CASE STUDY

# Indentation Plastometry of Hardox Steel Samples with WC Inserts for the Mining Industry

NOVEMBER 2020

Plastometrex

# INDENTATION PLASTOMETRY OF HARDOX STEEL SAMPLES WITH WC INSERTS FOR THE MINING INDUSTRY

# EXECUTIVE SUMMARY

This investigation relates to two types of sample sent to PLX in August 2020, supplied by Energy Densification Systems. These were both a shaped component of Hardox steel, with and without a cermet insert brazed into it. PLX were not nformed about the grade of Hardox. The study primarily involved carrying out indentation plastometry measurements, by creating a grid of indents on the Hardox surface, for both types of sample. In this way, it was possible to obtain stress-strain relationships for local areas of the component. There were some relatively minor point-to-point variations, attributable to different degrees of prior plastic strain (during manufacture of the component). The heat treatment associated with the brazing process (which was not revealed to PLX) induced significant changes in the stress-strain responses of all locations, mainly in the form of reductions in the yield stress, but also as increases in the subsequent work hardening rate. It is noted that monitoring of hardness numbers would have revealed much less definitive information about the effects.

# 1
# COMPONENT MICROSTRUCTURE

This study concerns components used for a highly demanding application, in which they are subjected to extreme tribological conditions involving high speed impact with rock fragments being pulverized. These components are made of Hardox steel, with cermet (WC-Co) inserts that have been brazed into place. Hardox, which is supplied by the Swedish company SSAB, offers an attractive combination of wear resistance and toughness. Commonly-used grades are often classed according to their Brinell Hardness Number, typically ranging from Hardox400 to Hardox600. Corresponding yield stress values are reported [1-3] to range from just over 1,000 MPa to around 1,700 MPa.

The chemical composition, which does not vary dramatically between grades, features very low levels of P and S and minor additions (~1-2%) of Cr, Ni and Mo. The harder grades tend to contain slightly higher levels of Ni and Mo, and slightly lower levels of Cr. Of these, only Mo is a strong carbide-former, promoting secondary hardening (at elevated temperatures). The Cr and Ni affect the stability of the austenitic phase and also the "hardenability" (mainly the cooling rate needed to form martensite). There are also reports of B and Nb being added, partly to promote carbide formation. The C content is, of course, important, being around 0.3% in most grades, but 0.45% for the Hardox600. It may, however, be noted that all of these levels refer to supplier specs, whereas published user-reported levels often deviate significantly from them.

In any event, the physical metallurgy of these alloys is complex, although it is clear that they should be regarded as martensitic low alloy steels and their high hardness levels are closely related to the nature and level of the martensite content. The microstructure and properties can be strongly affected by heat treatments and the microstructure of "as-supplied" metal can usually be regarded as "tempered martensitic". Unsurprisingly, there are concerns about the effects of uncontrolled heat treatments, such as in the HAZ of welds, which has been investigated in some depth [1].

The project is oriented towards thermal effects, being mainly concerned with possible effects on substrate mechanical properties of the heat treatment associated with the brazing operation used to attach the inserts. While the main impact loads during service are taken by the inserts, the substrates are also subjected to quite severe tribological conditions, so this is a potential concern. The investigation is focussed on using Indentation Plastometry to obtain stress-strain curves from local regions. Previous studies of such variations (for Hardox and, of course, for many other metals) have tended to focus on local measurement of a hardness number, which is a rather ill-defined and ambiguous "property".





On the other hand, a brazing operation is not expected to involve high (transient) thermal gradients or very different thermal histories in different locations (such as are created during welding). It's also rather unlikely that any significant long-range diffusion of chemical species will take place during brazing. Large point-to-point differences in mechanical properties are therefore not expected to arise, although some could be present in the substrate initially (as a consequence of local differences in plastic strain history during manufacture of the substrate). Indentation Plastometery does have a spatial resolution suitable for study of property variations within welds and associated HAZs, so there may be interest in its application to welds in Hardox (and other metals) in the future.

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# 2
# SAMPLE GEOMETRY AND INDENT LOCATIONS

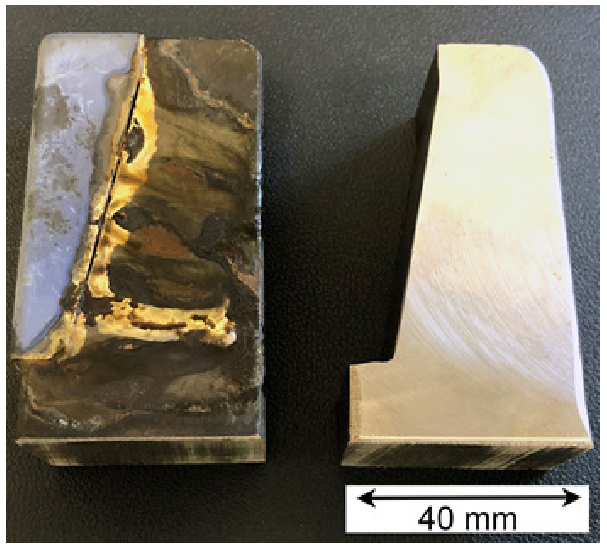


***Fig.1**: Photo of a brazed component (left) and a Hardox substrate (right).*

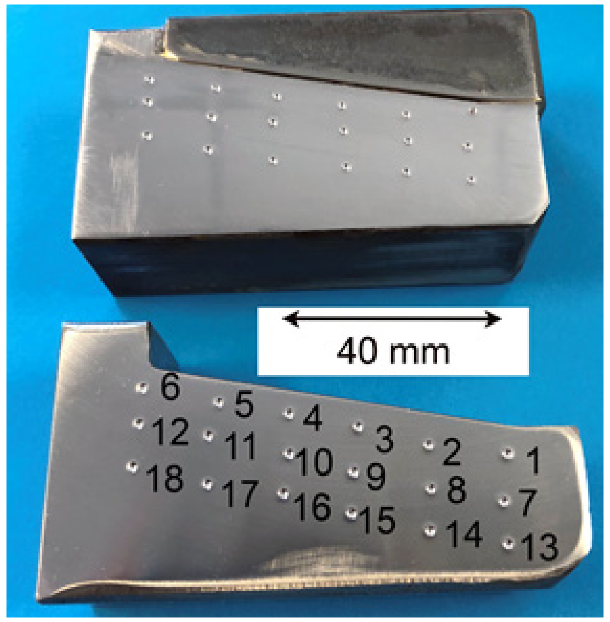


***Fig.2**: Photo of integrated (top) and Hardox substrate (bottom) samples, after indentation.*

Fig.1 is a photo showing typical as-received Hardox samples, with and without an insert attached. It can be seen that these are relatively large-scale components. It also appears that the braze tends to spread over the surfaces of both insert and substrate.

Samples were ground and then subjected to the standard Indentation Plastometry procedure, as described in §3. No polishing was required. A relatively coarse matrix of indents was produced, as can be seen in Fig.2. Since fine scale variations in properties are not expected, the spacings in the grid of points were not accurately defined, but were notionally an initial increment of 4 mm normal to the interface, followed by 5 mm increments, and then spacings of 10 mm parallel to it.

# 3 INDENTATION PLASTOMETRY

### 3.1 Procedure

The equipment used in this work was the Indentation Plastometer shown in Fig.3. Three steps are involved in obtaining the true stress – true strain relationship from an indentation test. These are: (a) pushing a hard indenter into the sample with a known force, (b) measuring the (radially-symmetric) profile of the indent, (c) iterative FEM simulation of the test until the best fit set of plasticity parameter values is obtained.

Samples were placed on the plinth of the Plastometer and indented with a spherical indenter of radius 1 mm, made of WC-Co cemented carbide, using a force of between 3.5 kN and 4.5 kN. (The force is automatically chosen from a set of possible values, so as to generate displacements (penetrations) of at least 200 μm (δ/R ~ 20%). Indent diameters were around 1 mm. A contacting stylus profilometer, with a depth resolution of about 1 μm, is incorporated into the Plastometrex machine. Tilt correction functions were applied to the raw data, based on the far-field parts of the scan being parallel. This procedure is carried out automatically under software control.

For any approach involving iterative simulation of a deformation process, the true stress-strain relationship (material plasticity response) must be characterized via a (small) set of parameter values.

Several expressions are in common use, but the current PLX methodology is based on use of the Voce equation:

$$\sigma = \sigma_S - (\sigma_S - \sigma_Y)\exp\left(\frac{-\varepsilon}{\varepsilon_0}\right) \quad (1)$$

where σ is the (true) stress, ε is the (true) plastic strain, $\sigma_Y$ is the yield stress, $\sigma_s$ is a saturation stress and $\varepsilon_0$ is a characteristic strain (for the approach of the stress to its saturation level). When implemented in the FEM model, these stresses and strains are von Mises values (deviatoric components of the stress tensor).

The underlying methodology for converging on the best fit set of parameter values, focusing on the residual indent profile as the target outcome, is described in the literature [4-6] and on the PLX website. Some details are also provided in a Webinar accessible at https://www.iom3.org/iom3-training-academy/introduction-indentation-plastometry. Isotropy is assumed, both elastically and plastically. The elastic constants are required as input data. The Young's modulus of these samples was taken to be 200 GPa. The Poisson ratio was taken to be 0.33. (The outcome of the modeling is not strongly sensitive to these parameters.)


***Fig.3***: *Image of the Plastometer, with the key components labeled.*



### 3.2 Experimental Outcomes

Sets of indents were produced on each type of sample (as shown in Fig.2). All of the indents exhibited radial symmetry, indicating that there was no significant (in-plane) anisotropy. All of these profiles were converted to a set of optimized Voce plasticity parameter values. These are shown in Table I. A small subset of the corresponding stress-strain curves (true and nominal) is shown in Fig.4.

The complete dataset is summarized in Figs.5 and 6, which show the inferred yield stress and UTS values as a function of their location, for both brazed and as-received conditions. A number of features are clear in these plots. One is that there are some point-to-point variations in the properties of the substrate before brazing. For example, there is a small, but significant, drop in the yield stress (by about 10-15%) on moving up from the base region (ie moving from location 6 to location 1 etc in Fig.2), although little change on moving inwards from this surface (ie through locations 6 – 13 – 18 etc in Fig.2). This is presumably due to differences in prior plastic strain during the forging of the component. There are similar trends in UTS, with the unbrazed material exhibiting little work hardening (so the UTS is not much greater than the yield stress). Further details, such as the shape of the work hardening curve and the strain at the onset of necking, are apparent in the individual stress-strain plots, such as those in Fig.5. It's also possible to derive the complete tensile stress-strain curve, up to and including the post-necking fracture event, via FEM simulation of a tensile test, although this has not been done in the current work.

It's also clear from Figs.5 and 6 that the brazing operation has substantially affected these properties. Drops in yield stress of up to 20% are observed, with the strain-hardened regions near the base of the insert being more strongly affected. On the other hand, it's also worth noting that the UTS values are now significantly higher than the corresponding yield stress values - ie the material is exhibiting more work hardening. This kind of behaviour – ie an "annealing" treatment leading to a reduced yield stress, but higher subsequent work hardening rates - is, of course, quite commonplace. In this case, it has actually led to UTS values that are similar to, or even slightly higher than, those of the unbrazed material.

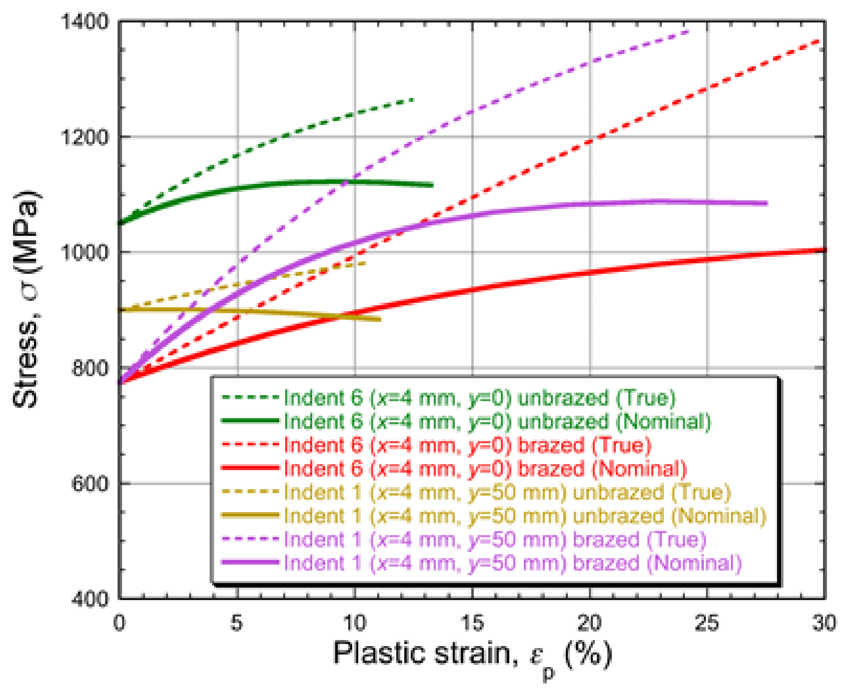


***Fig.4***: *Inferred stress-strain curves (both true – ie plots of the Voce equation – and nominal, obtained from the true curves using the standard conversion equations) for two different locations, with and without the brazing treatment.*

***Table I:*** *Outcomes of the indentation plastometry, in the form of best fit values of the Voce parameters giving the true stress – true strain relationship, plus the nominal stress at the onset of necking (ie the UTS) obtained from this.*

| Location Code | Best fit Voce parameter values [untreated : brazed] | | | Ultimate Tensile Stress $\sigma_{UTS}$ (MPa) |
|---|---|---|---|---|
| | Yield Stress $\sigma_Y$ (MPa) | Saturation Stress $\sigma_s$ (MPa) | Characteristic Strain $\varepsilon_0$ (%) | |
| 1 | [900 : 775] | [1100 : 1575] | [20 : 17] | [901 : 1093] |
| 2 | [925 : 850] | [1325 : 2950] | [33 : 100] | [933 : 1036] |
| 3 | [950 : 825] | [1550 : 3125] | [50 : 100] | [959 : 1061] |
| 4 | [1025 : 825] | [1425 : 3125] | [25 : 100] | [1047 : 1061] |
| 5 | [1025 : 850] | [1325 : 2950] | [10 : 100] | [1099 : 1036] |
| 6 | [1050 : 775] | [1350 : 3075] | [10 : 100] | [1122 : 1028] |
| 7 | [950 : 875] | [1150 : 1475] | [14 : 14] | [960 : 1090] |
| 8 | [950 : 875] | [1250 : 2875] | [20 : 100] | [968 : 1033] |
| 9 | [975 : 825] | [1275 : 1425] | [14 : 14] | [1019 : 1048] |
| 10 | [1000 : 850] | [1300 : 1350] | [10 : 10] | [1077 : 1066] |
| 11 | [1075 - 875] | [1550 - 1375] | [33 - 14] | [1068 - 1033] |
| 12 | [1075 : 800] | [1675 : 2900] | [50 : 100] | [1077 : 1001] |
| 13 | [950 : 875] | [1850 : 1675] | [100 : 33] | [950 : 1012] |
| 14 | [950 : 900] | [1450 : 2600] | [33 : 100] | [977 : 994] |
| 15 | [1000 : 850] | [1400 : 1350] | [25 : 14] | [1024 : 1011] |
| 16 | [1050 : 875] | [2050 : 2575] | [100 : 100] | [1050 : 975] |
| 17 | [1050 : 900] | [1750 : 1800] | [50 : 50] | [1065 : 980] |
| 18 | [1050 : 825] | [2250 : 1325] | [100 : 10] | [1055 : 1045] |

It's also clear from Figs.5 and 6 that the brazing operation has substantially affected these properties. Drops in yield stress of up to 20% are observed, with the strain-hardened regions near the base of the insert being more strongly affected. On the other hand, it's also worth noting that the UTS values are now significantly higher than the corresponding yield stress values - ie the material is exhibiting more work hardening. This kind of behaviour – ie an "annealing" treatment leading to a reduced yield stress, but higher subsequent work hardening rates - is, of course, quite commonplace. In this case, it has actually led to UTS values that are similar to, or even slightly higher than, those of the unbrazed material.

It's a little difficult to say whether the wear resistance would be impaired. It's often observed that "harder" materials are more wear-resistant, although this does depend on the wear mechanisms and materials that are hard, but brittle, sometimes perform poorly because the conditions lead to frequent micro-fractures, or even large scale fracture events. For this, and other, reasons, the use of a hardness number is often of little or no help. This is illustrated by the data in Figs.7 and 8, which show Brinell and Vickers hardness numbers that would be obtained in each of the locations where Indentation Plastometry was carried out. (These are obtained by FEM simulation of the hardness test, using the inferred true stress-strain relationships, and then "measuring" the indent diameter, as would be done in the tests concerned.). It can be seen that the outcome presents a much more vague and confused picture than that given by the stress-strain curves, or even by yield stress and UTS values taken from them. In practice, the large experimental error involved in actually measuring indent diameters would add further noise to this picture. It may incidentally be noted that the Brinell hardness numbers are all well below the values associated with the various Hardox grades, which are commonly taken to start with Hardox400. However, without any information about the grade of the samples supplied, it's difficult to comment further on this.

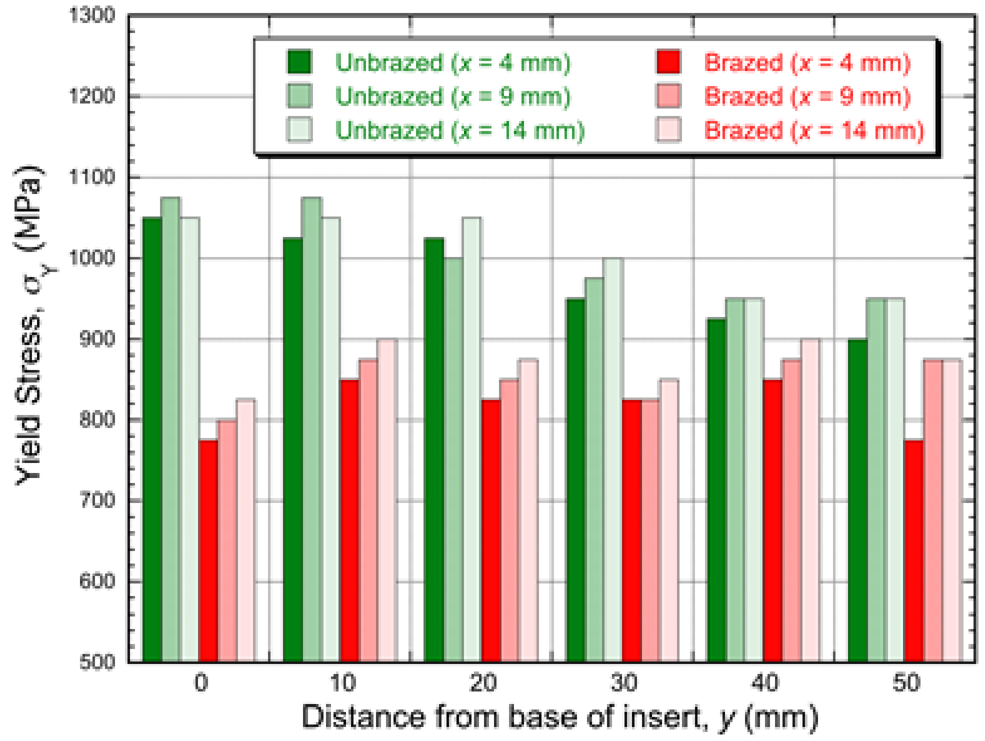


***Figure 5:*** *Bar chart showing indentation-derived yield stress values as a function of location, with y being the distance along the brazed interface and x the distance from it, for the as-received substrate and for the brazed*

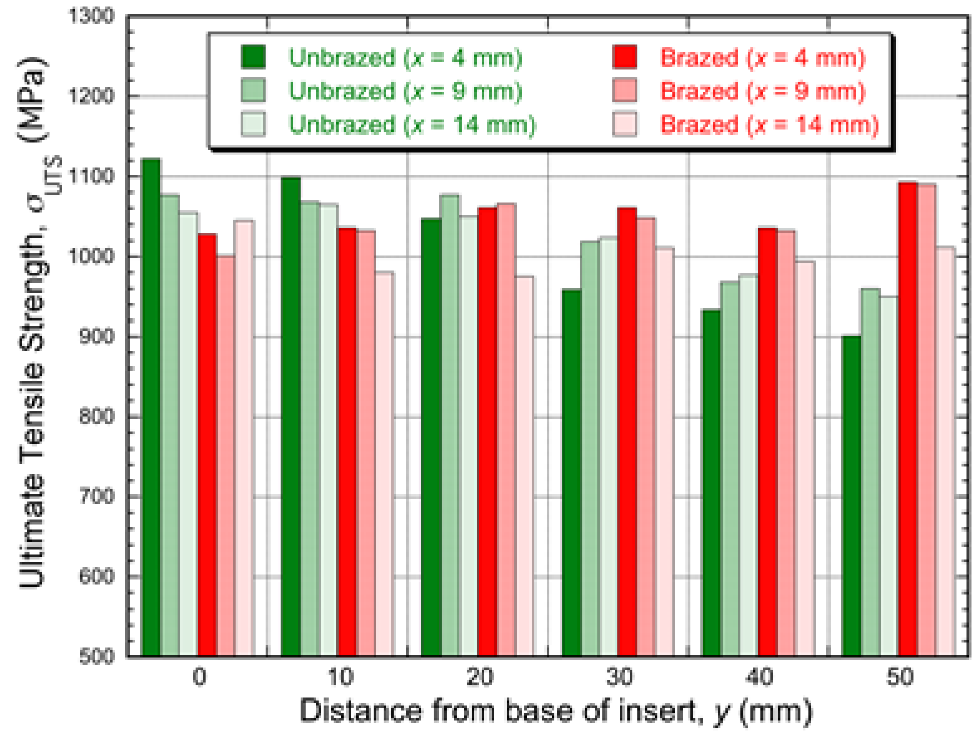


***Figure 6:*** *Corresponding bar chart to that of Fig.5, for the UTS data.*

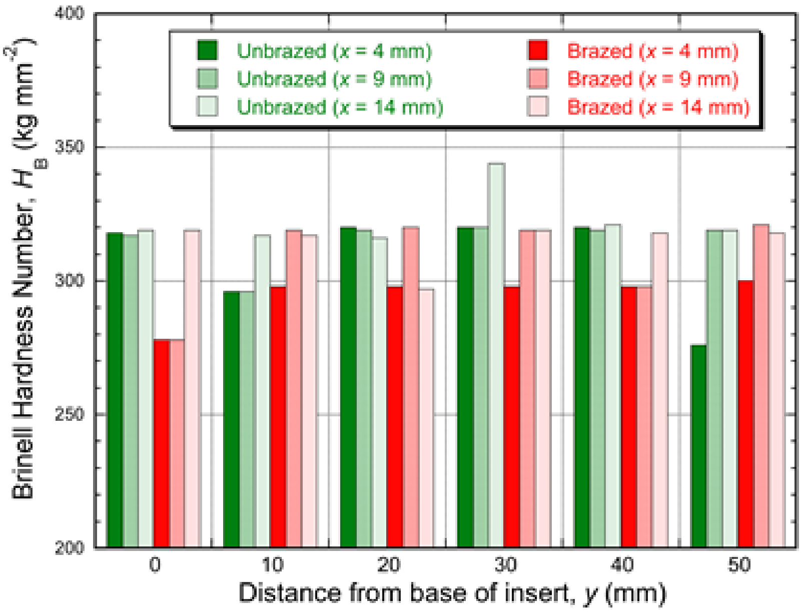


***Figure 7:*** *Brinell hardness numbers corresponding to the locations where Indentation Plastometry was carried out.*

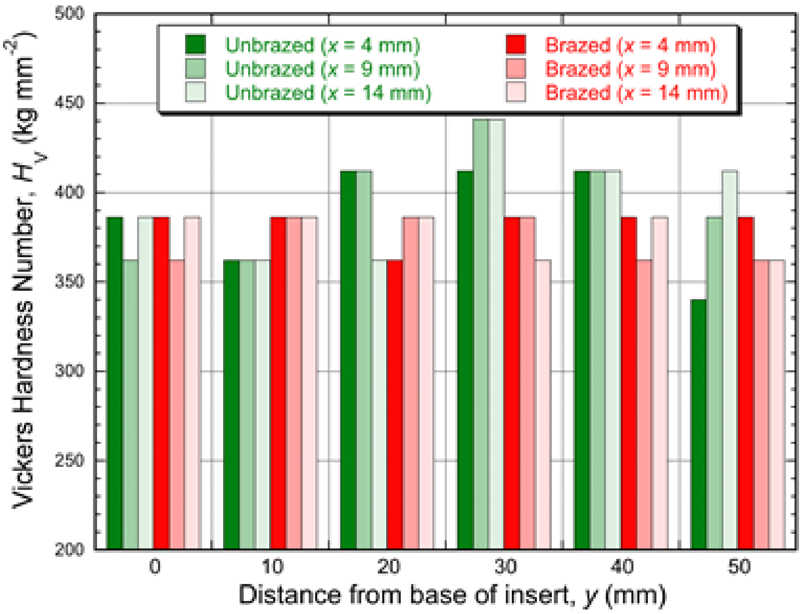


***Figure 8:*** *Vickers hardness numbers corresponding to the locations where Indentation Plastometry was carried out. The applied load was 5 kg.*

## References

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