Relationship between indentation creep rate and strain rate at representative points of deformed region in power-law materials

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Introduction

The instrumented indentation testing technique is known as a powerful tool for evaluating creep properties in a selected region of a small testpiece. It is expected to establish robustly the prediction process of a constitutive equation for tensile creep of power-law materials using this technique. However, there are few reports about it [1, 2].

The aim of this study is to determine the relationship between the indentation creep rate and the equivalent plastic strain rate at the representative points (RPs) where creep behavior in the deformed region beneath the indenter is represented.

Dimensional analysis for indentation creep

Indentation pressure p_a and indentation creep rate $\dot{\varepsilon}_{in}$ can be defined as follows;

$$p_a \propto \frac{F}{u^2}, \qquad (1) \qquad\qquad \dot{\varepsilon}_{in} = \frac{\dot{u}}{u}. \qquad (2)$$

When a conical indenter tip is pressed into the test surface of power-law materials ($\dot{\bar{\varepsilon}} = B\bar{\sigma}^n$) by the loading condition of $F = F_0 \exp(2\alpha t)$, we have a general expression for indentation creep;

$$f_1(B, F, n, u, \dot{u}) = 0. \qquad (3)$$

Appling the Π -theorem in dimensional analysis, Eq. (3) can be expressed by two dimensionless functions as follows;

$$f_1(\Pi_1, \Pi_2) = 0, \qquad (4)$$

where, $\Pi_1 = f_2\left(B \cdot \left(\frac{F}{u^2}\right)^n \cdot \frac{u}{\dot{u}}\right)$, $\Pi_2 = f_3(n)$. (5)

When $\Pi_1 - \Pi_2 = 0$ in Eq. (4), we obtain

$$f_2\left(B \cdot \left(\frac{F}{u^2}\right)^n \cdot \frac{u}{\dot{u}}\right) - f_3(n) = 0. \qquad (6)$$

Eq.(6) can be rewritten as follows;

$$f_4\left(B p_a{}^n \dot{\varepsilon}_{in}{}^{-1}\right) - f_3(n) = 0. \qquad (7)$$

When p_a and $\dot{\varepsilon}_{in}$ become constant values of $p_{a(s)}$ and $\dot{\varepsilon}_{in(s)}$,respectively, and $\bar{\sigma} = C_1 p_{a(s)}$ and $\dot{\bar{\varepsilon}} = C_2 \dot{\varepsilon}_{in(s)}$ hold at the RPs, Eq. (7) can be given by

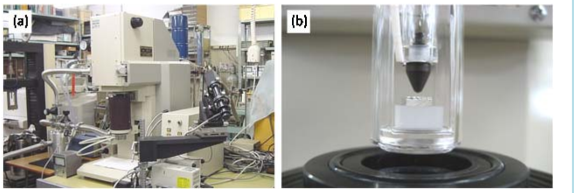
$$f_4\left(B \cdot \left(\frac{\bar{\sigma}}{C_1}\right)^n \cdot \frac{C_2}{\dot{\bar{\varepsilon}}}\right) - f_3(n) = 0. \qquad (8)$$

From $\dot{\bar{\varepsilon}} = B\bar{\sigma}^n$, we obtain

$$C_2 = C_1{}^n f_3(n) = f_5(n). \qquad (9)$$

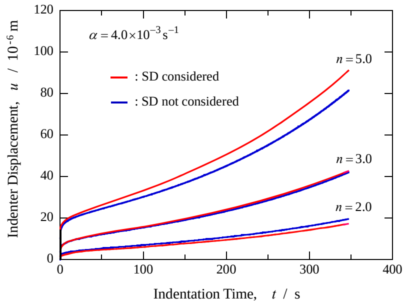
It is clear that C_2 depends on only the stress exponent *n*.

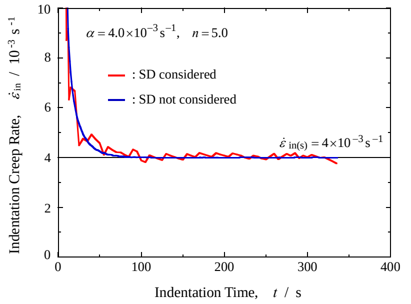
Microindenter

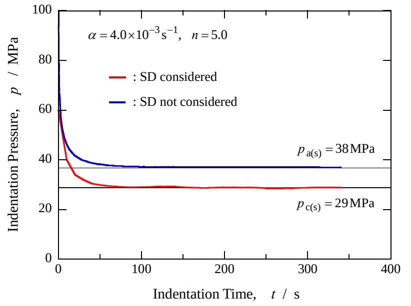


The picture (a) shows an overall view of the microindenter. The picture (b) shows a conical diamond indenter tip and a small sized specimen mounted on the quartz tube in the heater. The tests are carried out at high temperatures in a vacuum or an argon gas. The indentation load is given by an electromagnetic coil, and the indenter displacement is measured by a LVDT.

FE Simulation

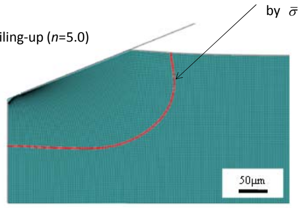






RPs (red line) is defined by $\bar{\sigma} = C_1 p_{c(s)} = p_{c(s)}/3$.[3]

Piling-up (*n*=5.0)



Indentation data

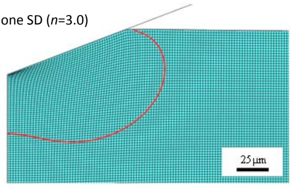
$p_{c(s)} = 29.1$MPa
$\dot{\varepsilon}_{in(s)} = 4.0\times10^{-3}\,\mathrm{s}^{-1}$

At RPs

$\bar{\sigma} = 9.70$MPa
$\dot{\bar{\varepsilon}} = 8.4\times10^{-4}\,\mathrm{s}^{-1}$

$C_{2(c)} = \frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_{in(s)}} = 0.21$

None SD (*n*=3.0)



Indentation data

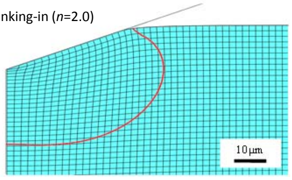
$p_{c(s)} = 129$MPa
$\dot{\varepsilon}_{in(s)} = 4.0\times10^{-3}\,\mathrm{s}^{-1}$

At RPs

$\bar{\sigma} = 43.0$MPa
$\dot{\bar{\varepsilon}} = 8.0\times10^{-4}\,\mathrm{s}^{-1}$

$C_{2(c)} = 0.20$

Sinking-in (*n*=2.0)



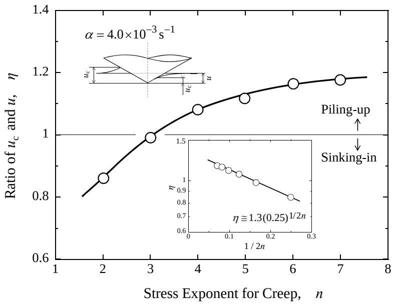
Indentation data

$p_{c(s)} = 819$MPa
$\dot{\varepsilon}_{in(s)} = 4.0\times10^{-3}\,\mathrm{s}^{-1}$

At RPs

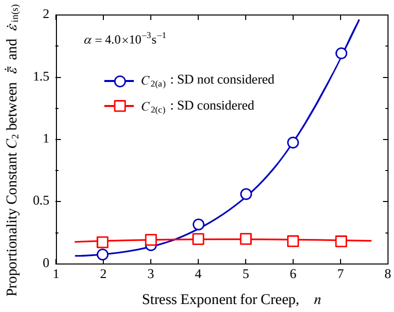
$\bar{\sigma} = 273$MPa
$\dot{\bar{\varepsilon}} = 7.5\times10^{-4}\,\mathrm{s}^{-1}$

$C_{2(c)} = 0.19$



- When the *n* value is 2 or smaller, sinking-in($\eta < 1$) occurs around the impression. In this case, u_c(contact depth) is smaller than *u*. In contrast, in the cases of $n = 4$ or larger, piling-up（ $\eta > 1$ ）takes place there and u_c is greater than *u*.
- Indentation creep rate $\dot{\varepsilon}_{in}$ and indentation pressure p become constant values of $\dot{\varepsilon}_{in(s)}$ and $p_{(s)}$, respectively, after an initial transition period. Here, $\dot{\varepsilon}_{in(s)}$ takes the same value in either case. In contrast, $p_{c(s)}$ is different from $p_{a(s)}$.

C_2 value and prediction process



$C_{2(c)}$ is given by

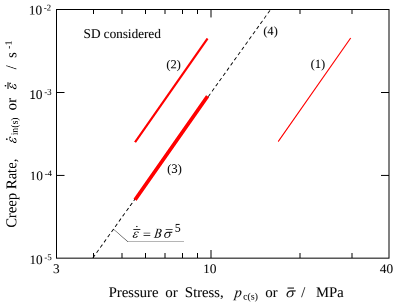
$$C_{2(c)} = \frac{C_{2(a)}}{\eta^{2n}}.$$

From FE simulation, we have

$C_{2(a)} \cong 0.023\exp(0.63n)$,
$\eta \cong 1.3(0.25)^{1/2n}$.

In the cases of $n = 2-7$, we have $C_{2(c)} \cong 0.20$.

$C_{2(a)}$ value increases exponentially with increasing the stress exponent. However, $C_{2(c)}$ takes an almost constant value of 0.2 ranging from $n = 2$ to $n = 7$.



(1) Indentation creep result
$p_{c(s)}$ vs. $\dot{\varepsilon}_{in(s)}$

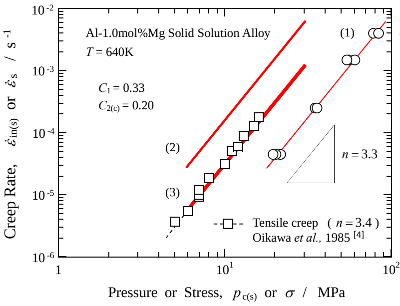
(2) $\bar{\sigma}$ $(= C_1 p_{c(s)})$ vs. $\dot{\varepsilon}_{in(s)}$

(3) $\bar{\sigma}$ vs. $\dot{\bar{\varepsilon}}$ $(= C_{2(c)} \dot{\varepsilon}_{in(s)})$

(4) Tensile creep result
$\bar{\sigma}$ vs. $\dot{\bar{\varepsilon}}$

The figure shows the prediction process of tensile creep data using indentation creep data.

Comparison indentation results with tensile results

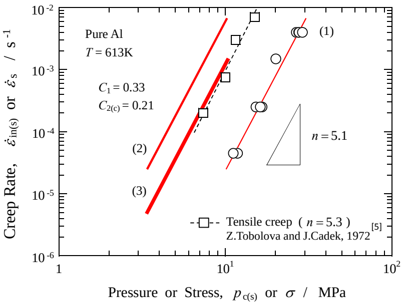


Predicted tensile creep data

$\dot{\bar{\varepsilon}} = 1.5\times10^{-8}\bar{\sigma}^{3.3}$

Experimental tensile creep data

$\dot{\varepsilon}_s = 1.5\times10^{-8}\sigma^{3.4}$



Predicted tensile creep data

$\dot{\bar{\varepsilon}} = 1.1\times10^{-8}\bar{\sigma}^{5.1}$

Experimental tensile creep data

$\dot{\varepsilon}_s = 4.5\times10^{-9}\sigma^{5.3}$

Conclusions

- When the SD is considered, the $C_{2(c)}$ value takes a constant value of 0.2 and it does not depend on the test temperatures.
- Using the above $C_{2(c)}$ values, the predicted tensile creep data are in agreement with the experimental tensile creep data which were reported by other researchers.
- The above result shows that the creep behavior at RPs represents that of the deformed region beneath the indenter.

References

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[3] D. Tabor, The Hardness of Metals, (Oxford University Press, Oxford, 1951).
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