Development of Load Reduction Technology by Swing-Type Forging and Lubrication for Large-Deformation Forging by High-Speed Large-Reduction Forging —Production Technology for Fine Grained Steel by Large Deformation Forging II—

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To reduce the forging load of the proposed large deformation forging technology, a new type of forging system is proposed. In this forging system, the contact length between forging dies and a work can be reduced by adjusting the swing motion of the dies during forging. This swing motion results in load reduction because contact length is a dominant factor of the load for this type of forging. Also, this forging technology is relatively stable when using lubrication because of its basic up-and-down motion. In this study, load reduction effect with the newly proposed forging system and lubrication are examined by laboratory-scale experiments and FE analysis. It appears that a nearly 30% load reduction is confirmed and seizure on the forging dies was prevented by lubrication.

Keywords: forging, large deformation, large reduction, fine grained steel, hot strip, lubrication

1. Introduction

The authors proposed a new forging technology having no biting limit in the roughing process of the hot strip mill in order to realize large reduction with a single pass with the aim of downsizing the roughing process and grain refinement of steel strips. In a previous paper, we clarified the deformation and load characteristics of the proposed technology. The contact pressure between the die and work increases sharply by frictional force, causing growth of a so-called “friction hill” and this may require an extremely large forging load in single pass working of a slab. Thus, the forging load must be reduced in order to realize the proposed forging technology.

Forging has high flexibility in die shape and working conditions, e.g., the forging load can be reduced by optimizing the inter-pass feed. However, if forging is used in a mass production hot rolling process for steels, it is essential to reduce the forging load without sacrificing high productivity. Lubrication is widely applied to reduce the rolling load in hot strip mills, but excessive lubricity leads to slippage, causing biting failure in strip head threading. In contrast, because the proposed technology uses a vertical forging motion, stable working with high lubrication is possible. Lubrication is very effective not only for reducing the rolling load but also for preventing seizure and wear, and thus is also important from the viewpoint of tool life.

In this paper, a swing type forging technology aiming at load reduction is proposed for practical application. Deformation and load characteristics are clarified by laboratory experiments and FE analysis. The load reduction effects and seizure prevention effects of lubrication are also discussed.

2. Load Reduction Technologies for Large Reduction Forging

2.1 Load reduction technology by innovative forging motion

In the proposed forging technology, maximum forging load occurs at the bottom dead center (BDC), as the material is basically reduced by vertical motion. The forging load can be expressed simply by eq. (1).

\[ P = Q_{p} \cdot k_{m} \cdot l_{d} \cdot W \]  

Where \( Q_{p} \) is a load function which expresses the pressure increase by friction, \( k_{m} \) is mean flow stress, \( l_{d} \) is the contact length between the dies and work and \( W \) is the work width. In eq. (1), the forging load changes in proportion to the contact length between the dies and work \( l_{d} \). This means the forging load can be reduced by shortening \( l_{d} \). Considering this relationship, we proposed a new method in which the forging load is reduced by pressing with die rotation under the same feed \( f \). Figure 1 shows the basic concept of the flying type motion, which, was proposed in the previous paper, and the

![Fig. 1 Basic concept of swing type forging; (a) Flying type motion (b) Swing type motion.](image-url)
newly-devised swing type motion. In the flying type motion, the contact length \( l_d \) at BDC is \( l_d = L_d + L_s \), while \( l_d \) becomes only \( L_d \) in the swing type motion because the slope part of the die is forced to separate from the work by die rotation (rotation angle \( \phi \)) during forging. Thus, with the proposed swing type forging method, the forging load \( P \) can be reduced by shortening the contact length \( l_d \) at BDC.

Figure 2 shows a schematics diagram of the width spread behavior in large reduction forging. In the previous paper, we showed that the minimum width spread \( \Delta W (= W_f - W_0) \) can be expressed by the geometrical contact length with the slope part of the die at BDC \( L_s \). Width spread can be reduced in the swing type forging because the contact length \( l_d \) is decreased by the die rotation in the initial stage of forging.

As mentioned above, the forging load and width spread can be reduced by swing type forging because the contact length between the dies and work is shortened. Next, we constructed a new high-speed large-reduction forging device which enables intermittent working of the whole work and conducted forging experiments for verification.

2.2 Outline of experimental equipment

Figure 3 shows the pressing mechanism, die orbit and die shape of the newly-developed forging equipment. In flying type forging (Fig. 3(a)), forging is performed by the eccentric motion of crankshafts which are connected to the top and bottom sliders and driven in the same phase while keeping the flat part of the die parallel. The radius of the eccentric motion is 13.5 mm. In swing type forging (Fig. 3(b)), the dies move in oval orbits with self-rotation at a certain angle which is generated by the motion of two connected sliders with attached crankshafts that are driven in different phases. The die rotation angle is 9.2°. Considering the rotating motion of the dies, the dies have four-step slopes on the flat part of the working surface to minimize the thickness deviation of the work after forging. Feed per forging pass is controlled by the motion of pinch rolls located at the entry side and exit side of the dies. The maximum load is 1.5 MN, motor power is 75 kW and forging speed is 100 cycles per minute. These specifications are common to the flying type forging device.

2.3 Experimental conditions

To verify the load characteristics of the swing type forging device, forging experiments were performed using hard lead containing 0.9 at% antimony. The die material was 40CrMoV5 tool steel, and the working surface was finished using a milling machine. The work size was 25.4 mm in thickness, 100 mm in width and 1000 mm in length, corresponding to one-tenth of the industrial size. Although the aimed reductions in thickness \( r_s \) were 50 and 70%, the actual reduction became 43 and 65% respectively, due to the elastic deformation of the forging machine and dies. Feed per pass was set in the range from 25 to 50 mm, and a lubricant was not used in this experiment.

2.4 Experimental results and discussion

2.4.1 Load reduction effect

Figure 4 shows the forging load variation of the two forging methods under the condition of 40 mm feed per pass. Small deviations exist in the maximum forging load of each forging pass, but because the change from the head end to the tail end of the work was negligible, the average value of the maximum load in each forging pass was evaluated. A large load reduction effect was confirmed with swing type forging, as the forging load was reduced by 30% (590 kN \( \rightarrow \) 390 kN) in comparison with flying type forging.
Fig. 5 Behavior of forging load history of flying type forging and swing type forging ($r_a = 43\%$, 65\%, $f = 40$ mm).

Fig. 6 Comparison of forging load between flying type forging and swing type forging versus feed per pass.

Figure 5 shows a typical forging load transition during a single forging motion. In flying type forging, the contact length between the dies and work increases in proportion to the contact time during forging, which means the forging load increases linearly up to BDC and then decreases sharply thereafter. In contrast, in swing type forging, the forging load rises slowly and then decreases gradually after passing the maximum load point due to the self-rotation of the dies.

Figure 6 shows the influence of feed pitch on forging load (actual reduction $r_a = 65\%$). In the plot, the symbols $\triangle$ and $\blacktriangle$ show experimental results, and solid lines show the results of numerical analysis using the commercial FEA software Abaqus-explicit. The mechanical properties used in the analysis are shown in Table 1, and the pressing orbit of the experimental equipment was replicated faithfully in the analysis. As shown in Fig. 6, the analytical and measured forging loads show good agreement in the case where the frictional coefficient between the dies and work is 0.22. The forging load in swing type forging is reduced greatly compared to that of flying type forging. In the analytical results, the load reduction effect decreases slightly at a large feed pitch. This tendency can be explained by the magnitude of the contact length in Fig. 1. That is, as the feed pitch $f$ (= $L_d$) increases, the ratio of the contact length of slope part of the dies $L_a$ to the total contact length $L_d + L_a$ decreases and this results in a decrease in the load reduction ratio.

2.4.2 Width spread behavior

Figure 7 shows the influence of feed pitch on minimum width spread $\Delta W$. In swing type forging, width spread is smaller than that in flying type forging, and this effect becomes larger as the feed pitch is increased. This is because width spread during forging is suppressed by the constraint from the non-deformed area, which means that width spread decreases as the contact length $L_d$ decreases. In flying type forging, the contact length $L_d$ increases in proportion to the feed pitch $f$, whereas, in swing type forging, the influence of the feed pitch on the contact length $L_d$ is small because the contact area is kept short by die rotation.

3. Load Reduction Characteristic by the Application of Hot Lubrication

3.1 Experimental procedure

To achieve a further load reduction in swing type forging, lubrication was applied to the forging dies during an experiment using hot steels. The experimental procedure is shown in Fig. 8. The work temperature was measured at the longitudinal center position by a thermocouple inserted through a hole drilled from the width edge surface to the
width center position at the thickness center. The work was heated to 1473 K in a furnace. After extraction and air-cooling for about 1 min, forging of the work was started when the work temperature reached 1323 K, and the whole work length was forged completely. In this condition, the temperature of the longitudinal center part of work reached around 1273 K during forging. Lubricant was sprayed continuously on both the top and bottom die surface from the downstream side by air atomizing at a pressure of 0.4 MPa.

The influence of the lubricant on die temperature was investigated from the view point of die life, i.e., seizure resistance and wear resistance. To measure the die temperature reached 1323 K, and the whole work cooling for about 1 min, forging of the work was started when the work temperature reached 1323 K, and the whole work length was forged completely. In this condition, the temperature of the longitudinal center part of work reached around 1273 K during forging. Lubricant was sprayed continuously on both the top and bottom die surface from the downstream side by air atomizing at a pressure of 0.4 MPa.

The influence of the lubricant on die temperature was investigated from the view point of die life, i.e., seizure resistance and wear resistance. To measure the die temperature at depth of 2, 6 and 11 mm from the working surface during forging, holes 1.2 mm in diameter were drilled 20 mm downstream from the intersection of the slope part and flat part of the top die, as shown in Fig. 9. Thermocouples (Φ1 mm) were inserted in the holes and fixed with a ceramic bond.

3.2 Experimental conditions

As our aim is to strengthen steels with a simple composition by grain refinement, Si–Mn steel (0.14%C–0.64%Mn) containing no other alloy elements was used. The work was 25.4 mm in thickness, 600 mm in width and 1000 mm in length. The actual reduction \( r_a \) ranged from 43 to 82%, and the feed pitch \( f \) was 35 mm. To evaluate the load reduction effect quantitatively as change in the frictional coefficient, finite element analysis was conducted as in the previous chapter. In the analysis, Misaka and Yoshimoto’s equation\(^5\) was used for flow stress.

Non-graphite type lubricants were used. A grease type lubricant (commercial hot rolling lubricant, 85% base oil + additives) and a soluble type lubricant (commercial mold lubricant for hot forging, 50% water + additives) were chosen. The feeding rate of the grease type lubricant was 100 cc/min. With the soluble type, the feeding rate was 160 cc/min and two concentration levels (10 and 50%) were used.

3.3 Experimental results and discussion

3.3.1 Load reduction effect

Figure 10 shows the forging load with the reduction \( r_a \) of 72% (no lubricant). In the hot forging experiments, the work temperature around the tail end decreases due to the longer waiting time after the start of the forging experiment and this leads to a gradual increase in the forging load. For this reason, the forging load at the longitudinal center position where the work temperature was monitored with a thermocouple (work temperature was around 1273 K) was chosen as the base condition of the evaluation.

Figure 11 shows a comparison of the analytical and measured forging load. The frictional coefficient of 0.24 corresponds to the no-lubricant condition which exhibits the 1060 kN forging load. In the following, the load reduction ratio \( R_p = (P_0 - P)/P_0 \times 100% \) is defined using the calculated forging load \( P_0 \) obtained for the frictional coefficient of 0.24.

The load reduction ratio calculated from the forging load \( P \) in experiments with and without the respective lubricant is shown in Fig. 12. The load reduction ratio increases with thickness reduction in both the experiments and analyses. This is because the pressure increase due to frictional force increases under large thickness reduction, so the decrease in
frictional force by lubrication has a large effect on forging load reduction. The load reduction effect of the grease type lubricant was larger, and a load reduction ratio of about 30% was achieved under the condition of large thickness reduction, which corresponds to the frictional coefficient of 0.12. With the soluble type lubricant, the influence of the lubricant concentration was not clear, but a load reduction ratio of 20% was achieved with the concentration of 10% under the condition of large reduction. It is considered that the grease type lubricant exists on the contact surface as a thin film during forging. However, the soluble type lubricant evaporates on the hot die surface, and then dried additives form a thin film that acts like a solid lubricant.

3.3.2 Suppression of die temperature rise

Figure 13 shows the measured die temperature with the grease type lubricant and the soluble type lubricant with 10% concentration. With grease type lubricant, the die internal temperature almost coincides with that of the no-lubricant condition, but with the soluble type lubricant, die temperature 2 mm below the working surface decreases about 70 K. It is considered that both lubricants have very small effect on the suppression of frictional heat generation, but the soluble type lubricant has a large die cooling effect due to its moisture content.

3.3.3 Seizure prevention effect

Figure 14 shows photographs and the measured surface profiles of the dies after a forging experiments without lubricant, with the grease type lubricant and with a 10% concentration of the soluble type lubricant. These surface profiles were measured by a surface roughness meter before and after forging experiments (machined finish surface) with a single workpiece. In the no-lubricant condition, bad seizures were observed on the working surface of the dies at a large thickness reduction, but no clear seizures were observed in the experiments with lubricant. The contact pressure is reduced by applying lubricant and a strong thin film of the grease type lubricant seems to prevent the occurrence of seizures. With soluble type lubricant, both the solid lubricant film formed from the additives and the temperature drop due to die cooling are effective for preventing seizure, whereas simply spraying water on the working surface has little effect in seizure prevention.

4. Conclusions

In this paper, the effects of newly-proposed swing type forging method and use of hot lubrication were examined as load reduction methods for high-speed large-reduction forging. The results are summarized below.

(1) In comparison with flying type forging with the proposed swing type forging method, load reduction ratios of 20–30% were achieved in the large-reduction region. Width spread caused by large thickness reduction was also decreased.

(2) By applying a grease type lubricant, a load reduction effect of more than 25% was achieved in the large reduction region. When the grease type lubricant was used in combination with swing type forging, the load reduction effect exceeded 45%.

(3) By applying a soluble type lubricant with 10% concentration, a load reduction effect of about 20% was achieved in the large reduction region. When the soluble type lubricant was used in combination with swing type forging, a load reduction effect of more than 40% was achieved.

(4) Seizures were reduced to a large degree by applying lubricant. In addition, elevated die temperature can be reduced by applying a soluble type lubricant.
The austenite grain refinement effects of the proposed high-speed large-reduction forging technology will be reported in a next paper.

Acknowledgements

The authors wish to express sincere gratitude to Mr. Takashi Nishii and Mr. Yasushi Dodo of IHI Corporation for their corporation in the design of the forging equipment.

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