Prediction of ductile fracture in cold forging

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Abstract

In the die design of cold forging, finite element analysis of forging is widely used for prediction of a material defect (underfill, crack, etc.). Various ductile fracture prediction equations have been proposed. But, in the case of use of the conventional equations, the analysis results cannot be matched to the fractures of real parts. Therefore, the authors developed a method for predicting ductile fracture independently, to improve the prediction accuracy of ductile fracture.

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Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Ductile fracture; Finite element analysis

1. Introduction

In recent years, automotive companies manufacture hybrid vehicles and electric vehicles to improve fuel economy of automobiles, as well as environmental performance. As with a conventional engine, forged parts are applied to components of the motor. The cold forging method is applied to the motor main shaft as the axis of the motor, and weight reduction is demanded. In order to realize the weight reduction of this motor shaft, we are developing a hollow shaft.

The cold forging process of the hollow shaft that we developed is shown in Fig. 1. The forging process of the hollow shaft is composed of backward extrusion and forward extrusion. The hollow shape reduces the weight of

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the part by 40%. In the early stages, to achieve good quality, it is necessary to use forging simulation and reduce trial and error for the die design. It is possible that ductile fracture of the material occurs, because the amount of deformation of the material is large. An accurate ductile fracture prediction method is effective for this reason.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\sigma_{\text{max}}$</td>
<td>max principle stress</td>
</tr>
<tr>
<td>$\bar{\sigma}$</td>
<td>equivalent stress</td>
</tr>
<tr>
<td>$a$</td>
<td>material constant</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>hydrostatic stress</td>
</tr>
<tr>
<td>$d\varepsilon$</td>
<td>increment of equivalent strain</td>
</tr>
<tr>
<td>$D_f$</td>
<td>damage factor (finite element analysis results of ductile fracture)</td>
</tr>
<tr>
<td>$r$</td>
<td>$r$ direction of a polar coordinate system</td>
</tr>
<tr>
<td>$\theta$</td>
<td>$\theta$ direction of a polar coordinate system</td>
</tr>
<tr>
<td>$z$</td>
<td>$z$ direction of a polar coordinate system</td>
</tr>
<tr>
<td>$\sigma_i$</td>
<td>stress components of a polar coordinate system ($r, \theta, z$)</td>
</tr>
<tr>
<td>$\varepsilon_i$</td>
<td>strain components of a polar coordinate system ($r, \theta, z$)</td>
</tr>
</tbody>
</table>

Fig. 1. Forging process of hollow shaft.

### 2. Problem of the ductile fracture prediction method

#### 2.1. Conventional ductile fracture prediction method

After designing the forging die of Fig. 1, the prototypes were forged. But, at the apical parts of the shaft, ductile fracture of the material has occurred. Before the forward extrusion, residual stress has been removed by an annealing process. In order to investigate the ductile fracture, the authors evaluate the fracture by using finite element analysis. The prediction equations of ductile fracture were Cockroft & Latham’s (1968) equation (Eq. (1)) and Oyane’s (1972) equation (Eq. (2)), which are widely used.

$$D_f = \int \frac{\sigma_{\text{max}}}{\bar{\sigma}} d\varepsilon,$$  \hspace{1cm} (1)

$$D_f = \int \left(1 + \frac{1}{a} \frac{\sigma_m}{\bar{\sigma}} \right) d\varepsilon,$$  \hspace{1cm} (2)
The type of the finite element analysis is elasto-plasticity analysis. The flow stress of the material was measured by column compression experiment. The shear friction coefficient is constant at 0.03. The part’s dimensions before forward extrusion are total length 310.5 mm, outer diameter $\phi 46.2$ mm, and inner diameter $\phi 31$ mm. The deformed shape error was within ±1.0 mm between the analysis results and experimental results after forward extrusion. Therefore, the deformed shape has been calculated with high accuracy.

However, the damage factor does not match the real ductile fracture. Fig. 3 shows the calculation result of Eqs. (1) and (2). We used $a = 0.2$ in Eq. (2) (the material constant). Whatever this value was changed to, there was no difference in the position of the distribution.

2.2. Problem of conventional ductile fracture method

The changes of stress and strain at the parts of high damage factor were tracked in Fig. 3. Fig. 4 and Fig. 5 show the results of the stress components and strain components. In the extrusion of the hollow shaft, the inner diameter is reduced, and the strain component of the $\theta$ direction is compressed. In Fig. 4, the strain component of the $\theta$ direction is represented by reversing the sign from minus to plus. At large increments of the von Mises equivalent strain (at the stroke 20 mm), the damage factor increases, because Eq. (1) includes $\psi$ strain. The strain of the $\theta$ direction and the equivalent strain are very similar in Fig. 4, and the increase of the equivalent strain corresponds to the $\theta$ direction. Also, as shown in Fig. 5, the max principal stress corresponds to the $z$ direction.

As stated above, the value of the damage factor is high because each different direction of the strain components and stress components are high. The conventional ductile fracture method can be applied to a simple deformation,
where each direction of stress and strain is same. But in a complex deformation, such as the actual part, it may not be applied.

3. New ductile fracture prediction method

3.1. New equation of ductile fracture prediction

The conventional prediction equation is expressed by multiplying the equivalent strain and stress. The author’s prediction equation is expressed by multiplying strain components and stress components that are in the same direction.

\[ D_f = \int \frac{\sigma_i}{\sigma} d\varepsilon_i, \quad (3) \]

In the conventional method, the increment of equivalent strain is a scalar quantity, and it is possible to predict the position of the ductile fracture, but the direction of the ductile fracture cannot be predicted. However, in the proposed method, it is possible to predict the direction of the ductile fracture by finding a component that is high.

By using the commercial forging software, DEFORM, and the User Subroutine function, the Eq. (3) was incorporated, and the damage factor was displayed. Fig. 6 shows the difference between the conventional method and the author’s method. The \( i \) component of Eq. (3) is the \( \theta \) direction in which ductile fracture occurs. By using our method, high damage values are matched to fracture of real parts.
3.2. Threshold of damage factor

The threshold of the damage factor, which is calculated by the ductile fracture prediction equation, is different according to the type of material and heat treatment method. In the forward extrusion of Fig. 1, the size of the damage factor can be controlled by changing the cross-sectional reduction rate. The prototype of the same shape as the simulation was forged. And the threshold value of the damage factor, at which ductile fracture occurs, was specified. By using different types of heat treatment, A and B, the threshold of damage factors was identified. Fig. 7 shows the changes in the damage factor of the part where ductile fracture has occurred.

In the heat treatment type A, ductile fracture occurs in the extrusion of the first stage. Ductile fracture was not seen at a damage factor of 0.4. However, ductile fracture occurs in 10% at a damage factor of 0.5. Therefore, the threshold of the damage factor was identified as 0.4 in the heat treatment type A. In the heat treatment type B, ductile fracture occurs at the extrusion of two stages. The threshold of the damage factor was identified as 1.4. In the heat treatment type B, the cross section reduction rate can reach 46%.

Fig. 8 shows the microstructure observations after the heat treatment. The heat treatment type B structure was a ferrite-pearlite microstructure. However, the heat treatment type A structure was a cementite microstructure. It is assumed that ductile fracture occurs at a low damage factor, because the cementite microstructure is brittle and has low ductility. Making a database of damage factor thresholds enables the application to other die designs. To enhance the database is a challenge for the future.
4. Forging tests of actual parts

Using ductile failure prediction, the authors designed the die to make the prototype. The material is S48C. Annealing, shot blasting, and phosphate coating were performed before the backward extrusion. The heat treatment B (Fig. 7) and phosphate coating were performed before the forward extrusion. Using a 1,600 ton hydraulic press, the average press speed was 45 mm/sec. Fig. 9 is the picture of the actual parts. The average of forging load (5 samples) was 238 tons for the backward extrusion, and 106 tons for the forward extrusion. The ratio L / D (the inner diameter D, the indentation depth L) reached 8.0 upon backward extrusion. As the number of the damage factor is below the threshold, the ductile fracture did not occur.

5. Conclusion

For more complex shapes, such as real forged parts, the conventional ductile fracture prediction may not be applied. Therefore, we proposed a new prediction equation which is expressed by multiplying strain components and stress components that are in the same direction. In the forward extrusion of hollow shaft, real fracture and simulation results can be matched.

For the damage factor calculated in the ductile fracture prediction equation, it has been found that the threshold of the ductile fracture is different according to the type of heat treatment. To widen the application of this method, the database of the damage factors will be required to be expanded.

References