TECHNotes

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HARDNESS TESTING TO MAP OR NOT TO MAP?

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EXECUTIVE SUMMARY

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. Buehler is the leading supplier of indentation hardness testing equipment, manufacturing machines to offer solutions for all of these methods individually or combined in one machine. The following article highlights Vickers testing of welded components and how it's also been applied to mapping of materials. 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 localised variations in hardness.

Weld testing

Weld joints of metallic components show varying mechanical properties starting from the weld itself, which might be of the same material as the welded workpieces or might be of a different material (alloy) compared to the components being welded together. Due to the high temperature nature of the process, a fusion process occurs resulting in localised change in microstructures from the weld, into the base materials. The change in microstructure around the weld region (in the base material) near the fusion line presents challenges to the integrity of the weld presenting a region prone to high residual stresses (1-2). Development of high stresses coupled with undesired microstructure presents an area with a high potential for the welded joint to fail. This region is classified as a heat affected zone (HAZ) in a weld and is predominantly observed in the base/parent material. The different components of a weld include the base metal showing the depth of penetration of the weld, the heat affected zone, the fusion line and the weld bead as shown in Figure 1 (a). For a multipass welded sample, the weld bead will have a corresponding HAZ, fusion lines and actual bead as the weld structure is built-up, as shown in Figure 1 (b), with 3 weld beads.

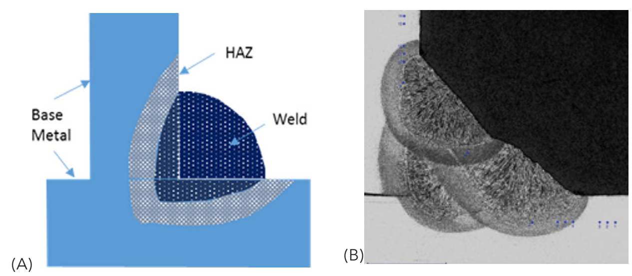


Figure 1 (a) is a schematic illustration of a weld, heat affected zone and base metal and (b) shows a fillet weld with three weld passes on a low alloy steel substrate etched using 2% Nital to reveal the weld, heat affected zones and the three weld passes making up the weld

To observe the weld microstructures, components are microscopically investigated by doing metallographic testing involving a series of grinding/polishing stages and etching to reveal the microstructure, Figure 1 (b). The degree and/or extent of heat affected zone can then be metallographically analysed for potential areas of extreme microstructural changes prone to micro-crack formation.

For quantitative understanding of weld microstructures, indentation hardness testing is normally carried out based on ISO 9015/15614, which describes how testing is done; specifying loads, number of indents for parent/base material, heat affected zones and welds, as well as the distances between indents and the depth below the surface of the welded joint. To meet the requirements stipulated in the standards can be quite challenging, time consuming and subject to operator skill/experience. We have simplified the process using our own in-house software – DiaMet as illustrated in Figures 2 and 3 for a fillet and a butt weld respectively.

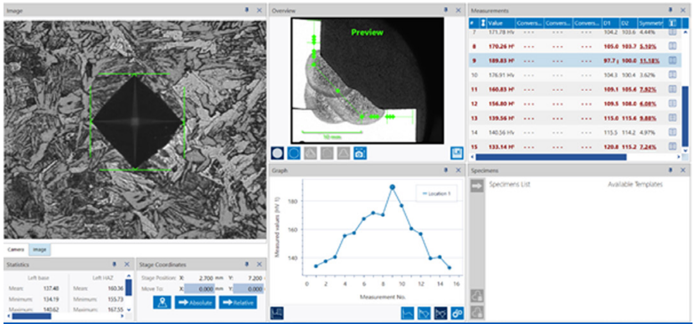


Figure 2. Illustrates hardness testing of a fillet weld with differences observed from the base metal, HAZ and weld regions

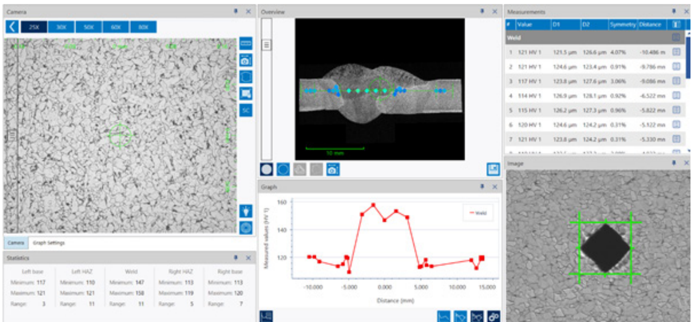


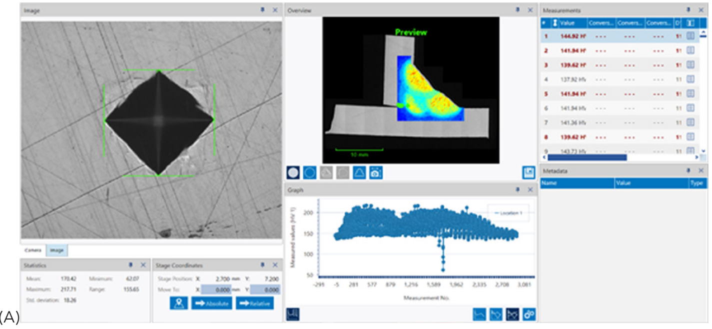
Figure 3. Illustrates hardness testing of a butt weld, the chart shows local variation around the heat affected zone (HAZ)

Depending on the weld and base metal type, the different regions of the weld will exhibit different microstructures. These microstructures have varying hardness levels as illustrated in Figures 2 and 3 above. As you traverse towards the weld, you will start with uninterrupted base metal, followed by a region with tempered and intercritical HAZ, a fine grained HAZ, a coarse grained HAZ towards the weld fusion line and then the weld. The HAZ region exhibits a varied microstructure and will always be prone to localised variations in hardness as shown on the chart, blue circles, Figure 3. It's clear that standard techniques based on ISO9015 might capture local variations in hardness around the HAZ since it involves doing a row of indents. For a complete picture of the weld, weld mapping can provide an exhaustive overview of this localised variations and potential site of high stresses.

Mapping

With automated hardness testing, improved testing speeds and development in hardness testing software, an alternative method of qualitative and quantitative testing of welded components is now possible. This involves carrying out multiple indentations on a scanned area of a weld and then assigning the differences in hardness values from the base material into the weld a colour code, from which the software gives a visual output of the variations in hardness. The main advantage of using the indentation mapping is the ease of identification of regions where high residual stresses exist. The maps can also be used to qualitatively investigate the heat affected zone, the base material and the welded regions without the need to etch the sample. Figure 4, illustrates the weld sample in Figure 1 & 2, mapped with approximately 3000 indents.
Comparing Figure 4(b) and Figure 1 above, there is a good correlation between the etched and mapped out micrographs with both methods showing the weld beads, the heat affected zone and base/parent materials.

(A)



(B)

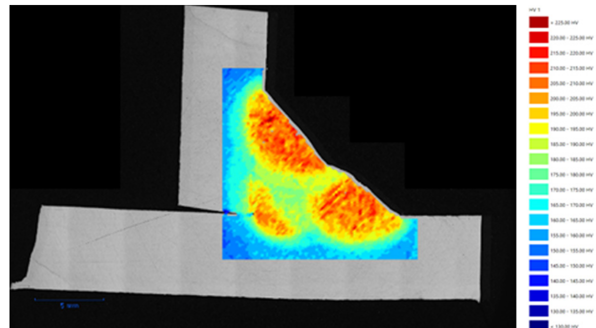
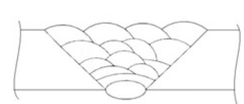


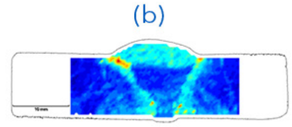
Figure 4 (a) illustrates weld mapping with chart showing actual Vickers values and (b) showing map with weld passes (harder in red), heat affected area (light blue) and base metal coloured blue.

Figure 5 shows steel butt welded samples built up through a sequence of multi-passes (a). These types of welds are generally taken through a post weld heat treatment (PWHT) to alleviate the residual stresses generated during build-up. However, residual stresses are not completely removed and examination of the weld after PWHT will also reveal these regions as shown in Figures 5(b) and (c). It's evident from the maps where high residual stresses exist (high hardness values), primarily around the HAZ, Cap and root areas.

(a)



(b)



(c)

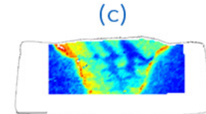


Figure 5 (a) shows a sequence of weld passes from the root to the weld cap, (b) & (c) show two butt welded components after mapping. The weld maps show high stress areas characterised by high hardness around the toes on the weld face, down the heat affected zone near the fusion line and in the root areas of the weld.

Additive Manufactured Components

Additive manufactured components are built up by adding material layer by layer. These components can be manufactured from steels, titanium, Inconel alloys among many others. Manufacturing processes include directed energy deposition (DED) and Powder bed fusion (PBF) techniques. The DED method generally has a higher build up rate compared to the PBF technique with both techniques resulting in residual stress development due to repeated thermal cycles during layer addition. These residual stresses play a crucial role in performance, integrity and lifetime of the components and thus the ability to evaluate them is critical (3-4). To map these components out, they have to first be metallographically prepared with the level of surface finish depending on the load being used during Vickers indentation testing.

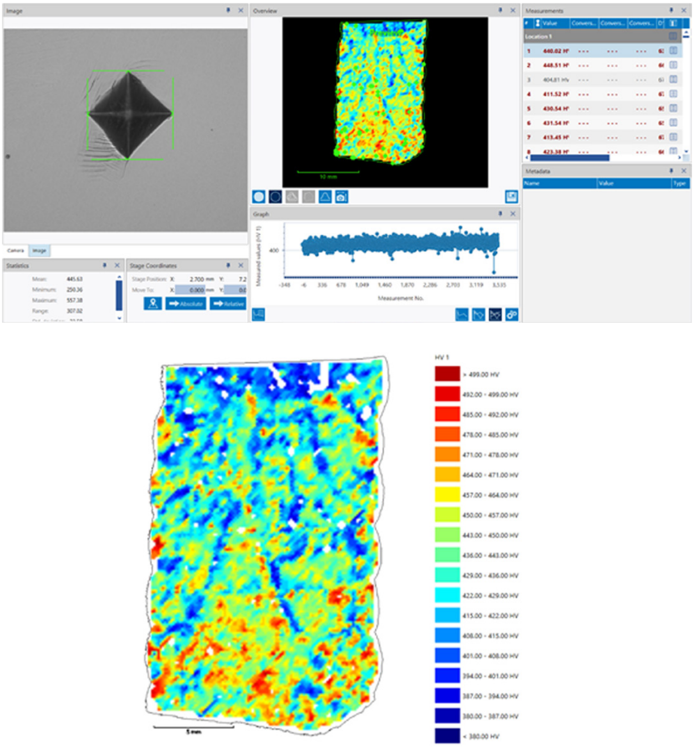


Figure 6 illustrates an additive manufactured component mapped out illustrating regions that would be considered as having high residual stress (red).

Case/Induction Hardened Surfaces

Certain mechanical components are normally surface hardened to improve their mechanical performance by improving surface wear characteristics with the advantage of low core strength characteristics to absorb stresses without cracking from repeated usage. Examples include gears (Figure 7), induction hardened cranks and cam shafts found for example in automotive sectors. How uniformly these surface treatments are carried out, and their conformance to operational specified hardness limits, provides a degree of confidence on the final mechanical performance. Traditional methods involve carrying out effective case depth or case hardness depth studies on a single row of hardness indents starting from the surface into the core of the material and noting where the hardness values go below 550 Vickers point. This is a snapshot view of how hardening has been carried out (see Figure 7).

The alternative and a more comprehensive way of validating the case/induction hardening process is to map out an area of interest as shown in Figure 7 above, which highlights uniformity in hardness as a function of the core hardness using mapping tools in DiaMet software.

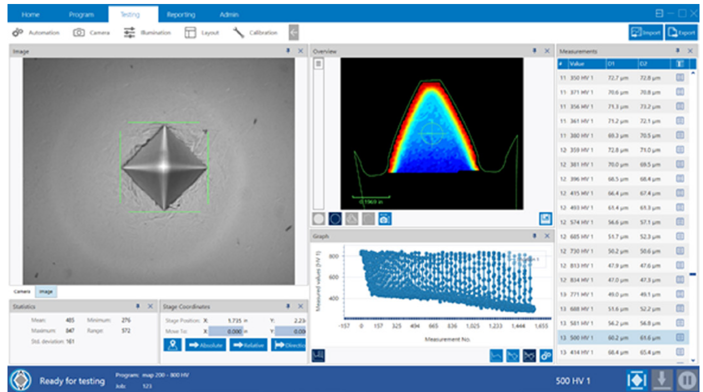


Figure 7 illustrates a hardened gear tooth mapped out to illustrate the case hardened outer region and its uniformity across the gear tooth. High hardness regions in red have Vickers values approaching 800Vickers whereas low hardness areas typical of core at approximately 400Vickers

Summary

- Weld measurements based on ISO standards can be relatively quick and easy to carry out with the weld tool on DiaMet software. Traditional techniques would take a longer time and were also subject to operator skill/experience.
- We've also demonstrated there is good correlation between etched weld samples and hardness mapped area. It is easy to identify the base/parent metal, heat affected zones and the weld from mapped micrograph akin to an etched weld sample. It's also clear from the micrographs that it's relatively easy to identify weld passes in a multipass weld and how each corresponding weld bead affects the adjoining one as the weld is built up.
- Additive manufactured components can be mapped highlighting local variations in hardness as a way of identifying areas of high residual stresses
- Case hardened materials can be mapped thus providing a comprehensive pictorial view of uniformity of a hardening process.

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