1. Introduction

Open die forging is a metal forming method by which materials are pressed between flat or simple contour dies, such as V-dies and swage dies. It has been extensively used to manufacture large bulk products, such as crankshafts, spindles, back up roll, rotor shafts, among others. Knowledge about microstructure evolution during hot forming is the key technology to optimize grain size and mechanical properties of forged product. Metal forming processes such as rolling, forging and extrusion exhibit complicated three-dimensional deformations, and they are closely related to grain size distributions in austenite phase. Reliable analytical method to predict microstructure evolution as well as plastic deformation is strongly requested to optimize forming conditions to get products with acceptable geometry and mechanical property. A lot of researches have been made with aims to analyze microstructure evolution during hot forming. However, most of them have been focused on the hot rolling process\(^1\)–\(^3\) and only a few reports have been presented about forging process.\(^4,5\)

Microstructure evolution in hot bar stretching, in which strong inhomogeneous plastic deformation takes place, is investigated in this paper. Incremental formulations for the change of microstructure in austenite phase are coupled with three-dimensional rigid-plastic FEM for the analysis of transient change and cross-sectional distribution in plastic deformation. Through investigation, it has become clear that transient change in microstructure is very rapid with higher amount of plastic deformation. Microstructure analysis using incremental approach with three-dimensional finite element analysis for plastic deformation is helpful to evaluate rapid change in cross-sectional grain size distribution after hot bar stretching.

KEY WORDS: numerical analysis; hot bar stretching; microstructure analysis; finite element method; recrystalization.

2. Experimental Procedure

2.1. Dies and Materials

Complicated three-dimensional deformation occurs in materials under hot forming, and inner microstructure such as grain size is affected by an amount of plastic deformation. Figure 1 illustrates dimensions of dies and material in hot bar stretching investigated in this paper. Plastic strain distributions in the deformation zone, and it will affect the
progress of recrystallization. Austenite grain size distribution resulting from plastic deformation is measured at predetermined zones A, B and C (please see right of Fig. 1).

The chemical composition of the round bar steel used in these experiments is shown in Table 1. SC20 mild carbon steel is chosen in this study in order to reduce the effect of alloying elements in the recrystallization process. As recrystallization kinetics for mild carbon steel were consistently clarified, theoretical investigation about the effect of plastic deformation on grain refinement is possible for hot bar stretching of mild carbon steel.

2.2. Controlled Quenching System

Rapid controlled quenching system is newly developed to freeze the recrystallized austenite grains just after deformation. It is intended to control different delay time (duration between the end of forging and the start of quenching) and could be easily operated. Effect of forging reductions and delay time on the recrystallized austenite grain size could be easily followed. The deformed metal can be quenched at pre-determined delay time with the average cooling rate of 750 K/s from 1273 K, and 2000 K/s from 873 K. Figure 2 shows the controlling system of rapid quenching system. The control process consists in using a displacement sensor (X0) to detect the movement of the bottom die. This electrical signal is used to trigger a timer device (T0) of the PLC (Programmable Logic Controller). Duration of the timer T0 depends of the required delay time. It means that T0 controls the delay time to energize a second timer device (T1), which automatically energizes two electromagnetic induction valves (Y10) installed in water supply system. Delay time is controlled changing T1 by personal computer. Time necessary for the water to reach workpiece after inflated from the valve is compensated to send signal T1 to PLC from personal computer. Water from the tank is supplied to the nozzles by a magnet pump at a pressure of 0.9 kg/cm² and 15 l/min. Figure 3 shows hot compression testing machine with controlled quenching system. Cooling curves obtained by controlled quenching system are shown in Fig. 4. Dimension of specimen is shown in Fig. 1. Quenching has started at the end of forging, which is around 0.1 s after the start of forging. It is clear that faster cooling rate is attained by controlled quenching system than immersion into water, because spray water blows the vapors at workpiece surface.

Table 1. Chemical composition of SC20 steel used for experiment.

|   | C   | Si  | Mn  | P   | S   | Cu  | Cr  |
|---|-----|-----|-----|-----|-----|-----|-----|
| wt.%| 0.19| 0.20| 0.40| 0.019| 0.011| 0.16| 0.11|

Fig. 2. Controlling system for rapid quenching.

Fig. 3. Hot compression testing machine with controlled quenching.
2.3. Experimental Conditions

Table 2 shows the experimental conditions, and Fig. 5 shows the heat treatment curve in hot bar stretching. Before hot deformation, the workpiece was normalized to 1143 K for 1 h and cooled by air. Then, the specimen was reheated in an induction furnace to a temperature of 1473 K at a heating rate of 40 K/s and holding time of 20 min. This heat treatment resulted in uniform grain size of 80 μm before hot deformation. Then, the specimen was transported into the compression machine to deform it at the predefined forge reduction in diameter (56%) at vertical strain rate of around 10 s⁻¹. Specimen is fast cooled with the delay time of 0.01 s, 0.1 s, 0.3 s, and 2.5 s. To reveal the austenite grain size, saturated aqueous picric solution with 30 drops of concentrated HCl and a wetting agent as surface active reagent (sodium dodecylbenzen sulfonate) was used. Average linear-intercept grain size was measured using the method described in the ASTM E112 standards. In order to reconfirm accuracy in the austenite grain size measurements, the grain size for the same micrograph was measured independently by two persons. The discrepancies were verified by recounting again the intercepts.

### Table 2. Experimental and analytical conditions.

| Condition                  | Value       |
|----------------------------|-------------|
| Flow stress (MPa)          | 90 MPa      |
| Die velocity (mm/s)        | 10 mm/s     |
| Friction coefficient       | 0.3         |
|Forging temperature         | 1453 K      |
|Forging reduction (%)       | 56%         |
|Workpiece’s diameter (mm)   | 13 mm       |
|Width of the bar (mm)       | 7.8 mm      |
|Edge die radius (mm)        | 1.04 mm     |
|Delay time(s)               | 0.01, 0.10, 0.3, 2.5 |

3. Analytical Procedure

General construction of analysis for the evolution of microstructure is shown in Fig. 6. First, strain rate distribution is calculated by using COPRESS System which is a three dimensional FE code.\(^6\) Figure 7 shows the FE mesh after hot bar stretching. A half volume of bar is illustrated in Fig. 7 to show the deformation zone clearly, but the numerical analysis has been made for the one-eighth part of the bar. The discretized model includes 2720 elements interconnected at 3465 nodal points for one-eighth part of the round bar. Strain rate distribution for every integration points in FE analysis (there exit eight integration points for one finite element) are transferred to incremental formulations for the evolution of microstructure.\(^7\)\(^8\) Temperature is assumed to be uniform in deformation analysis and microstructure analysis. Then analytical values with respect to plastic deformation and grain size distribution may include errors because heat transfer to anvils and heat generation during deformation is neglected in the analysis. More accurate analysis may be possible if we couple temperature analysis, but basic characteristics in grain size distribution resulting from inhomogeneous plastic deformation could be analyzed and discussed.

Hot forming experiment is conducted by using hot compression machine in which anvil is driven mechanically by cam. Cam profile used for experiment was designed to assure constant vertical strain rate of 10 s⁻¹ when initial workpiece height is 13 mm. Transient change in die velocity driven by cam is shown in Fig. 8. Numerical analysis was made under constant anvil speed shown in Fig. 8 as the difference in grain size for the change in transient anvil speed is relatively small. It should be noted that distribution in plastic deformation and grain size distribution may include errors because heat transfer to anvils and heat generation during deformation is neglected in the analysis. More accurate analysis may be possible if we couple temperature analysis, but basic characteristics in grain size distribution resulting from inhomogeneous plastic deformation could be analyzed and discussed.

Initial austenite grain size before hot forging is assumed to be 80 μm, which is the same value in experiment. Material data for the evolution of microstructure such as recrystallization kinetics, rate of recovery, rate of grain growth and work hardening obtained by Yada et al.\(^9\) are used in microstructure analysis by incremental formulations.

It is worth noting that both dynamic and static changes of microstructure are implemented in the analysis. Also, in hot forging, the strain rate distributes in a wide range in a deforming body so that static recrystallization and dynamic
Recrystallization may occur at the same instant in different regions. Then, practical parameter to judge the onset of static change of microstructure is requested to analyze microstructure evolution in hot forging. Driving force for dynamic recrystallization of austenite may be related to temperature compensated strain rate, i.e. Zener–Hollomon parameter ($Z \equiv \dot{\epsilon} \exp(Q/RT)$). We could suppose that some variations in this value during hot deformation could be associated with the suppression of dynamic recrystallization that may also be considered as the starting point for static events during deformation.

In this investigation, critical Zener–Hollomon parameter $Z_C$ is introduced to judge the onset of start static microstructure change. However, for the dead zone, critical Zener–Hollomon parameter with different value $Z_C^*$ is also introduced. Critical Zener–Hollomon parameter should be identical in whole region under analysis, but lower accuracy in the strain rate at dead zone obtained by FE analysis and the chilling of workpiece by the die may necessitate introducing the different value for the dead zone. $Z_C = 10^9$ and $Z_C^* = 3.7 \times 10^{10}$ are used in numerical analysis.

4. Results and Discussions

Table 3 shows the predicted evolution of austenite grain size and measured one at the positions indicated in Fig. 1. Microstructure evolution at the center of bar (zone A), dead zone (zone B) and transition zone (zone C) will be explained and discussed in the followings.

4.1. Transition of Austenite Grain Size at Zone A

Figure 9 shows the transition of the austenite grain size at Zone A. This zone suffers complete dynamic recrystallization during deformation as the equivalent plastic strain is bigger than 120%. From Fig. 9, fast growth of austenite grain size just after hot deformation (within 1 s) can be observed. The reason of this fast growing could be associated with the large distribution of dislocation density of the dynamically recrystallized structure, which represents a dri-
ving force for so-called post-dynamic recrystallization. This grain growth rate differs from the normal grain growth driven by grain boundary energy. After 1 s, growth rate becomes smaller which follows normal grain growth driven by grain boundary energy. Figure 9 also shows measured austenitic grain size at different delay time. We can observe that the predicted grain size and experimental measurements are agreed with each other. Figure 10 shows micrographs for the evolution of microstructure at point A. We could see that austenite grains are successfully frozen and etched by the experimental procedure shown before.

Table 3. Austenite grain size distribution at different delay time.

| Delay time (s) | Austenite grain size (μm) | Point A (Center of bar) | Point B (Dead Zone) | Point C (Transition Zone) |
|---------------|---------------------------|-------------------------|---------------------|--------------------------|
| 0.01          | Predicted                | 26.4                    | 76.0                | 58.6                     |
|               | Measured                 | 26.1                    | 70.9                | 61.3                     |
|               | (Relative difference)    | (1.4%)                  | (8.4%)              | (4.4%)                   |
| 0.10          | Predicted                | 29.6                    | 75.8                | 45.7                     |
|               | Measured                 | 27.2                    | 70.5                | 50.2                     |
|               | (Relative difference)    | (2.0%)                  | (7.5%)              | (22.8%)                  |
| 0.3           | Predicted                | 32.0                    | 68.7                | 38.0                     |
|               | Measured                 | 29.1                    | 67.1                | 52.8                     |
|               | (Relative difference)    | (10.4%)                 | (2.4%)              | (28.0%)                  |
| 2.5           | Predicted                | 47.9                    | 69.7                | 47.4                     |
|               | Measured                 | 34.5                    | 65.1                | 50.0                     |
|               | (Relative difference)    | (28.8%)                 | (6.7%)              | (5.2%)                   |

Fig. 9. Transition in austenite grain size at zone A.

Fig. 10. Microstructure obtained by experiment at zone A.

Fig. 11. Transition in austenite grain size at zone C.

Fig. 12. Transition in recrystallized fractions at zone C.
4.2. Transition of Austenite Grain Size at Zone C

Figure 11 shows the evolution of the austenite grain size at transition zone (Zone C). In this zone, because the equivalent plastic strain during deformation exceeds the critical value for the onset of dynamic recrystallization, nuclei are present in the deformed structure so that softening after deformation occurs increasingly by post-dynamic recrystallization as well as static recrystallization. Figure 11 also compares the measured grain size with the predicted grain size. Figure 12 shows recrystallized fractions at zone C. We can observe that partial dynamic recrystallization occurs in hot forming, and it is followed by classical static recrystallization.

4.3. Austenite Grain Size Distribution in Hot Bar Stretching

Figure 13 shows grain size distribution at different delay time in a longitudinal cross section on a forged round bar. Experimental values are also indicated. We can observe good agreement between experimental values and analytical values.

5. Conclusions

Microstructure evolution in hot bar stretching was investigated analytically and experimentally. Transition of austenite grains after hot bar stretching was successfully obtained by hot forging experiment with rapid quenching system. Analysis for the evolution of microstructure was made using three-dimensional FEM and incremental formulations for the evolution of microstructure. Analytical results agree well with the experimental measurements. Basic characteristics for the evolution of microstructure were made referring experimental measurements and analytical results.

FE-based analysis for the evolution of microstructure may be helpful for the innovation of hot forming technology because simultaneous optimization for the product geometry and product quality can not be made without coupled analysis of plastic deformation and microstructure. More detailed investigation into transformation, effects of alloying elements on microstructure evolution and application to hot rolling processes will be promoted on the basis of achievement shown in this paper.

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