standards

- Three measurements were performed on each base plate and HAZ, and five measurements were executed on the weld joint
- Test pattern distances between measurements were 1.5 mm in the base materials, 0.3 mm in the HAZ and 3.0 mm in the weld joint

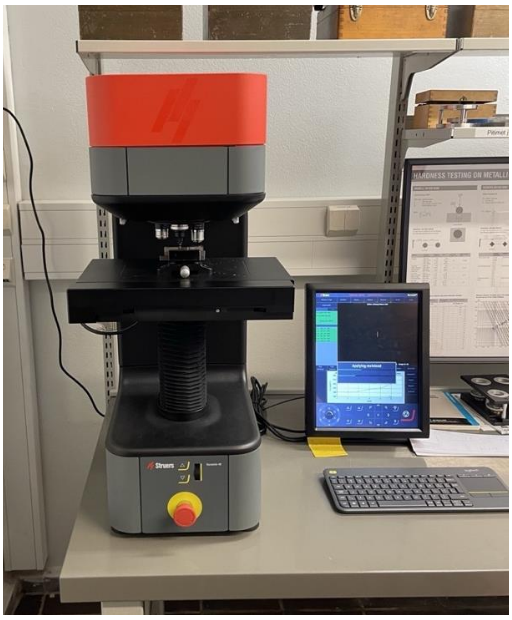

Figure 1. Struers Duramin-40 hardness tester used for the measurements.

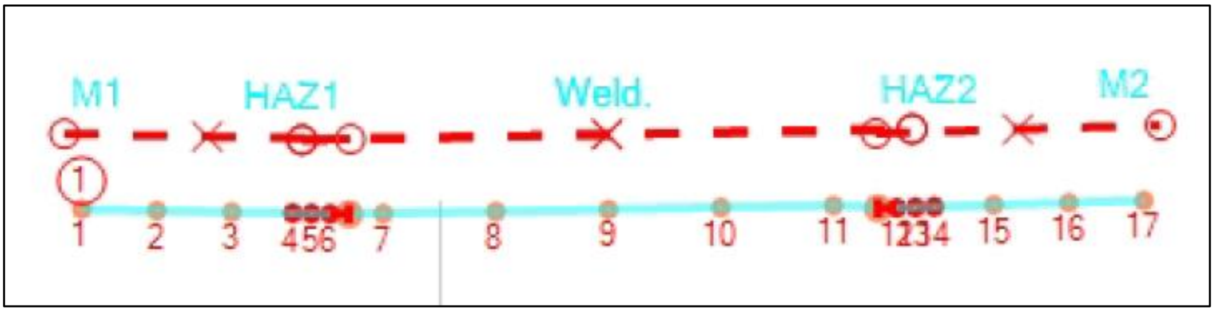

Figure 2 Test pattern used in testing.

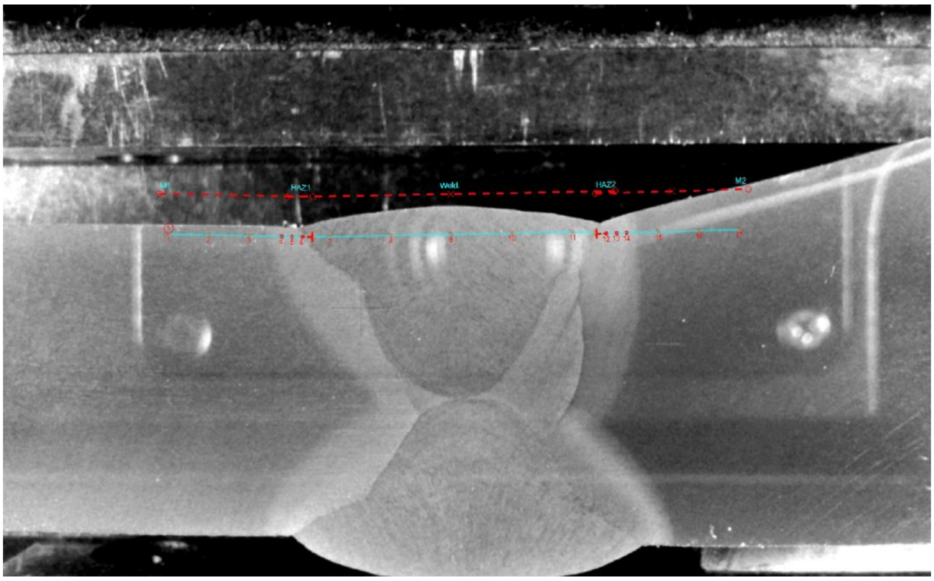

Figure 3 Snapshot of the test specimen with the locations of the indentations performed.

3. Results

The hardness values were automatically calculated from the size of the indentations caused by the controlled impact by the machine (see Appendix A). The calculated results were then plotted to achieve a better overview of the values for each point, as illustrated in Figure 4. Additionally, statistical values for the measurement group were calculated and printed Table 3. All hardness values were between 183 and 281, with clear differences in hardness of each measurement region. The lowest values are in the M1 region and can therefore be presumed to be the softer S355 grade base plate. The HV1 hardness of approximately 185 does also agree with the theoretical range of 160 – 200 HV1 presented earlier.

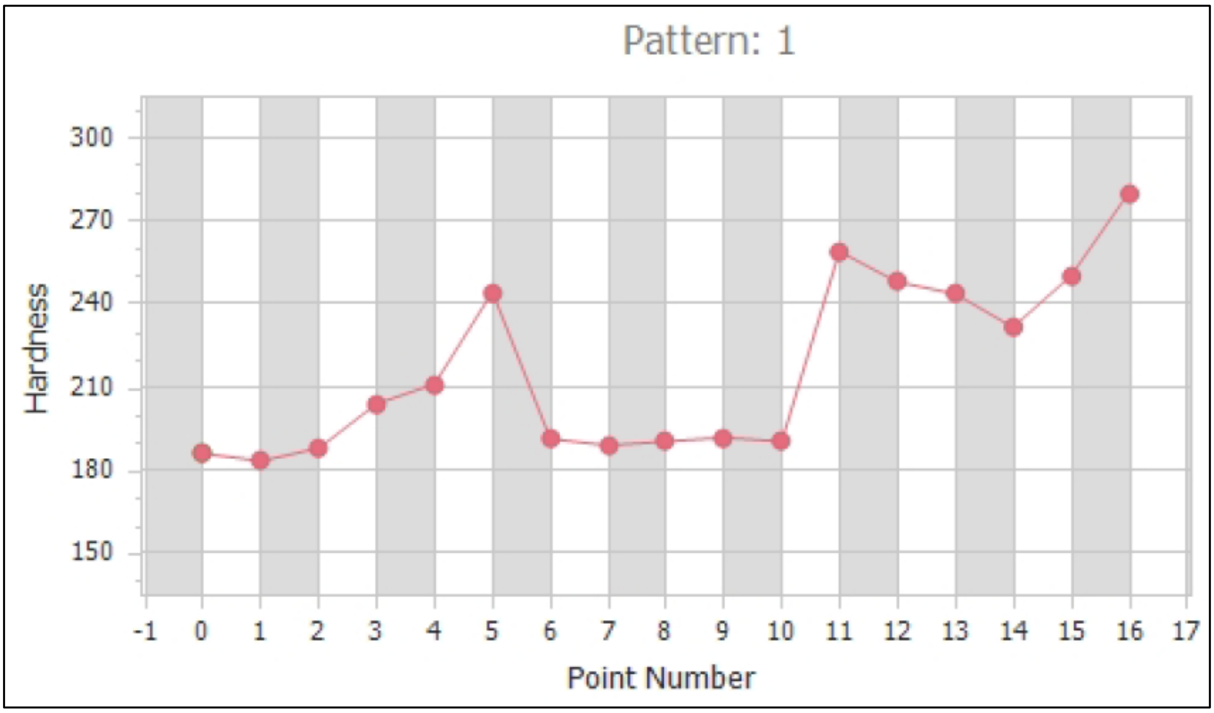

Figure 4 Hardness values of each indentation performed in the main test.

Table 3. Statistical values for the measured points.

Pattern	Mean	Min	Max	SD	Range	USL	LSL	Cp	Cpk
1	216.43	183.03	280.23	31.87	97.20	0.00	0.00	0.00	-2.26

The measurements done on the weld joint are extremely consistent and slightly greater than those for the left-hand side base plate. This indicated that the weld was successfully executed making the specimen satisfactory for hardness testing. Conversely, points 15 to 17 deviated a lot from each other and were consequently measured again, except now a bit further away from the weld (see Appendix B). The results from the control measurement are presented in Figure 5 and Table 4, and showed improved correlation with the value furthest away from the weld in the first measurement. The two hardness values of approximately 280 HV1 from the control test does likewise correspond with the theoretical hardness values of 240 HV1 – 300 HV1, confirming that it in fact is the S690 grade base plate.

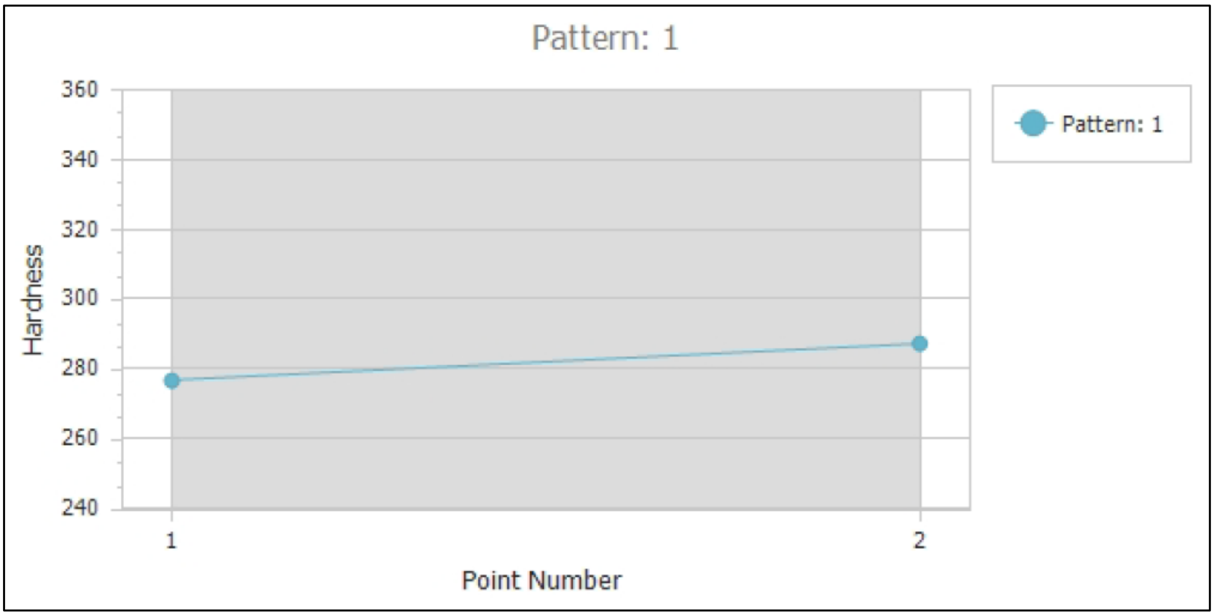

Figure 5. Hardness values of each indentation performed in the control test.

Table 4. Statistical values for the two control points.

Pattern	Mean	Min	Max	SD	Range	USL	LSL	Cp	Cpk
1	282.05	276.82	287.28	7.39	10.45	0.00	0.00	0.00	-12.72

The hardness values in the HAZ1 and HAZ2 regions express greater variation compared to the other zones. This is potentially partly due to the HAZ being relatively narrow, resulting in more significant measurement errors. Moreover, both HAZ1 and HAZ2 seem to be harder towards the weld seam, due to the greater temperatures altering the microstructure of the steel.

4. Discussion

4.1 Different hardness measurement methods

Hardness of a material refers to the ability of a material to resist penetration by a harder material. It is an empirical measurement of material properties indicating the ability of a material to withstand indentation under a static load or scratching. The resultant hardness value depends on the testing method. The main methods are;

1. Brinell; which uses a tungsten carbide ball indenter with hardness value calculated from the diametrical relation between the ball and the impression made and the test force used
2. Rockwell; which uses a conical diamond or a tungsten carbide ball indenter with hardness values calculated from the relation between the indentation depth under a large load compared to that made by a preload
3. Vickers and Knoop; which uses a diamond indenter with the former having a pyramid shaped diamond and the latter with a rhombohedral shaped diamond indenter, the hardness value is calculated from the force used and the length of the diagonals of the resultant indent.

There are a wide variety of machines on the market that carry out hardness testing based on the above testing methods. For this experiment, Vicker's hardness test method was employed. Indentation mapping relates to the ability to map out variations in hardness across a sample due to non-homogenous nature of materials. Non-homogeneity, manifested in variations in hardness across a test piece, is attributable to processing parameters. This will be illustrated for a welded and an additive manufactured metallic component. Mapping can also be applied to materials with dual or multiphase components exhibiting localized variations in hardness.

As the weld was of two dissimilar metals, the behavior of the hardness invariability was evident in the curve in figure 4. The hardness increases from left to right as the parent hardness of the material at the right of the weld was higher. Although point 5 and 11 showed some anomalies, that can be attributed to variable cooling cycles at that point or a momentarily increase in current when the welding operator was approaching that part.

4.2 Sources of potential weaknesses in the welded joint

All materials can include flaws. This is especially true for welded materials, where the weld itself can introduce new sources of weakness. Welding two dissimilar materials together only increases the risk for weaknesses, due to possible incompatibilities between the base materials. Although, the specimen tested by the authors did not present any noticeable weaknesses in regards of hardness, possible issues that could have arisen include:

- Welding defects: For example, improper weld penetration or use of incorrect shielding gas during the welding process. This category does also include local stress points caused by unsuitable welding order.
- Base metal imperfections: The base metals could be porous or have other types of imperfections affecting the weld quality. Moreover, the base metals could be incompatible with the filler metal used during the welding process.
- HAZ effects: The HAZ can alter the microstructure of the base metals close to the weld joint, possibly resulting in degraded mechanical properties.

5. Conclusion

A Vicker's hardness test was successfully performed on two dissimilar base metals with a common welded V-butt joint. Both base materials were distinguished from each other, with the left-hand side base plate being identified as the S355 grade steel plate and the right-hand side as the S690 grade steel plate. Furthermore, possible sources of potential weaknesses in the weld joints were classified as in the base materials, the weld joint and in the HAZs.

References

Finnish Standards Association. (2012). SFS_EN ISO 9015-1:en. Destructive test on welds in metallic materials. Hardness testing. Part 1: Hardness test on arc welded joints (ISO 9015-1:2001). Helsinki.

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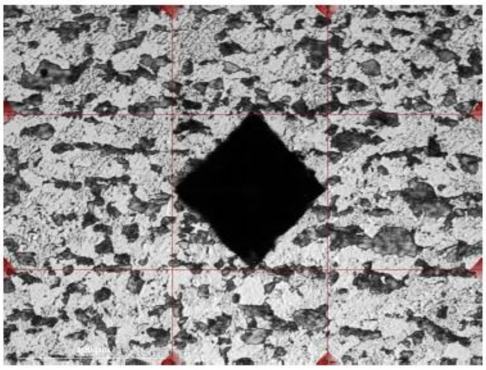
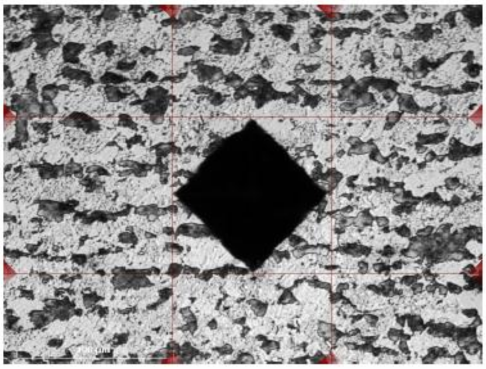
Appendix A

The indentations captured by the camera during the main measurement set are presented in this appendix.

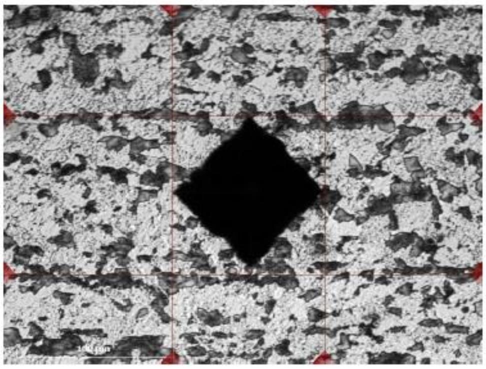
ID	**1 (1/1)**
Hardness	185.72 HV1
d1	0.0995 mm
d2	0.1003 mm
position	x: 95.37 mm y: 66.82 mm
Conversions	
Time	1:27:36 PM



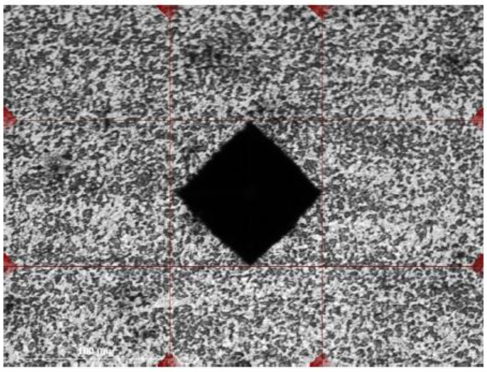
ID	**2 (1/1)**
Hardness	183.03 HV1
d1	0.1015 mm
d2	0.0998 mm
position	x: 97.37 mm y: 66.78 mm
Conversions	
Time	1:28:20 PM

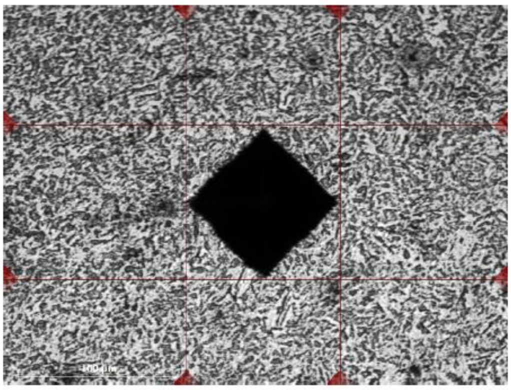


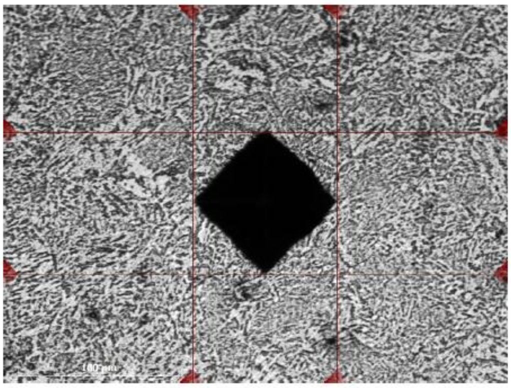
ID	**3 (1/1)**
Hardness	187.7 HV1
d1	0.0975 mm
d2	0.1013 mm
position	x: 99.37 mm y: 66.75 mm
Conversions	
Time	1:29:06 PM

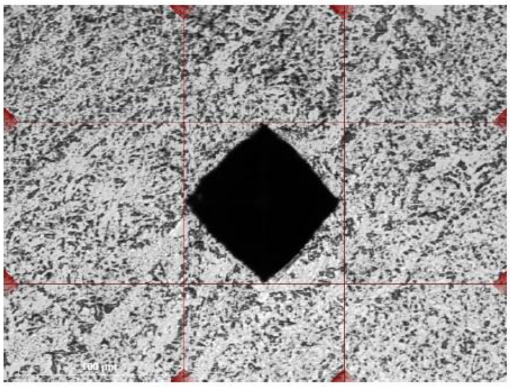


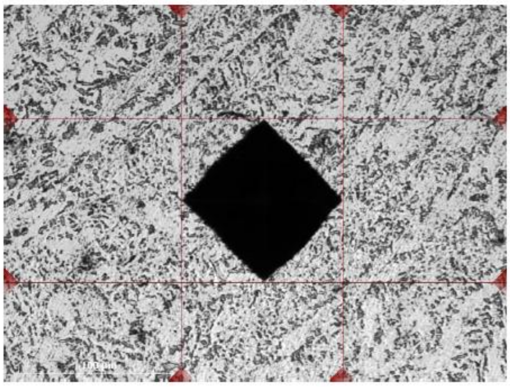
ID	**4 (1/1)**
Hardness	203.83 HV1
d1	0.0975 mm
d2	0.0933 mm
position	x: 100.99 mm y: 66.72 mm
Conversions	
Time	1:29:51 PM



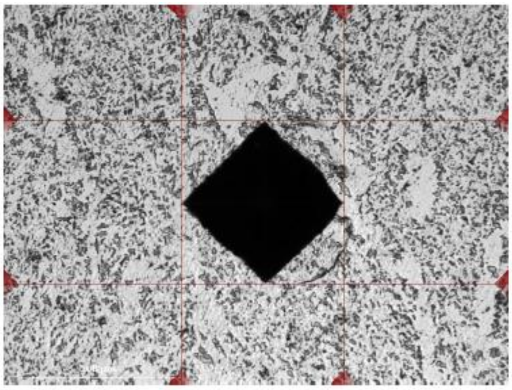
ID	**5 (1/1)**	
Hardness	210.92 HV1	
d1	0.0938 mm	
d2	0.0938 mm	
position	x: 101.49 mm y: 66.71 mm	
Conversions		
Time	1:30:36 PM	

ID	**6 (1/1)**	
Hardness	244.31 HV1	
d1	0.0880 mm	
d2	0.0862 mm	
position	x: 101.99 mm y: 66.70 mm	
Conversions		
Time	1:31:21 PM	

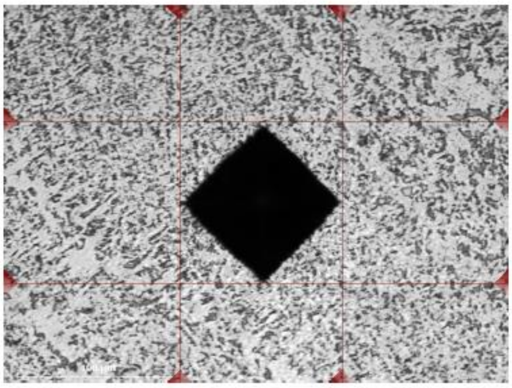
ID	**7 (1/1)**	
Hardness	191.03 HV1	
d1	0.0980 mm	
d2	0.0990 mm	
position	x: 103.41 mm y: 66.71 mm	
Conversions		
Time	1:32:06 PM	

ID	**8 (1/1)**	
Hardness	188.66 HV1	
d1	0.0985 mm	
d2	0.0998 mm	
position	x: 106.40 mm y: 66.76 mm	
Conversions		
Time	1:32:51 PM	

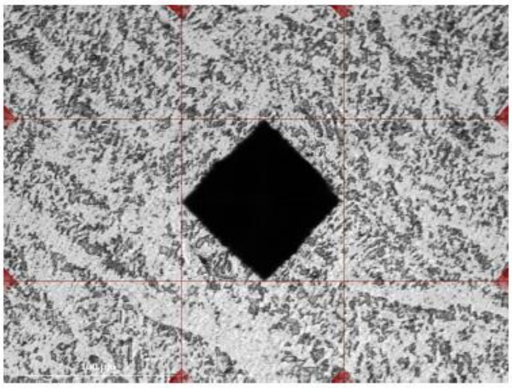
ID	9 (1/1)
Hardness	190.09 HV1
d1	0.0988 mm
d2	0.0988 mm
position	x: 109.40 mm y: 66.81 mm
Conversions	
Time	1:33:36 PM



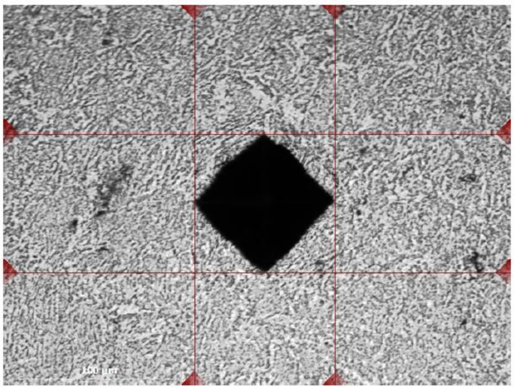
ID	10 (1/1)
Hardness	191.52 HV1
d1	0.0985 mm
d2	0.0983 mm
position	x: 112.40 mm y: 66.87 mm
Conversions	
Time	1:34:21 PM



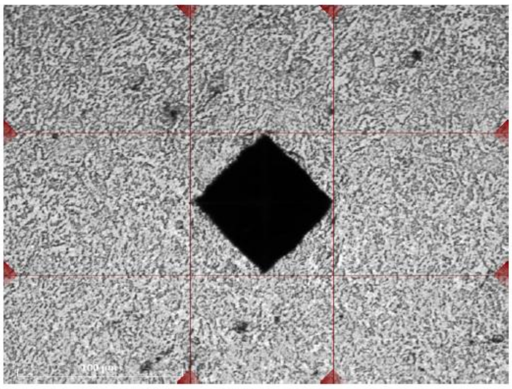
ID	11 (1/1)
Hardness	190.1 HV1
d1	0.0988 mm
d2	0.0988 mm
position	x: 115.40 mm y: 66.92 mm
Conversions	
Time	1:35:05 PM



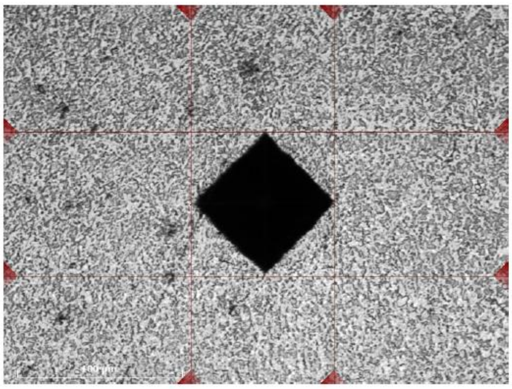
ID	12 (1/1)
Hardness	259.0 HV1
d1	0.0852 mm
d2	0.0840 mm
position	x: 117.09 mm y: 66.86 mm
Conversions	
Time	1:35:50 PM



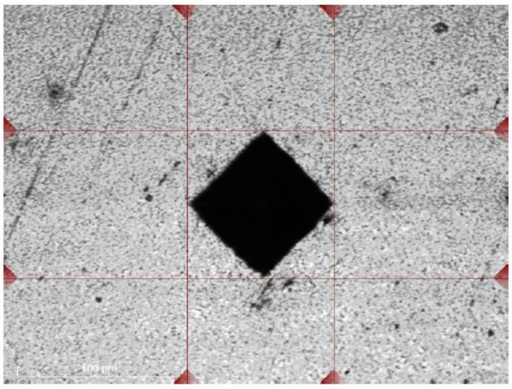
ID	**13 (1/1)**
Hardness	247.93 HV1
d1	0.0872 mm
d2	0.0857 mm
position	x: 117.59 mm y: 66.87 mm
Conversions	
Time	1:36:36 PM



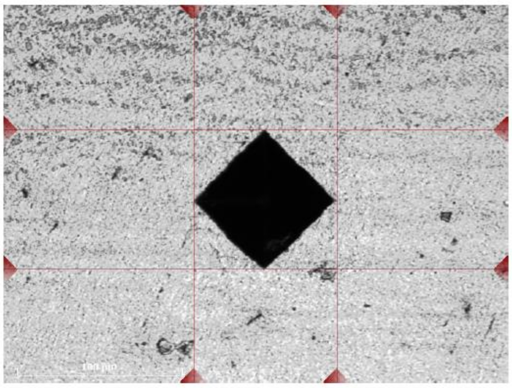
ID	**14 (1/1)**
Hardness	243.64 HV1
d1	0.0872 mm
d2	0.0872 mm
position	x: 118.08 mm y: 66.89 mm
Conversions	
Time	1:37:21 PM



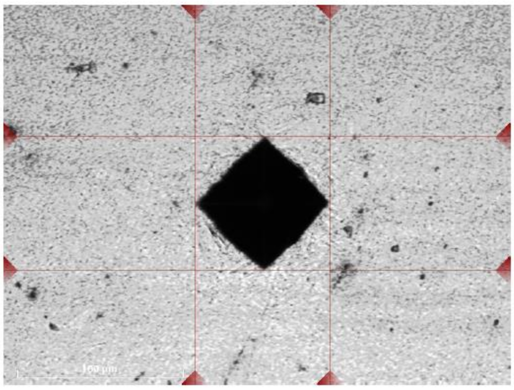
ID	**15 (1/1)**
Hardness	231.55 HV1
d1	0.0895 mm
d2	0.0895 mm
position	x: 119.67 mm y: 66.93 mm
Conversions	
Time	1:38:06 PM



ID	**16 (1/1)**
Hardness	250.1 HV1
d1	0.0872 mm
d2	0.0850 mm
position	x: 121.67 mm y: 66.99 mm
Conversions	
Time	1:38:50 PM



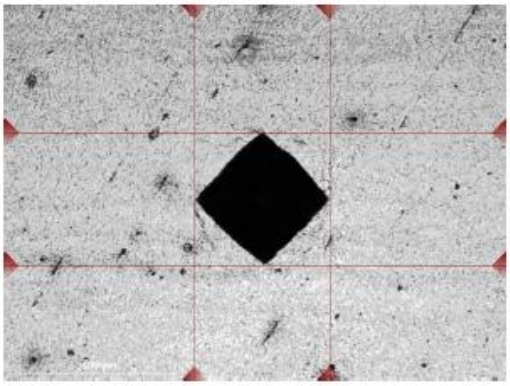
ID	**17 (1/1)**	
Hardness	280.23 HV1	
d1	0.0817 mm	
d2	0.0810 mm	
position	x: 123.67 mm y: 67.05 mm	
Conversions		
Time	1:39:35 PM	



Appendix B

The indentations captured by the camera during the control measurement set are presented in this appendix.

ID	**1**
Hardness	276.82 HV1
d1	0.0825 mm
d2	0.0812 mm
position	x: 124.23 mm y: 67.05 mm
Conversions	
Time	1:48:08 PM



ID	**2**
Hardness	287.28 HV1
d1	0.0805 mm
d2	0.0802 mm
position	x: 124.91 mm y: 67.05 mm
Conversions	
Time	1:49:19 PM