Plastometrex

From Fragments to Answers:
An Insightful Alternative to Hardness Numbers for Failure Analysis

CASE STUDY

Challenge

Where machining tensile specimens for testing is not an option, hardness is often considered as a solution. This poses a significant limitation; while hardness testing offers advantages such as affordability, speed, ease of use, and suitability for testing small specimens, a hardness number is not a fundamental material property. Furthermore, practitioners are limited to conversions into a limited set of material property values, as hardness numbers cannot give full stress-strain curves, which means that without further information finite element modelling cannot always be conducted accurately.

Hardness numbers are produced by measuring the lateral extent or depth of an indent performed at a known load and applying a standard equation for the specific indenter used. These results are then frequently converted into UTS (ultimate tensile strength) and sometimes, albeit less frequently, yield stress values. Conversions can only be performed using empirical relationships, some of which can be found in standards published by ASTM and ISO.

These standards contain warnings for the user, such as in BS EN ISO 18265:2013 where it states, 'Conversion from one hardness value to a tensile strength value involves uncertainties which must be taken into account.' These uncertainties include the relationship between hardness and UTS, which is only available for certain specific categories of alloy, which limits the use of these procedures to these metals. Despite this, hardness data is often used extensively to inform design/safety decisions and as a material quality release test. This reliance on hardness numbers alone poses a problem for failure analysis and end users alike as it can lead to the need for approximations as well as a loss of potential significant information about the materials' behaviour.

Objectives

The aim of this case study, conducted in conjunction with HSE Science Division, was to determine whether PIP testing could provide the insights required for better understanding of the reasons for failure of components, as well as overcoming the challenge of testing of fragments from the failed component due to limited availability of the material.

In this study, we compare hardness, PIP (Profilometry-based Indentation Plastometry), and tensile testing to obtain mechanical properties and stress-strain relationships for a wide range of metals. Tensile testing is often considered the benchmark for determining these properties, however it does come with some drawbacks; these include the size of sample required, the uniaxial nature of the results and the need to machine specific geometries for testing. In comparison to this, hardness testing is much more convenient and can be performed quickly on a wide array of samples.

These advantages of hardness testing are shared by PIP. The difference between these techniques is in the results produced; with PIP producing a full stress- strain curve, similar to tensile testing, while hardness testing generates a single number for the material, from which other parameters can be determined based on empirical relationships. The ability for mechanical characteristics to be extracted from this hardness number has been an area of substantial research with many empirical relationships found and implemented in different situations.

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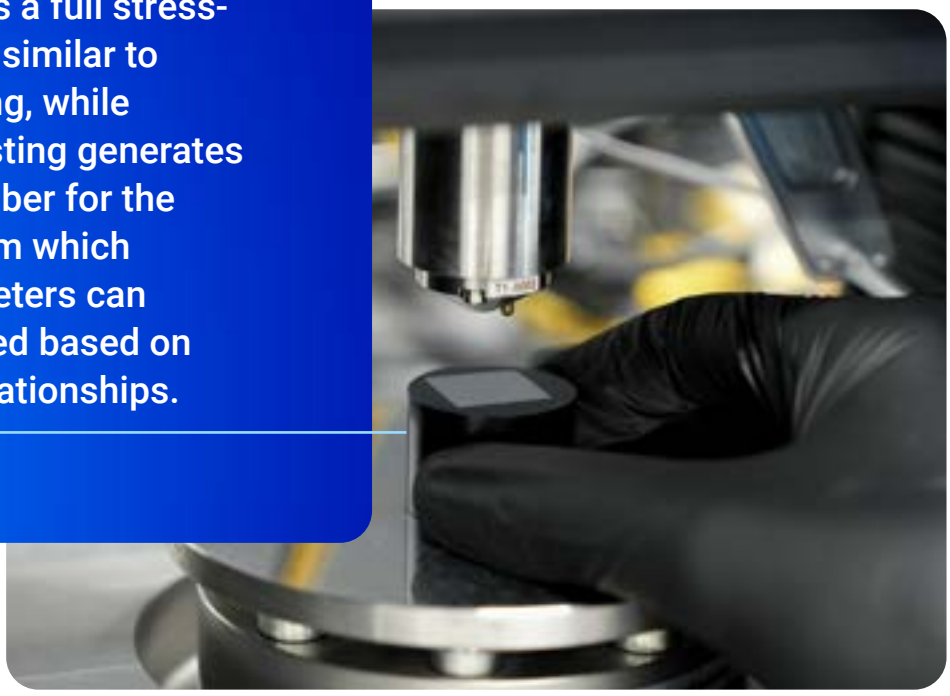

Materials

12 different materials were used in this work:

A. Waspaloy

B. Aluminium 7075

C. Martensitic Steel

D. Carbon Steel

E. 316L Stainless Steel

F. S355 Low Alloy steel

G. 4340 Low Alloy Steel

H. 2D Steel

I. Rail Steel

J. Plain Carbon Steel

K. As-received Copper

L. Annealed Copper

Tensile specimens had 5 mm diameter and were tested with an extensometer gauge length of 25 mm. Indentation samples were in the form of small samples, with a thickness of at least about 5 mm and lateral dimensions of the order of 10-20 mm. Surfaces for indentation were polished to at least a 6 µm finish.

Measurements

The mechanical properties were measured using an Instron 3369 loading frame for uniaxial testing specimens and a PLX-Benchtop, a compact indentation-based device for PIP testing. PIP uses an accelerated inverse finite element method to infer accurate stress-strain curves from indentation test data.

The PLX-Benchtop comes with both 2 mm and 1 mm diameter indenter tips, allowing stress-strain measurements to be taken as close as 5 mm and 2.5 mm apart, respectively. The test itself is fully automated and takes less than 5 minutes without the need for separate samples or extensive sample preparation. The larger diameter indenter was used in this work for testing all samples.

Hardness testing was carried out using a Buehler Wilson VH3300 automatic Vickers hardness tester, with a load of 10 kg. The indent diagonal was taken to be the average of the two measurements (made via the built-in optical microscopy system). In general, these two diagonals were very close, reflecting the isotropy of these materials, and also their relatively fine grain structures – even with the harder materials, the indents still tended to straddle at least several grains. These measurements were repeated in 5 different locations for each material.

Results

In this case study, results from uniaxial tensile testing were compared with those obtained from PIP tests and with hardness tests converted to UTS values. PIP testing provides the full stress- strain curve of each material directly as part of its data output, however hardness numbers cannot directly be compared to full tensile tests as empirical relationships are used to convert hardness values to UTS values.

One example of these empirical relationships is found in BS EN ISO 18265:2013 for unalloyed and low alloy steels and cast steels. It is important to note the text of this standard which describes the caution that should be used when applying this relationship:

"While hardness-to-hardness conversion involves considerable scatter and systematic errors, conversion of hardness to tensile strength values produces even greater scatter. One reason for this is that a great uncertainty can be affected by microstructural changes (e.g. resulting from heat treatment or cold working) within even the same type of steel."

This is described in the standard as scatter bands of ± 25 Hv10 for the hardness and ± 85 MPa for the UTS. In addition, this standard method can only be used on specific subsets of alloys, such as 'unalloyed and low alloy steels' whereas PIP can be applied to any metallic material and can account for the effects of microstructural changes which result in different mechanical responses of the material.

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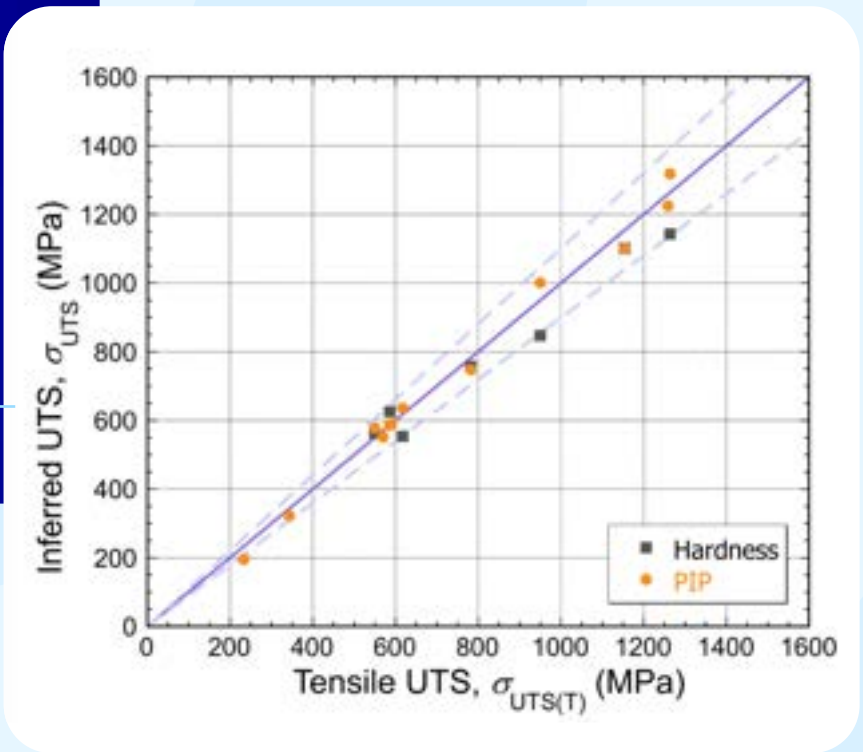
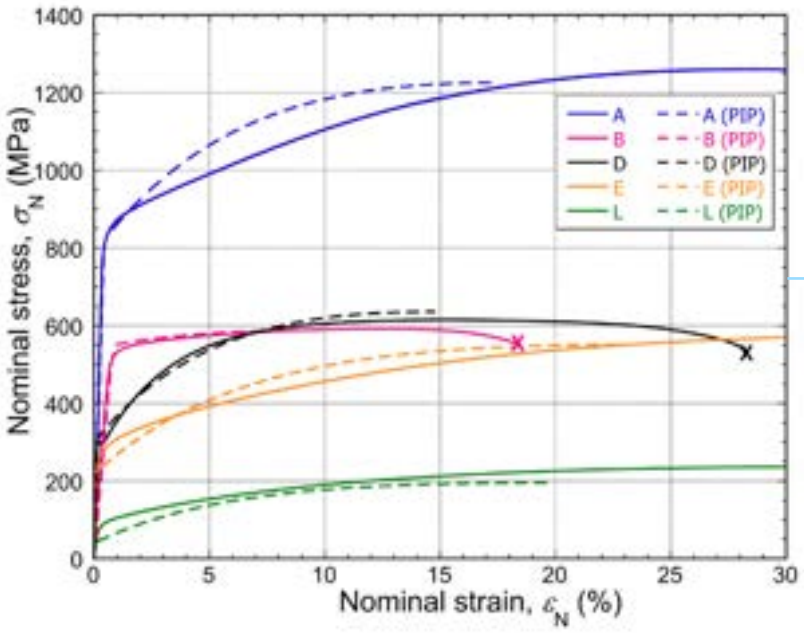


Figure 1: *Plot of inferred UTS from PIP and hardness testing using BS ISO-18265:2013 against corresponding tensile tests.*

Results

This standard method was applied to the subset of materials in this study for which the conversion is permitted. PIP tests were carried out on all the samples, and the UTS values obtained from these two methods are compared on a unity plot with the tensile measurements in Figure 1. Perfect agreement with tensile testing is indicated by the solid unity line with deviations of ±10% shown by dashed lines. **PIP values of UTS align 2.96 percentage points more closely with tensile measured values than hardness converted values, having a mean absolute percentage error of 3.8% compared to 6.8% for hardness testing.**

While hardness conversions can be used only to estimate UTS values, PIP can also provide the full stress-strain curve including yield stress and hardening behaviour. Figure 2 demonstrates the agreement between the full stress-strain curves from tensile testing and PIP for a subset of the materials in this work covering a wide variety of properties. In general, the level of agreement between PIP-derived and directly measured tensile curves is very good. This full stress-strain curve cannot be obtained from a hardness test, which can result in blind spots when trying to use hardness values to understand the mechanical properties of metallic components.



PIP values of UTS align 2.96% more closely with tensile measured values than hardness converted values, with a MAPE of 3.8%.

Figure 2: *Nominal stress – nominal strain curves for selected materials, from tensile testing and from PIP. The latter are shown only up to the onset of necking (peak in the plot).*

Outcomes

As demonstrated, hardness testing within failure analysis, may be used as a complementary technique to tensile testing. When use of tensile testing is not possible, hardness numbers can provide useful indicators of the resistance to plastic deformation. Empirical correlations from standards can be used to convert these hardness numbers to UTS values, for a limited subset of alloys. These standards cannot be applied universally and detail that conversions should 'be used with caution'.

In contrast to hardness testing, PIP testing provides the full stress-strain curves of the metal being tested, including the yield stress. This results in detailed quantitative information and higher levels of confidence in the yield stress, ultimate tensile strength and complete stress-strain curve of metal parts. Furthermore, when it comes to applying the learnings from failure analysis work, the PIP data can also be used as a reliable and important input for finite element modelling to understand if high stress areas are at risk of failure.

Find out more about PIP testing:

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