Determination of high-temperature elastoplastic properties of welded joints by indentation test

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The stress and strain fields formed in the heat-affected zone (HAZ) of welds in pipes in thermal power plants has recently attracted attention as a key plant management issue. The microstructure in the HAZ changes locally as a result of the thermal history imposed by the welding procedure; these changes are manifested in the form of a stress–strain response different from that of the base metal. In the present study, a method based on indentation tests is proposed to estimate the variation of yield stress over the HAZ. The well-known indentation tests to infer the stress–strain curve from indentation load and penetration depth measurements are familiar. However, there are difficulties in applying this approach at high temperatures. An alternative procedure based on impression size is proposed and applied to evaluate the variation of mechanical properties of Grade 122 steel over the HAZ in a welded part at 873 K.

Keywords: Indentation test, Mechanical property, Welded parts, HAZ, High temperature

Introduction

An indentation test is a method used to evaluate the mechanical property such as elastic modulus and yield stress based on the relationship between the indentation load and penetration depth obtained by applying an indenter to a sample surface.1–5 Micro- and nano-impression size testing devices have been developed to estimate the mechanical property of the very small sample area, which would be unfeasible with a typical tensile test.

However, there are some difficulties involved in applying such commercial testing devices to estimate the mechanical property at a high temperature, since the penetration depth sensor attached to the devices causes drift because of heat transfer from the electro furnace.6,7 This limits the information obtained from the indentation test performed at high temperature in terms of the indentation load and the impression remaining on the sample surface after removing the indenter.

Currently, cavity-accumulated damage or cracking occurring in a heat-affected zone (HAZ) in welded parts of high-temperature pipes in thermal power plants has attracted attention as an important plant management issue.8,9 The microstructure in the HAZ region changes locally with the influence of heat history in the welding process, which emerges in a stress–strain response unlike that of base metal. Accordingly, to evaluate the damage for the welded part appropriately, such localized change in the damage model must be taken into account.

In this study, an alternative procedure which can estimate the elastic modulus and yield stress of the sample from the impression size rather than the penetration depth is discussed. First, an analytical solution related to the change in impression size with indentation load is shown by solving a typical problem of an elastic-perfect plastic semi-infinite medium subjected to indentation of a rigid sphere. By rearranging the solution for elastic modulus and yield stress, a formula to estimate all properties is induced. The applicability of this formula to the strain-hardening model resembling an actual response is checked by conducting non-linear finite-element analysis, to which an empirical correlation factor is introduced to improve predictive accuracy.

Finally, the high-temperature mechanical property of a high (~11%) Cr ferritic heat-resisting steel (Grade 122 steel) is examined using the high-temperature indentation tester fabricated in this study, and the distribution of the mechanical property over the HAZ region is successively evaluated at temperature 873 K.

Analytical solution

The semi-infinite region occupied by an elastic-perfect plastic solid, to which a rigid spherical indenter of radius R is applied, is indicated in Fig. 1. It is assumed that the semi-infinite media behaves as an elastic-perfect plastic solid characterized by the elastic modulus E, Poisson’s ratio v and yield stress σy. The spherical indenter is applied to the sample surface with contact radius a and penetration depth h under the indentation load P. Such aspect brings about the following stress field in the semi-infinite region: the full
Here, we shall conform to this assumption in formulation. When the indentation load increases from \( P \) to \( P + \Delta P \) and the associated penetration depth from \( h \) to \( h + \Delta h \) the radius component in displacement at the core surface is \( da(a) \), and the boundary between elastic and plastic regions grows only on the outside.

To retain the volume of the core region, we require

\[
dh = 2 \frac{du}{dc} \mid_{r=a} \, dc
\]

Substitution of the radius component in displacement in the plastic region \((a \leq r \leq c)\)

\[
n(a) = \frac{\sigma_y}{E} \left[ 2(1 - 2\nu) \left\{ \ln \left( \frac{r}{c} \right) - \frac{1}{3} \right\} + (1 - \nu) \left( \frac{c}{r} \right)^3 \right]
\]

into equation (2) leads to an increment in the penetration depth

\[
\Delta h = 2 \frac{\sigma_y}{E} \left[ -3(1 - 2\nu) \left( \frac{r}{c} \right)^2 + (1 - \nu) \left( \frac{c}{r} \right)^3 \right] \, dc
\]

The ratio of change in the penetration depth to the associated contact radius can be given by

\[
\frac{dh}{da} = \frac{dh}{dc} \mid_{r=a} \left( \frac{dc}{da} \right)
\]

Assuming that the plastic region grows under geometrical restriction \( dc/da = (c/a) \), equation (5) is reduced to the simple form

\[
\frac{dh}{da} = \frac{dh}{dc} \mid_{r=a} \left( \frac{c}{a} \right)
\]

Substituting equation (4) into equation (6), we have

\[
\frac{dh}{da} = 2 \frac{\sigma_y}{E} \left[ 3(1 - \nu) \left( \frac{c}{a} \right)^3 - 2(1 - 2\nu) \right]
\]

Conversely, the geometrical consideration for the spherical shape in the indenter reveals the following simple relation

\[
h = \frac{1}{2} \left( \frac{a^3}{R} \right)
\]

Substituting equation (8) into equation (7) and solving details of the plastic region size \((c/a)\) yields

\[
\left( \frac{c}{a} \right) = \left[ \frac{1}{6(1 - \nu)} \frac{a}{\sigma_y} \left( \frac{a}{R} \right)^2 + \frac{2}{3} \left( \frac{1 - 2\nu}{1 - \nu} \right) \right]^{\frac{1}{3}}
\]

Here, the assumption of \( 0 \leq \nu \leq 0.5 \) provides the relation

\[
0 \leq \frac{2}{3} \left( \frac{1 - 2\nu}{1 - \nu} \right) < \frac{2}{3}
\]

This also allows us to use the following approximation

\[
\left( \frac{c}{a} \right) \sim \left[ \frac{1}{6(1 - \nu)} \frac{a}{\sigma_y} \left( \frac{a}{R} \right)^2 + \frac{2}{3} \right]^{\frac{1}{3}}
\]

The traction \( p \) may be also related to the plastic region size through the following form

\[
p = \left\{ 2 \ln \left( \frac{c}{a} \right) + \frac{2}{3} \right\} \sigma_y
\]

By substituting equation (10) into this equation, the following important formula is obtained

\[
p = m \ln \left( \frac{a}{R} \right) + n
\]

where

\[
m = \frac{2}{3} \sigma_y
\]

\[
n = \frac{2}{3} \sigma_y \left\{ 1 + \ln \left( \frac{1}{6(1 - \nu)} \sigma_y \right) \right\}
\]

The authors should now reiterate that only the impression radius \( \tilde{a} \) remains on the sample surface after removing the indenter, which can be determined from the indentation test. Here let us discuss the difference between the contact radius \( a \), which appeared in the formula, and the impression radius \( \tilde{a} \). The radius component in displacement at the core boundary \((r = a)\) recovering after removing the indenter can be given by

\[
u_k = - \frac{1 + \nu}{E} \sigma_y \left\{ \ln \left( \frac{c}{a} \right) + \frac{1}{3} \right\} a
\]
It is easy to obtain the impression radius by adding it to the original core radius

\[
\bar{a} = a + u_R = a \left( 1 - \frac{1 + \nu}{3E}\sigma_y \right) - \frac{1 + \nu}{E}\sigma_y \ln \left( \frac{c}{d} \right) a
\]

(16)

Substitution of equation (11) into equation (16) gives the following approximation

\[
\left( \frac{a}{\bar{a}} \right) = 1 - \frac{1}{2} \left( \frac{1 + \nu}{E} \right) p \sim 1
\]

(17)

It emerges that the order of the impression size is almost equal to the contact radius. Hence the impression radius will be regarded as the contact radius \(a\) appearing in equation (12) in the following arguments.

**Estimation procedure of material property by high-temperature indentation test**

An evaluation procedure based on formula (12) with equations (13) and (14) is illustrated in Fig. 2. In performing the high-temperature indentation test, the impression size \(2a\) is measured for several indentation loads, whereupon the mean contact pressure \(p = P/(\pi a^2)\) is plotted as a function of a logarithm of the non-dimensional impression radius \(\ln (a/R)\). The mechanical property of the sample can be evaluated from the gradient \(m\) and \(y\) axis intercept \(n\) in the graph, which are included in equations (13) and (14).

**Verification of analysis solution by finite-element analysis**

Here, finite-element analysis is performed to verify equation (12). The finite-element model used in this study is shown in Fig. 3. The model was divided with four noded isoparametric elements, and the region near the contact point was divided with fine elements. Nonlinear calculation was performed using the commercial finite-element code MARC with the option of a large deformation and contact.

It was assumed that the friction coefficient \(\mu\) is 0.0, which corresponds to frictionless contact mode. As a preliminary calculation, the authors conducted frictional contact analysis under the coefficient \(\mu = 0.5\). It was confirmed that the assumption of friction contact did not contribute to the impression size change. The material constant used in this calculation is indicated in Table 1. The spherical indenter was assumed to be an elastically deformable solid with elastic modulus \(E_{\text{ball}} = 370\) GPa and Poisson’s ratio \(\nu_{\text{ball}} = 0.3\). The sample was also assumed to be a bilinear hardening solid with hardening slope \(d\) called herein. Poisson’s ratio of the tested sample as well as the indenter also was set \(\nu_{\text{sub}} = 0.3\). In order to examine the influence of elastic modulus and yield stress on the impression size, calculations with \(2 \times E_{\text{sub}}\) and \(0.5 \times E_{\text{sub}}\) were added as extra.

The indentation calculations were conducted under the indentation load \((P = 196, 392, 588, 980\) N) and the indenter radius \((R = 1.0, 2.0\) mm), which were decided based on the following experimental condition.

The analysis procedure is as follows: first, elastoplastic contact analysis is conducted until reaching the set load condition. Subsequently, the indenter is removed, and the distance between the centre and peak in the profile of the deformed sample surface was treated as the impression radius \(a\).

The relationship between the mean contact pressure \((P/\pi a^2)\) and the non-dimensional impression radius \((a/R)\) arranged from the numerical analysis is shown in Fig. 4, which is in the case of the indenter radius \(R = 1.0\) mm. The circle symbol, square symbol, triangle and overturned triangle indicate 293, 773, 873 and 973 K, respectively. It is found that the mean contact pressure decreases with increasing temperature, i.e. decreasing with yield stress. It was recognized that the mean contact pressure was proportional to a logarithm of the non-dimensional impression radius \(\ln (a/R)\) regardless of the testing temperature condition.

Figures 5 and 6 indicate the variation of the parameter \((\sigma_y/m)\) as a function of \(\sigma_y\). It was presumed from equation (13) induced previously that the parameter \((\sigma_y/m)\) assumes a constant value of 1.5, regardless of analytical conditions such as the indenter radius and yield stress. For this consideration, the parameter decreases

![Image](https://example.com/image.png)

2 Procedure used to estimate the mechanical property from the high-temperature indentation test
with increasing yield stress and then approaches to a desirable value of 1.5; however, it was recognized to be quite different between analytical and FEM results in a low yield stress. The difference in a low yield stress case was caused by the elastic/plastic boundary as shown in Fig. 1 being expanded to the more outward direction, so that the full plastic semi-infinite media problem has to be assumed instead of our elastoplastic problem. On the other hand, elastic modulus does not affect the parameter.

The correlation factor for the formula about yield stress must be considered as follows

\[ \sigma_y = (mf_1)^{1/2} \]  

where

\[ f_1 = 86.689, \quad f_2 = 1.79 \quad \text{when} \quad R = 1.0 \text{ mm} \]

\[ f_1 = 2265.3, \quad f_2 = 1.21 \quad \text{when} \quad R = 2.0 \text{ mm} \]
Conversely, equation (14) can be rearranged as
\[
\frac{3}{2} n = a \sigma_y \left\{ \ln \left( \frac{E}{\sigma_y} \right) + 1 \right\} + b
\]
which is applicable for estimating the elastic modulus. Figure 7 indicates the relation between \( \frac{3n}{2} \) and \( \sigma_y \ln \left( \frac{E}{\sigma_y} \right) + 1 \), which means that equation (19) indicates the useful formula. Here, \( a = 1.1596 \) and \( b = 454.83 \). Solving the elastic modulus in equation (19), the following formula is obtained
\[
E = \sigma_y \exp \left[ \frac{1}{a \sigma_y} \left( \frac{3}{2} n - b \right) - 1.0 \right]
\]
which facilitates estimation of the elastic modulus of the sample.

High-temperature indentation test

Test procedure

Figure 8 is a schematic illustration of the high-temperature indentation testing device, which is handmade. This device is composed of the part imposing a compressive load on the sample surface, the compressive load of which is generated by a lever with a leverage ratio of 1:10, and the electric furnace heats up the whole sample at temperature \( T \).

The testing procedure is as follows: an alumina ball is adhered to the sample surface with instant glue, all of which could be volatilized during the test and is set on the stage inside the electric furnace. This sample is then heated up to the testing temperature under proportional-integral-derivative control (PID) control. After reaching the desired temperature, a weight is suspended within 5 s at the tip of the lever to exert a compressive load on the sample surface via an alumina ball. After completing those processes, the weight is removed and the electric furnace is shut down. Reaching room temperature, the sample is taken out to measure the impression radius \( 2a \).

Results for high Cr ferritic heat-resisting steel

Grade 122 steel was employed as high Cr ferritic heat-resisting steel for the high-temperature indentation test. Table 2 indicates the chemical composition of this steel, which was heat treatment with normalized (1323 K | 1 h with air cooling) and tempered (1043 K | 1 h with air cooling) conditions. Figure 9 indicates the microstructure of Grade 122 steel utilized in this study. The sample is a plate shape 10 × 10 × 5 mm in size. The surface of the plate after cutting was completely polished.

Figure 10 indicates the relationship between the mean contact pressure and the non-dimensional radius. It is obvious that the non-dimensional radius increases with mean contact pressure and is independent of the ball size and temperature condition. The mean contact pressure decreases with increasing temperature, since the
impression size increases with a decline in yield stress subjected to a higher temperature experience. Those trends coincide with the finite-element results previously obtained in Fig. 4.

Figure 11 indicates the estimation results of the yield stress based on equation (18) and the slope $m$ which was identified by the correlation curve in Fig. 10. It is confirmed that the yield stress of Grade 122 steel can be estimated under all cases of testing temperature and indentation radius conditions, which helps us to verify the evaluation scheme based on the impression size in the high-temperature indentation test.

**Table 2 Chemical composition of the base metal (%)**

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Al</th>
<th>N</th>
<th>W</th>
<th>B</th>
<th>Ta</th>
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<tr>
<td>0.11</td>
<td>0.26</td>
<td>0.64</td>
<td>0.016</td>
<td>0.002</td>
<td>1.03</td>
<td>0.39</td>
<td>10.87</td>
<td>0.31</td>
<td>0.20</td>
<td>0.054</td>
<td>0.001</td>
<td>0.064</td>
<td>1.86</td>
<td>0.034 × 10⁻³</td>
<td>–</td>
</tr>
</tbody>
</table>

**Figure 10 Relationship between the mean contact pressure and the non-dimensional radius**

**Application to the welded joint part of high Cr ferritic heat-resisting steel**

Attempts were made to measure the yield stress distribution around the HAZ region in the welded joint of Grade 122 steel followed by the estimation scheme. Table 3 indicates the chemical composition of the welded sample employed in this study. After tungsten
inert gas (TIG) welding process for binding the base metals together, the post-heat treatment was conducted at 1018 K for 75 min to reduce residual stress. The sample has a plate shape with geometry of $28 \times 6 \times 3$ mm cut by a diamond cutter from a near-weld line in the large-size welded plate. Subsequently, the surface of the plate was polished completely and then etched chemically to facilitate optical microscope observation of the microstructure around HAZ. Figure 12a and b indicates the microstructure of weld metal and the associated HAZ.

A high-temperature indentation test was conducted at temperature 873 K, and an indented point to estimate the yield stress was taken at intervals of 3 mm along a line perpendicular to the weld line using a ball size of 1 mm. Furthermore, the relationship between the mean contact pressure and non-dimensional radius was plotted at each indentation.

Table 4 and Fig. 13 indicate the change in yield stress estimated for the indentation points. Table 4 also includes the yield stress obtained by conducting a tensile test using specimens cut from the weld and base parts individually. In Fig. 13, the fusion line was taken as the origin in a horizontal axis, with the weld metal covers in the positive axis and the base metal covers in the negative one, as shown in the upper part of the figure. It is revealed that the estimated yield stresses in the metal and weld parts virtually match those obtained by the tensile tests (see the slash lines corresponding to the latter). Figure 13 also shows Vickers' hardness distribution before heat exposure, which shows the hardness peaking at the fusion line, and it decreases towards the metal and weld region. It should be noted that hardness is lowest around the HAZ region. Those trends completely match with that of the yield stress seen around the fusion line.

### Table 3 Chemical composition of the weld metal (%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>Al</th>
<th>N</th>
<th>W</th>
<th>B</th>
<th>Ta</th>
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<tbody>
<tr>
<td>0.08</td>
<td>0.22</td>
<td>0.36</td>
<td>0.006</td>
<td>0.004</td>
<td>0.03</td>
<td>0.41</td>
<td>9.66</td>
<td>0.94</td>
<td>0.20</td>
<td>&lt;0.01</td>
<td>0.005</td>
<td>0.20</td>
<td>0.040</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>

11 Yield stress of the base metal estimated by the estimation scheme

12 Microstructure of weld metal and HAZ zone.
Conclusions

In this study, a scheme for estimating the mechanical property at high temperature was presented based on the indentation test technique. The main findings and implications obtained in this study are summarized as follows:

1. A formula was developed to estimate yield stress and elastic modulus from the indentation test conducted at high temperature. It was verified by performing a non-linear finite-element calculation.
2. High Cr ferritic heat-resisting steel was employed for the indentation tests, and the associated yield stresses at various temperatures were estimated based on the analytical formula. It was confirmed that the estimated yield stresses virtually match that obtained by the tensile tests, which help us to verify the evaluation scheme.
3. The scheme was applied to the welded joint of high Cr ferritic heat-resisting steel. The yield stress peaked at the fusion line and decreased at the base and weld metal region. The lowest yield stress was recorded at the HAZ region, which revealed that the yield stress was distributed in a complicated manner around the weldment.

Acknowledgements

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References


### Table 4

<table>
<thead>
<tr>
<th>Position from weld line x (mm)</th>
<th>Estimated yield stress (MPa)</th>
<th>Yield stress obtained from tensile test (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−14</td>
<td>388</td>
<td>356 (base data)</td>
</tr>
<tr>
<td>−7</td>
<td>162</td>
<td>–</td>
</tr>
<tr>
<td>−4</td>
<td>217</td>
<td>–</td>
</tr>
<tr>
<td>0</td>
<td>753</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>533</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>423</td>
<td>398 (weld data)</td>
</tr>
</tbody>
</table>

13 Yield stress distribution over the welded sample as estimated by the high-temperature indentation test at 873 K

![Graph](image-url)