 Fundamental Characteristics of Work Deformation and Forging Load by High-Speed Large-Reduction Forging — Production Technology for Fine Grained Steel by Large Deformation Forging I —

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A high-speed large-reduction forging technology has been developed to improve the hot strip production process. This technology can be used to produce fine-grained steel by enhancing the dynamic recrystallization caused by high strain. And it has specific features in width deformation caused by intermittent and large deformation. In this paper, laboratory-scale experiments and FE analysis are carried out to clarify the fundamental characteristics of the deformation and stress field. Large reduction results in a large width spread, and intermittent working causes periodic width deviation. The influences of die shape, the amount of feed per pass and the aspect ratio of the width against the thickness of the initial works on width spread and deviation are discussed. Large forging load results in a chevron-like indentation profile of the die surface and produces a thickness profile of the work.  

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1. Introduction

Demands for improve fuel efficiency in transportation equipment such as automobiles have increased in recent years in response to rising environmental consciousness. This requires higher strength steels, which make it possible to reduce vehicle body weight while also enhancing collision safety. Solid solution, precipitation and phase transformation strengthening by adding alloy elements have been used to increase steel strength. As another approach, numerous researches of grain refinement by new thermo-mechanical processing techniques have been conducted with the aim of reducing consumption of valuable alloy elements.\(^1\)–\(^4\) However, from the industrial viewpoint, many issues in connection with production methods for these high strength steels remain to be solved.\(^5\)–\(^7\) Large rolling loads are inevitable in this kind of thin strip rolling because it is conducted under a low temperature condition around transformation from the austenite phase to the ferrite phase in the finishing mill. Moreover, the amount of reduction which is possible with a single rolling pass is restricted by the biting limit.

In previous work, the authors proposed a new forging technology having no biting limit in the roughing process of the hot strip mill to realize large reduction with a single pass.\(^8\) This is based on the idea that austenite grain refinement by large reduction in the roughing process, while in the high temperature region, promotes grain refinement by rolling load reduction in the finishing process. The sizing press machine, which enables slab width reduction of hot slabs has long been used in practical operation,\(^9\) but no slab thickness reduction technology by forging has been reported for hot strip production. Therefore, deformation characteristics, which have a large influence on grain refinement behavior, and forging load characteristics, which are important from the viewpoint of practical application, are not known.

In this paper, the deformation and load characteristics of intermittent large reduction forging with over 60% reduction are investigated by laboratory experiments using a model material and FE analysis.

2. Experimental and Analytical Methods

2.1 Experimental method

Figure 1 shows a schematic diagram of the die shape and experimental procedure. Hydraulic compression equipment with the maximum load capacity of 2.5 MN was used. The dies were mounted on a fixed bottom ram and a top ram which can move in the vertical direction. The working surface of the dies has a flat part and a slope part. In this research, slope angles of the dies \(\theta\) were 12, 20 and 30\(^{\circ}\), reduction \(r\) was 60 or 80\% and feed per pass \(f\) was varied from 10 to 50 mm. The surfaces used to examine the influence of the frictional condition on the forging surface of the dies were a milled surface (Smooth die: surface roughness \(Ra\ 0.5–1.0\ \mu m\, abbreviated\ S-die) and a shot-blasted surface (Rough die: surface roughness \(Ra\ 10\ \mu m\, abbreviated\ R-die)). The work size was 32 mm in thickness \(\times\) 40–200 mm in width \(\times\) 200 mm in length (1/8 of actual size). A hard lead
alloy was used as a model material to simulate the deformation of hot steel. The die material was S45C. The first contact length between the die flat part and the work head \(L_0\) was 10 mm, after which the work was fed downstream by a certain amount \(f\) during each inter-pass until the whole work was pressed. The work was fed by a pusher.

### 2.2 Analytical method

The commercial FEA software Abaqus-explicit was used to examine the internal stress-strain field of the work in the proposed forging technology. Assuming symmetry, a 1/4 cross-sectional region was modeled, and large deformed areas such as the width edge and top surface were divided into fine meshes (5 meshes in the thickness direction and 10 in the width direction). To examine the influence of friction between the die surfaces and the work, the friction coefficient \(\mu\) was changed from 0.15 to 0.4. Table 1 shows the analytical conditions. The flow stress curve of the hard lead material was measured by a uni-axial compression test and formulated as a function of strain and the strain rate. A forging analysis with inter-pass feed from the work head up to 5 passes was carried out in accordance with the experimental procedure shown in Fig. 1.

### 3. Experimental Results and Discussion

#### 3.1 Basic characteristics of deformation and forging load

Figure 2 shows an example of the top view of the forged work (work width 150 mm, R-die, \(\theta = 12^{\circ}\), \(r = 60\%\) and \(f = 30\) mm). In non-steady deformation regions such as the head and tail of the work, a flare shape is formed by width spread in a manner similar to that in rolling. In the steady-state deformation region, periodic width and thickness fluctuations caused by intermittent working are observed.

Figure 3 shows the relationship between feed and maximum load at BDC (bottom dead center). The analytical results are also shown in the plot in order to discuss the influence of friction. Comparing the experimental and analytical results, the friction coefficient can be estimated to be 0.3 to 0.4 with the R-die and 0.15 to 0.3 with the S-die in 60 and 80% reduction, respectively. The lead material has low friction coefficient characteristics, while the R-die, the surface of which was roughened by shot blasting, may represent the hot working condition.

Figure 4 shows an analytical result of vertical stress \(\sigma_l\) in the longitudinal direction on the contact surface and center of thickness at the width center \((\theta = 12^{\circ}\), \(r = 60\%\), \(f = 30\) mm and \(\mu = 0.3\)). \(\sigma_l\) increases from 40 MPa, which corresponds to the yield stress at the boundary between the non-deformed area and the contact area with the slope part of the dies, reaches a maximum value, and then decreases rapidly toward the end of contact on the downstream side. This vertical stress distribution is called a “friction hill”, and grows under the condition of high friction and long contact length between the dies and work in comparison with the average work thickness on the inlet and outlet sides. This result shows that friction has a large influence on the forging load in this working technology.

### Table 1 Analytical conditions.

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus/GPa</th>
<th>Poisson’s ratio</th>
<th>Flow stress/MPa</th>
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<tr>
<td>Die</td>
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<td>206</td>
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<td></td>
<td></td>
<td>0.3</td>
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<td>Work</td>
<td></td>
<td>25</td>
<td>37.0,0.15,0.042</td>
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<td></td>
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<td>0.44</td>
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Fig. 2 Plan view example of pressed specimen.

Fig. 3 Influence of friction coefficient and intermittent feed on press load (experimental and FEM results).

Fig. 4 Vertical stress distribution on the contact surface and thickness center by large reduction forging.
3.2 Discussion of the width spread and its variation characteristics

To examine the width spread characteristics of this working technology, the relationship between the width profile after forging and the contact condition during forging was examined. Figure 5 shows a comparison of the measured width profiles after complete forging and after an intermediate pass. Width spread is formed with reduction in region I, where the work is in contact with the die slope part, and a convex width profile is formed in region II, where the work is in contact with the die flat part.

Figure 6 presents the definitions of parameters such as the initial width of the work \( W_0 \), the minimum width after forging \( W_I \) and the width deviation \( \Delta W \). These parameters are used to discuss the width spread behavior quantitatively. As shown in Fig. 7, forging behavior is classified into type (a) and type (b) based on the geometrical relationship between the geometrical contact length with the slope part of the dies \( L_s \) and the inter-pass feed \( f \). In type (a), inter-pass feed \( f \) is smaller than the contact length between the slope part of the dies and the work \( L_s \), thus the slope part of the work is in contact with the flat part of the dies. Conversely, when the inter-pass feed \( f \) is larger than \( L_s \) in type (b), the non-deformed flat part of the work is in contact with the flat part of the dies. Considering the width spread behavior in the forged areas I and II in Fig. 5, minimum width spread \( \Delta W \) \((W_I-W_0)\) was related to \( L_s \), and the convex width deviation \( \Delta W_I \) was examined in conjunction with the geometrical pressed area by the flat part of the dies \( S_f \).

Figure 8 shows the relationship between \( L_s \) and \( \Delta W_f \) \((f=10-50\text{ mm})\). Width spread is substantially proportional to the contact length with the slope part of the dies regardless of the die angle. As in rolling, width spread in the high frictional condition with the R-die is larger than that with the S-die. Because the material flow on the contact surface is restricted by frictional force, and as a result, bulging deformation grows around the width edge region. Although the defined contact length \( L_s \) is not affected by inter-pass feed \( f \) under the same reduction, width spread increases with inter-pass feed. A small amount of width spread also occurs in area II in Fig. 5 because larger inter-pass feed rates lengthen the contact area, and this has a slight effect on width spread behavior.

Figure 9 shows the relationship between the amount of convex width deviation \( \Delta W_f \) and the geometrical pressed area by the flat part of the dies \( S_f \). With all die angles, \( \Delta W_f \) depends on \( S_f \), and the R-die with the high friction coefficient causes large width spread. In the area pressed by the flat part of the dies, width spread is restricted by the neighboring deformed area I on the upstream side and non-deformed area III on the downstream side. As a result, the width spread profile becomes a convex shape which has a maximum value at the center of area II in the longitudinal direction.

Figure 10 shows the influence of the initial work width \( W_0 \) on width spread \( \Delta W_f \) and \( W_0 \). It can be seen that the amounts of both width spread and width deviation decrease when \( W_0 \) increases. To discuss the relationship between the longitudinal strain and lateral strain which are generated by thickness reduction, two parameters were defined, as shown in eqs. (1) and (2).

\[
R_L = \frac{\varepsilon_L}{\varepsilon_T} = \frac{\ln(L_f/L_0)}{\ln(f_0/f_1)}
\]

\[
R_W = \frac{\varepsilon_W}{\varepsilon_T} = \frac{\ln(W_f/W_0)}{\ln(f_0/f_1)}
\]

\( \varepsilon_L, \varepsilon_T \) and \( \varepsilon_W \) represent strain components in the longitudinal, thickness and width directions, respectively.
and \(t\) are the length and thickness of the work. And the subscript 0 and 1 are the conditions before and after forging, respectively. \(R_L\) and \(R_W\) show the ratio of strain converted into the longitudinal and lateral directions from the thickness direction.

In Fig. 11, the horizontal axis shows the ratio of the initial work width to thickness, and the vertical axis shows \(R_L\) and \(R_W\). Under the same forging condition, the longitudinal elongation component becomes larger and width spread becomes smaller as the initial work width increases. \(R_L\) and \(R_W\) are almost saturated in the width range over 5 times the thickness. This is because the deformation restriction in the width direction by the neighboring non-deformed area becomes larger as the work width increases, and the plane strain condition expands except at the width edge region.

### 3.3 Thickness profile and its variation characteristics

Figure 12 shows the thickness profiles in the longitudinal direction at the width center, quarter position in the width direction and 10 mm from width edge (R-die, \(\theta = 12^\circ\), \(r = 60\%\) and \(f = 30\) mm). Periodic fluctuations can be seen, corresponding to the inter-pass feed distance. Figure 13 is a thickness profile in the width direction at the position A–A’ in Fig. 12. In addition to the experimental results, the plot also shows the analytical results at BDC, where the forging load reaches its maximum, and the unloaded condition, when the dies separate from the work (friction coefficient: 0.3).

Figure 14 depicts the contact pressure distribution on the die surface calculated by FEM. The contact pressure forms a cone-shaped distribution with its vertex at the center of the contact area. The flattening profile of die surface, which is caused by this pressure distribution decides the shape of the convex thickness profile.
The thickness profile of the work is formed by transcription of the die surface shape. Thus, a convex-shaped thickness profile with its maximum value around the width center and periodic fluctuations in the longitudinal direction are generated in this forging process.

4. Conclusions

In this paper, the deformation and load characteristics of a proposed intermittent large reduction forging technology which enables large deformation in a single pass are discussed, aiming at grain refinement and compactification of the roughing process in a hot strip mill. The results are shown below:

1) In this forging technology, large pressure (working load increase) is generated by friction because the contact length between the dies and work is large relative to the average thickness of the work.

2) Large width spread due to large thickness reduction and periodic thickness fluctuations due to intermittent working are generated. These behaviors can be characterized by the die shape, thickness reduction and feed conditions.

3) A convex-shaped thickness profile is formed in the width direction. This is explained by the fact that the variation of width spread under large thickness reduction generates a longitudinal tension distribution, and this causes a cone-shaped pressure distribution which deforms the die surface into a concave flattened shape.

REFERENCES


