Experiments on Wedge Indentation of a Porous Material *
(Indentation Hardness of a Porous Material : 2nd Report)

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Experiments on the wedge indentation of a porous material are carried out using workhardened and annealed specimens of sintered copper powder. Studies are made on influences of the initial relative density, the wedge angle and the frictional condition on the indentation pressure. The indentation pressure is compared with the flow stress obtained from tests of plane strain compression of sintered copper powder. The deformation pattern is also obtained by means of the grid method.

1. Introduction

Sintered powder metals have recently come to be used in various machine parts. For extension of these metals to a wider range of applications, it will be helpful to establish a non-destructive method for estimating the mechanical properties of porous materials. From this point of view, the indentation hardness of porous materials has been studied in this series of reports. In the 1st report1), an analysis of the wedge indentation of the porous material, which has a characteristic of changing in volume (or density) with plastic deformation, has been made using the simple line field theory for porous materials2). The indentation pressure, the change in density and the mean effective strain in the plastically deforming region were calculated in variations of the wedge angle, the frictional condition, the initial density and the yield stress of the porous material.

In this report, experiments on the wedge indentation of the porous material were carried out using workhardened and annealed specimens of sintered copper powder. Plane strain compression tests of the specimens were also done and the flow stress was compared with the indentation pressure. Further, deformation pattern was observed by distortion of grids provided on the surface of the specimen.

2. Experiments

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Table 1 Particle size distribution of copper powder (%)

<table>
<thead>
<tr>
<th>mesh</th>
<th>100</th>
<th>145</th>
<th>200</th>
<th>250</th>
<th>350</th>
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<td>30-45</td>
<td>25-35</td>
<td>5-15</td>
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Fig.1 Schematic representation of set-up for wedge indentation
\( \rho_0 = 0.55 \), 0.85 (for \( \rho_0 = 0.65 \)) and 0.95 (for \( \rho_0 = 0.75 \)) for each repressing pressure. By this method of producing the specimens, namely, by increasing the relative density of 0.20 for each preform, the strain of workhardening was controlled to be almost the same for every specimen. These were called the workhardened specimens. On the other hand, the annealed specimens were made by annealing the workhardened specimens at 400°C for two hours in a vacuum. The shape of the specimens was 40\( \times \)15\( \times \)50 mm rectangular parallelepiped made by machining. Top and bottom surfaces of the specimens were finished with buffing.

Fig.1 is a schematic representation of a set-up for the wedge indentation. Deformation in the direction normal to the paper surface (15 mm thickness of the specimen) is restricted and the plane strain state is kept. The load was applied by an Instron testing machine. The indenting velocity was 0.5 mm/min. The displacement of the wedge was read by a dial gauge. Wedge semi-angles \( \alpha \) were 30°, 45°, 60° and 68°. Two conditions of lubrication, dry and lubricated, were taken. The former was obtained by cleaning the wedge and the specimen with acetone and the latter was obtained by lubricating with vaseline repeatedly after each increment of the indentation depth of approximately 0.3 mm. The depth of indentation was determined such that the width of indentation was smaller than 4 mm. This is because the plastically deforming region will not reach the side or bottom surfaces of the specimens within that depth.

In order to observe the pattern of deformation and the profile of piling-up or sinking-in, specimens were made by matching two rectangular parallelepipeds of 40\( \times \)7.5\( \times \)50 mm, on one of the matching surfaces of which 0.25 mm square grids were provided.

### 2.2 Compression test of sintered copper powder

To examine the relationship between the indentation pressure and the flow stress of the porous material, plane strain compression tests of sintered copper powder were carried out. Specimens for the compression tests were 15\( \times \)15\( \times \)15 mm cubes which were machined from the specimens for the wedge indentation.

To avoid the non-homogeneous deformation by barrelling, the compression process was divided into several steps and after each step the barreled surfaces of the specimen were machined flat. Teflon sheet was used as a lubricant between the specimen and the tools.

### 3. Results and discussion

Fig.2 shows stress-strain curves of sintered copper powder. Solid and broken curves are for the workhardened and annealed specimens, respectively. The workhardening exponent increases with a decreasing initial relative density \( \rho_0 \). The workhardening exponent for the porous material is dependent upon both workhardening of the matrix metal and densification. When \( \rho_0 \) is low, the rate of densification is so high that the workhardening exponent will have a high value. As mentioned before, the workhardened specimens were made by repressing the sintered preforms such as to increase the relative density of

![Fig.2 Stress-strain curves of sintered copper powder](image)

![Fig.3 Variation of indentation load L with depth of indentation t](image)
In this method, the workhardening strain arising in the matrix metal varies with the relative density of the preform. According to the plasticity equations for porous materials proposed by Oyane et al.\(^4\), the equivalent strains arising in the matrix metal are calculated as 0.30, 0.27 and 0.25 for the specimens of \(\rho_1=0.95, 0.85\) and 0.75, respectively. These values of strain are not large enough to make it possible to assume that the matrix is non-workhardening. It must be noted that even if the matrix metal is non-workhardening, the workhardening exponent is not zero because of densification.

Fig. 3 shows the variation of the indentation load \(L\) with the depth of indentation \(t\). Fig. 3(a) is for the indentation by the dry wedge of \(\alpha=45^\circ\). Solid and broken curves show the variations for the workhardened and annealed specimens, respectively. Fig. 3(b) is for the indentation of the workhardened specimens of \(\rho_1=0.85\) by the lubricated wedge. It is found from Fig. 3 that all of the relationships between \(L\) and \(t\) are nearly linear. Since there are no points where the \(L-t\) relationship ceases to be linear such as Dugdale\(^5\) and Shindo\(^6\) observed in the wedge indentation of solid materials, it can be said that the plastically deforming region does not reach the side or bottom surfaces of the specimens within that depth of indentation.

Fig. 4 shows the ratio of the projected width \(w\) to the depth \(t\) of indentation. In consequence of piling-up or sinking-in, the width \(w\) becomes larger for the indentation of the workhardened specimen of a higher initial relative density by the lubricated wedge.

Fig. 5 shows the variation of the indentation pressure \(p\) with the wedge semi-angle \(\alpha\). \(p\) is derived from the indentation load \(L\) divided by the projected area obtained from Fig. 4. \(p\) increases with a decreasing \(\alpha\) for the dry wedge. On the other hand, when the wedges are lubricated with vaseline, \(p\) reaches the highest value at \(\alpha=45^\circ\). The difference in the indentation pressures under the dry and lubricated conditions is very small for a large \(\alpha\) and becomes larger with a decreasing \(\alpha\). Fig. 6 shows the variation of the indentation pressure \(p\) with the initial relative density \(\rho_1\), which is rewritten from Fig. 5. It is found from Fig. 6 that there are straight-line relationships between \(p\) and \(\rho_1\), and the gradients of the lines for the workhardened specimens are larger than that for the annealed specimens. The difference in the indentation pressures for \(\alpha=30^\circ\) and \(60^\circ\) is smaller for the workhardened specimens than for the annealed specimens, and is almost constant regardless of the initial relative density. Therefore, the workhardening strain can be known from the value of this difference, further the initial relative density of the porous material can be also predicted from the value of \(p\).

Fig. 7 shows the non-dimensional indentation pressure \(P/\rho_1^\prime\), where \(\rho_1^\prime\) is the yield stress of the sintered copper powder.
The experimental value of $q_0'$ is given by the mean value of the flow stress to a theoretical strain $\varepsilon_m$ in the stress-strain curve shown in Fig.2. For example, when $\varepsilon_m = 0.25$ for the workhardened specimen of $\rho_d = 0.95$, $q_0'$ is obtained by the value of stress which makes two shaded areas in Fig.2 equal. $\varepsilon_m$ was dependent upon the initial relative density $\rho_d$, the wedge semi-angle $\alpha$, and the coefficient of friction $\mu$. Since $\mu$ was unknown in the experiments, $\varepsilon_m$ was obtained in three cases, (a) $\mu = 0$, (b) $\mu = 0.1$ and (c) perfectly rough or dead metal cap, and further $q_0'$ and $p/q_0'$ are derived for each case. The results are shown in Fig.7. The theoretical results of $p/q_0'$ are also shown by solid curves. The experimental results agree with the theoretical results for the frictional condition of (c). It must be noticed that $p/q_0'$ increases with an increasing $\rho_d$ in both the experimental and theoretical results. If the hardness is defined by the indentation pressure, this fact shows that we cannot predict the yield stress of the porous material from the hardness because the hardness is dependent upon the relative density as well. It is also found from Fig.7 that the experimental values of $p/q_0'$ decrease with an increasing $\alpha$ and this tendency is contrary to the theoretical values. This matter can be explained as follows. The theoretical results are derived by assuming that the matrix metal of the porous material is non-workhardening. However, in the experiments, sintered copper powder is used which has the workhardening matrix metal. In comparison between the results for the workhardened specimens shown in Fig.7 and the results for the annealed specimens which will be shown later, the former is closer to the theoretical results. This means that if the porous ma-

![Fig.7 Experimental and theoretical relationships between non-dimensional indentation pressure $p/q_0'$ and wedge semi-angle $\alpha$ (workhardened, dry)](image)

![Fig.8 Relationship between non-dimensional indentation pressure $p/q_0'$ and wedge semi-angle $\alpha$ (annealed, dry)](image)

![Fig.9 Relationship between non-dimensional indentation pressure $p/q_0'$ and wedge semi-angle $\alpha$ (workhardened, lubricated)](image)
terial with the non-workhardening matrix is used, the experimental results will be in good agreement with the theoretical results. Evaluation of the yield stress of the porous material, namely the mean value of the flow stress to the theoretical strain $e_\text{y}$, may also be one of the causes of the disagreement. There may be a more approximate method of evaluation.

Figs.8 and 9 show the variation of the non-dimensional indentation pressure $p/\sigma_0'$ with the wedge semi-angle $\alpha$ for the annealed specimens indented by the dry wedges and that for the workhardened specimens indented by the lubricated wedges, respectively. In these figures, the values of $\sigma_0'$ are obtained for two cases, that is, $\mu=0$ and perfectly rough or dead metal cap. Therefore, the frictional conditions in Figs.8 and 9 correspond to Figs.7(a) and (c). Theoretical values for these cases are the same as shown in Figs.7(a) and (c). $p/\sigma_0'$ for the annealed specimens decreases with an increasing $\alpha$ similarly to that for the workhardened specimens shown in Fig.7(a), but, the rate of decrease in $p/\sigma_0'$ for the annealed specimens is higher than that for the workhardened specimens. When $\alpha$ is small, Fig.8 shows that $p/\sigma_0'$ becomes larger for a lower $\rho_1$. It is found from Fig.9 that $p/\sigma_0'$ in the case of the workhardened specimens and the lubricated wedges, does not vary greatly with $\alpha$ and reaches the highest value at $\alpha=45^\circ$ or $60^\circ$. When $\alpha$ is large, $p/\sigma_0'$ in Figs.7 and 9 have nearly the same values, that is, the influence of lubrication is small. Therefore, it can be said that the indenter angle for the hardness test should be large.

Fig.10 shows profiles of the indenta-

(c) Workhardened, dry, $\alpha=45^\circ$, $\rho_1=0.85$

(d) Annealed, dry, $\alpha=30^\circ$

(e) Workhardened, lubricated, $\alpha=30^\circ$, $\rho_1=0.85$

Fig.10 Profiles of indentation and distortion of grids
tion and the distortion of grids. Fig. 10(a) is for the workhardened specimens indented by the dry wedge of $\alpha=30^\circ$. For all initial relative densities, grids are cut by the wedge and the material below the tip of wedge is deformed very little. This pattern of deformation is similar to that obtained from the slip line field theory. The deformation is larger for a specimen of a lower $p_4$. This is because densification is larger for a specimen of a lower $p_4$. This behaviour may be considered one of causes of sinking-in. The area of the plastically deforming region, which can be known from the displacement of grids, increases with an increasing $p_4$. The largest displacement of the vertical lines of grids for $p_4=0.95$ takes place at the surface of the specimen, and that for $p_4=0.75$ takes place a little inside of the surface. Fig. 10(b) is for the workhardened specimens indented by the dry wedge of $\alpha=60^\circ$. Piling-up is small compared with Fig. 10(a) and sinking-in is observed when $p_4$ is low. The material below the tip of wedge seems to be subjected to a deformation of compression. The area of the plastically deforming region increases with increasing $p_4$. Fig. 10(c) is for the workhardened specimen of $p_4=0.85$ indented by the dry wedge of $\alpha=45^\circ$. A middle deformation pattern between cutting ($\alpha=30^\circ$) and compression ($\alpha=60^\circ$) is observed. Fig. 10(d) is for the annealed specimens indented by the dry wedge of $\alpha=30^\circ$. Sinking-in occurs even if $p_4$ is high. The largest displacement of the vertical lines of grids takes place a little inside the surface of the specimen. For the annealed specimen, a smaller width and a larger depth of the plastically deforming region are observed, compared with that for the workhardened specimen. The material below the tip of wedge is subjected to the deformation of compression even when $\alpha=30^\circ$. In comparison between Fig. 10(d) and Fig. 10(a), the deformation pattern for the workhardened specimen of a low initial relative density is similar to the one for the annealed specimen. This matter corresponds to the fact that the workhardening exponent in the stress-strain curve for the workhardened specimen of a low $p_4$ is large and is similar to that for the annealed specimen as shown in Fig. 2.

Fig. 10(e) is for the workhardened specimen of $p_4=0.85$ indented by the lubricated wedge of $\alpha=30^\circ$. Piling-up takes place more remarkably and the width of the plastically deforming region is larger than that indented by the dry wedge shown in Fig. 10(a).

4. Conclusions

Experiments on the wedge indentation of the porous material, i.e. the compressible material, were carried out using sintered copper powder. The following conclusions are drawn: (1) The indentation pressure $p$ increases with a decreasing wedge semi-angle $\alpha$ for the dry wedges. When the wedges are lubricated, $p$ reaches the highest value at $\alpha=45^\circ$ or $60^\circ$. There is a straight-line relationship between $p$ and the initial relative density $p_4$ under the same condition of indenting. (2) The non-dimensional indentation pressure $p/p_0'$, where $p_0'$ is the yield stress of the sintered copper powder, increases with an increasing $p_4$. This behaviour shows that we cannot directly know $p_0'$ from the hardness test, because the hardness is dependent upon $p_4$ as well. The indenter angle for the hardness test should be large in order to make the influence of lubrication negligible. (3) For the workhardened specimen of a high $p_4$ indented by the lubricated wedge, a remarkable piling-up is observed and the area of the plastically deforming region is large. The deformation pattern for the workhardened specimen of a low $p_4$ is similar to the one for the annealed specimen.

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References