Aalto University
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MEC-E6007 Mechanical testing of Materials

Laboratory report

Hardness Mapping

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Introduction and Scope

Hardness testing is vital for metals for manufacturing process and manufacturing induced defects. Hardness testing is a fine indicator to determine the mechanical characteristics of metals (G. Sundararajan, 2001). In prospective environmental change and global sustainability focus develops new challenges for engineers, especially in transportation. For example, achieving sustainability in the maritime sector necessitates the efficient utilization of high-strength steels within the extensive welded frameworks.

Moreover, new structural designs can significantly reduce the weight of cruise ships. The bigger challenge is to cope with the issue induced during the manufacturing process. Due to the extensive manufacturing processes involved, ships require significant welding and cutting work. To optimize the cutting and welding in the maritime industry to fully utilize the strength of high-speed materials.

In this test, the hardness values of a welded sample consisting of two different grades of steel were measured in a linear fashion across both base materials, the main weld zone and the heat-affected zones of the base materials in the immediate proximity of the weld. The Vickers scale was used. The results of this measurement process were analysed and discussed. The purpose of this type of joint is to be used in the construction of a ship, where the application of high strength steels is a major research topic. Using high strength materials can help shipbuilders reduce the weight of the vessels and therefore lower the energy consumption both in manufacturing due to the decrease in material consumption as well as during the lifetime of the ship.

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Materials and Instrumentation

Sr.#	Material (Steel)	Hardness method	Welding Technique	Instrument
01	S690 grade	Vickers	Submerged arc welding (SAW)	Duramin-40 AC2 of Struers
02	S355 grade			

First, the procedure includes the preparation of specimens for testing the hardness. The specimen is already prepared. We have used the Vickers hardness test for calculating the hardness of the provided specimen. The test is performed on Duramin-40 AC2 of Struers hardness testers. It is motorized XY-stage and with an overview camera. The tester includes an integrated PC with a separate monitor for touchscreen or mouse operation.

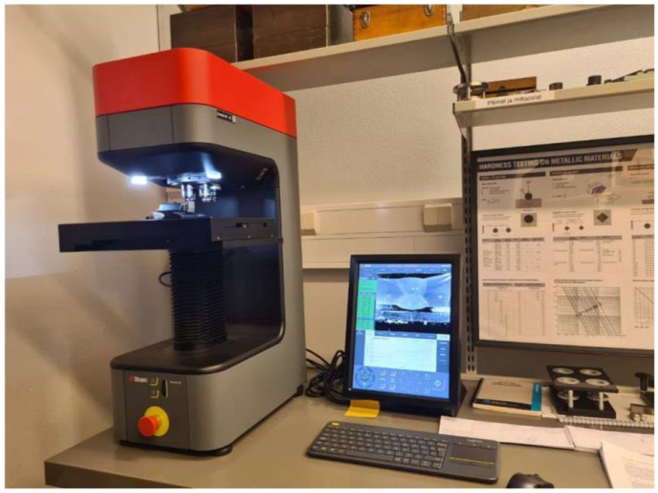

Figure 1: Duramin 40 AC2 Testing Apparatus.

Method

Vickers Hardness Test uses a diamond pyramid indenter to measure material resistance to deformation. Results are given as a Vickers hardness number (HV) with load and duration specified. The specimen is placed in the machine and adjusted accordingly. The specimen comprises two different grade materials welded together, resulting in distinct zones crucial for indentation analysis. These zones include the base metal of Steel 355, fusion zone/weld and its corresponding heat-affected zone and the other Steel 690 zone. There are 21 intent points marked on the intermediate line of specimen in different zones area to detect the hardness number, A load of 10 kgf is applied. Different indent points on the welded zones are shown below.

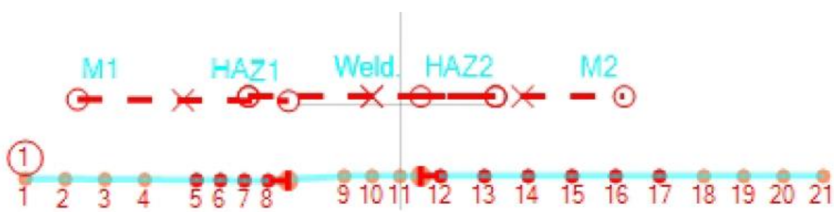

Figure 2: Indent setup for specimen.

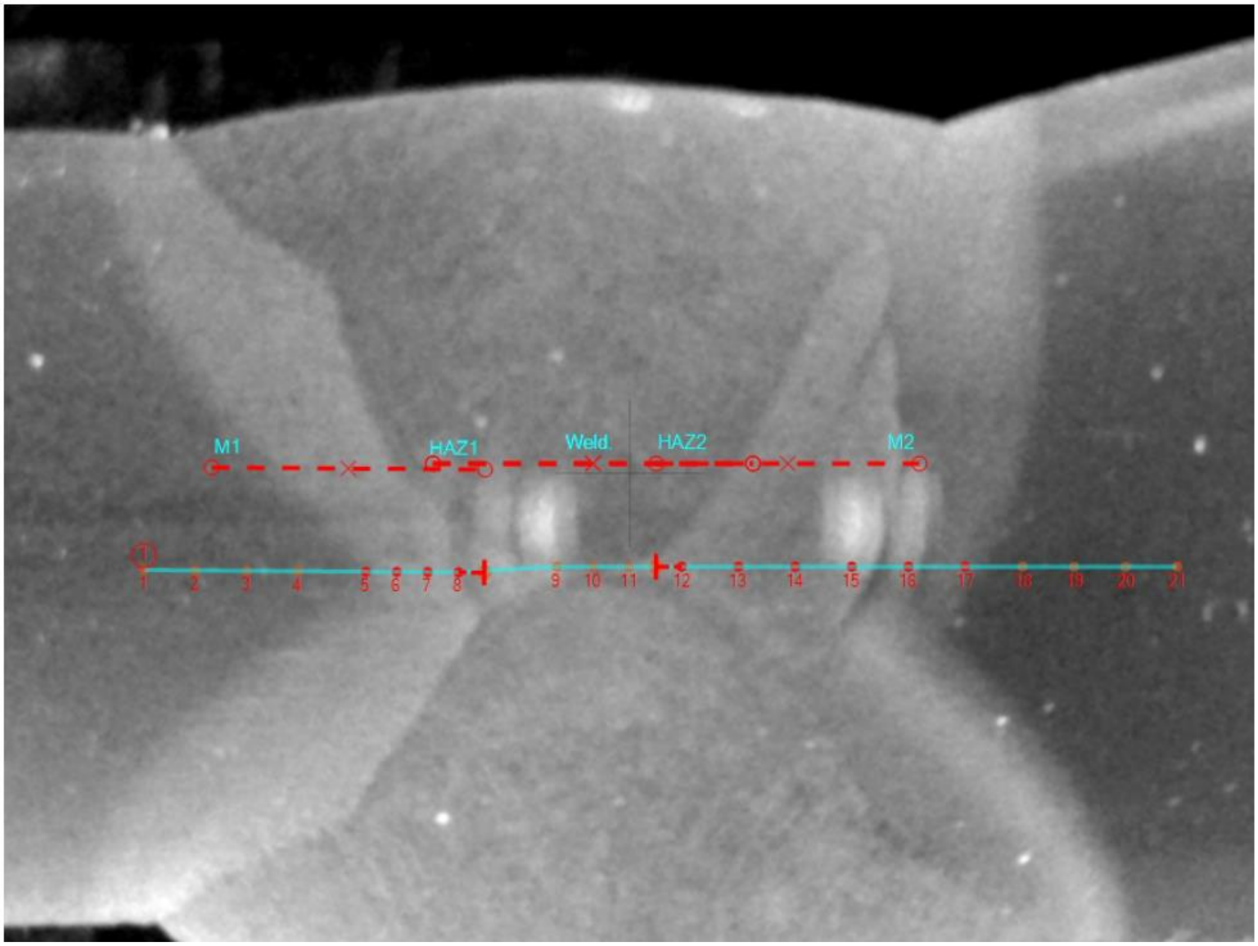

Figure 3: Image captured from Duramin-40 AC2 camera.

Results

The result of the hardness mapping test is shown in Figure 4.

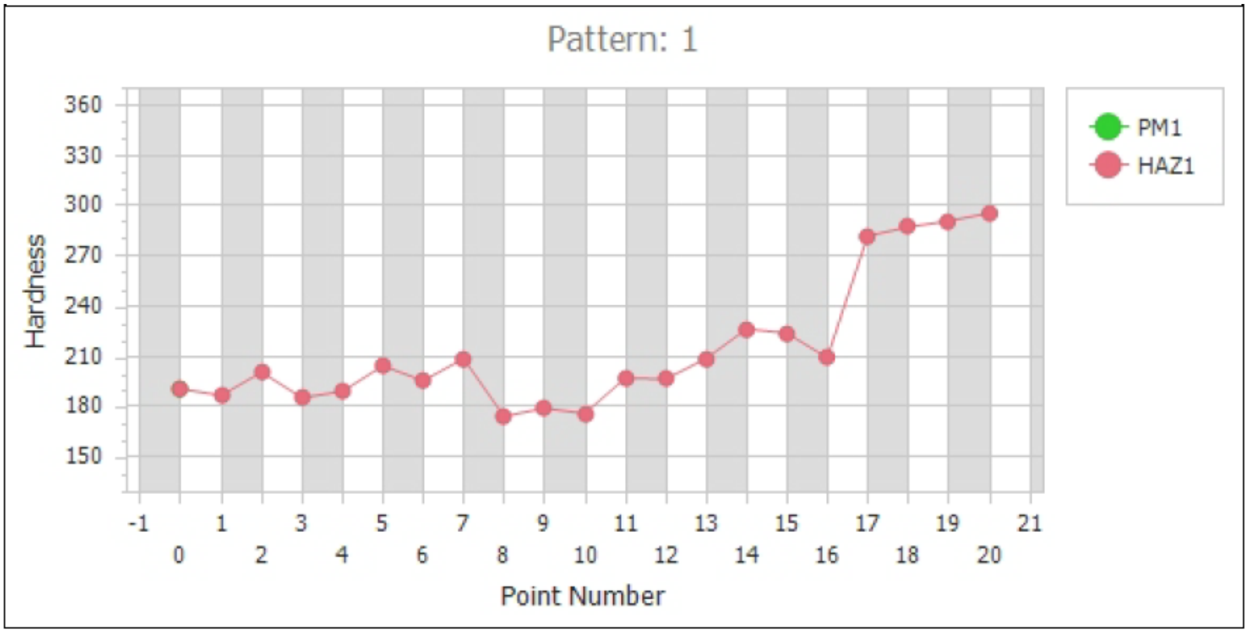

Figure 4: Hardness mapping results.

As can be seen in the figure, there are five ranges of hardness corresponding to specific zones of the sample that was tested.

Discussion

The different ranges in the results show the effect of the welding process on the materials as well as the difference in the hardness of the two materials. As previously mentioned, the sample was made of two grades of steel. Namely, S690 and S355 which have varied hardness values as is also shown in the test results. The material to the left side of the weld (M1, points 1 to 4), has a mean hardness value of 190.82 HV1, and the material on the right (M2, points 18 to 21) has a mean hardness value of 288.92 HV1.

According to the literature, S690 is a high-strength steel that has alloying elements such as manganese, molybdenum, nickel, and chromium which results in higher strength and hardness values than S355, which is a low carbon structural steel with only manganese as alloying elements. The difference in hardness clearly shows the effect of the alloying elements.

Points 9 to 11 present the hardness of the region in the sample where the roots of the welds on each side of the sample meet. It has a mean hardness value of 176.42 HV1, the lowest compared to all other zones in this sample's cross section. This soft region is mostly caused by the filler material used in the welding of the two sides of the sample. In addition, another factor could be that the microstructure of the weld is formed as it cools down from a molten state while covered by the protective layer of particles on top which affects the growth of grains and their ultimate size.

The Points in ranges 5 to 9 (mean hardness value of 199.43 HV1) and 12 to 17 (mean hardness value of 210.32 HV1) on the graph represent the two heat-affected zones. These zones are composed of multiple subregions that have significantly different mechanical properties that can be seen from the hardness measurements as well. Closest to the weld is the coarse grain heat-affected zone (CGHAZ), characterized by the clear growth in the material's grain size. It also often experiences the formation of hard but brittle martensitic microstructures as the austenitic crystal structure decomposes while cooling. The cooling is quite rapid as the heat quickly dissipates to other regions of the components, leading to noticeable hardening (Y.Q. Zhang, 2009).

After the CGHAZ there is the fine-grain HAZ (FGHAZ), where the grain sizes are quite small, and the mechanical properties are superior in comparison to the CGHAZ. The lower temperatures when compared to the CGHAZ leave the grain sizes smaller, making this region tougher. The temperatures in FGHAZ are above the critical temperatures of steels, leading to the formation of austenitic structures during the welding and similar hard microstructures will form during the cooling phase as in the CGHAZ, increasing the hardness.

The inter-critical HAZ (ICHAZ) is the next region. It is characterized usually by partial austenite formation alongside some martensite while being mainly ferritic in nature. The austenite regions are typically high in their carbon content, which can stabilize them so that they remain austenitic even at low temperatures. These regions can reduce the toughness of the ICHAZ. The exact ratios are determined by the cooling rate of the weld and the alloying of the steel. The region is typically hard due to the martensite and the precipitation of carbides from the martensite to the grain boundaries. After the ICHAZ is the tempered zone of the HAZ, also known as the subcritical HAZ (SCHAZ) which is exposed to low enough temperatures that it does not become thoroughly austenitic, but it is tempered instead. Tempering is a process in which the internal stresses in steels are relieved. If the steel contains any martensitic structures before the welding, the carbon in them will be precipitated out during the welding. This will result in softer material in this region, as seen from the measured sample results. For example, point 17 (209.29) that is located on the border close to the base material is the softest measured point in the HAZ next to the S690 material, being softer than both the base material (281.99 HV1 on point 18) and the inner HAZ subzones (223.96 HV1 on point 16) next to it. As the amount of hard but brittle microstructures is generally low, the tempered zone is often tougher than the other HAZ regions, but sometimes precipitation of carbides at grain boundaries can occur, leading to some hardening and embrittlement of this region (Jiang, 2023).

The regions closer to the weld are typically harder as described above, which is also supported by the measurements carried out during this test and the tempered zones close to the base materials are softer. Most of the HAZ are softer than the S690 alloy but clearly harder than the soft S355. The SCHAZ close to the S355 is remarkably close in hardness to the base material. S355 is a low carbon steel that does not form substantial amounts of martensite. Therefore, the tempering effect would have much less softening consequences than with S690. The higher hardness in the CGHAZ and FGHAZ on the S355 side is possibly due to the formation of some carbides in the material. The softer nature of the HAZ next to the S690 could be caused by the tempering effects of the heat that is being conducted to the HAZ from the weld. As the hardness of the HAZ is largely caused by the formation of martensite, the residual heat could lower the hardness by causing the carbon to precipitate from the martensite. S690 steel often also has martensite within it as it is quenched and tempered during manufacturing. As the base material is further from the weld, the tempering effect it is subjected to due to the welding process is lower, so the hardness stays higher.

Conclusion

The hardness variations in the welded specimen indicate the impact of welding on different steel grades. S690 steel shows higher hardness compared to S355, highlighting their distinct compositions. Heat-affected zones (HAZ) showed varied hardness, influenced by welding parameters and cooling rates. Tempering effects were noticeable near base materials, affecting hardness. Overall, this analysis underscores the complexity of welding-induced microstructural changes and understanding these variations is crucial for optimizing welding procedures in practical applications.

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