研 究 速 報

Microstructure Simulation in Hot Open Die Forging by Using the Incremental Formulation (Preliminary Report)

熱間自由鍛造における内部組織変化（第1報）

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1. Introduction

Knowledge about microstructure evolution during hot forging is the key technology to optimize austenite grain size and mechanical properties of forged product. 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] and only a few reports have been presented about forging process.[2]

Present investigation attempts to establish an adequate microstructure simulation model for hot open die forging. In hot open die forging, strain rate distributes in a wide range so that an adequate microstructure simulation model to deal with mixed recrystallizations (static, dynamic and metadynamic recrystallizations) is indispensable. The term of critical Zener-Hollomon parameter is introduced as an indicator to distinguish static microstructure change from dynamic microstructure change. Predicted austenite grain size was compared with experimental measurements.

2. Formulation of the Mathematical Model

2.1 Plastic Deformation and Microstructure Evolution

First, strain rate and strain distribution were calculated by using COPRESS SYSTEM which is a three dimensional FE code[3].

Computational conditions to simulate the plastic deformation in hot open die forging are shown in Table 1.

The discretized model includes 2142 elements interconnected at 2800 nodal points for one eighth part of the round bar. Strain rate distribution was used as input data in the mathematical model to predict dynamic microstructural changes and static microstructural changes[4-5].

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Table 1　Hot open die forging conditions for computation

Flow stress	$\sigma = 8.5(\bar{\varepsilon})^{0.21}(\dot{\bar{\varepsilon}})^{0.13}$
Die velocity	90 mm/s
Friction coefficient	0.3
Forging temperature	1180℃
Forge reduction	56 %
Workpiece's diameter(D)	13 mm
Width of the die(W)	7.8 mm
Edge die radius(R3)	1.04
Delay Time(s)	1.3 and 2.5
Initial Grain Size (μm)	80.0

Experimental equations for recrystallization kinetics and recovery et.al for C-Si-Mn steel developed by Yada et. al[6] were used in the analysis.

2.2 Criteria to Start Static Microstructural Change after Hot Deformation.

In hot die 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.

As driving force for dynamic recrystallization of austenite may be related to Zener-Hollomon parameter ($Z = \dot{\bar{\varepsilon}} \exp (Q / RT)$), which is temperature compensated strain rate, we could suppose that some variations in this value during hot deformation could be associated with the suppression of dynamic recrystallization which may also be considered as the starting point for static events during deformation.

In this investigation, critical Zener-Hollomon parameter Zc_1 is introduced to start static microstructure change. However, especially for the dead zone, critical Zener-Hollomon parameter with different value Zc_2 is also introduced. Lower accuracy in the strain rate at dead zone obtained by FE analysis and the chilling of workpiece by the die may necessitate to introduce the second critical Z value, Zc_2. Several combinations of Zc_1 and Zc_2 were tested. The best analytical results were obtained for $Zc_1=1x10^9$ and $Zc_2=7x10^{10}$. Needless to say, more detailed investigations are necessary because only one critical Z value should be applicable to all of the deforming material.

3. Experimental Procedure

3.1 Material

The chemical composition of the steel used in the experiments is indicated in Table 2. SC20 carbon steel was chosen in this study in order to reduce the effect of alloying elements to recrytallization process.

Table 2　Chemical Composition of the S 20 C steel

	C	Si	Mn	P	S
%	0.19	0.2	0.4	0.019	0.011

The dies used to perform this experiment have a simple plane contour with a width (W) of 7.8 mm and a radius edge (R) of 1.04 mm as shown in Fig. 1.

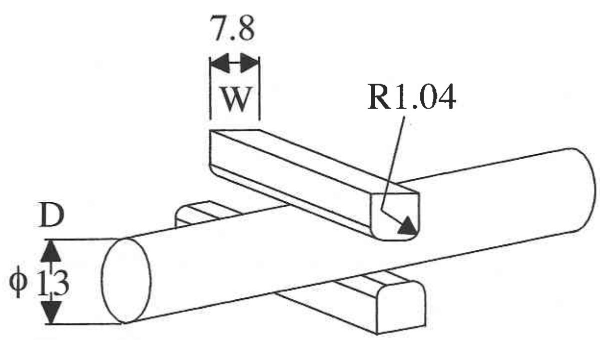

Fig. 1　Dimensions of the workpiece and plane dies

3.2. Experiment procedure

Before hot deformation, the workpiece was normalized to 870 °C for 1 hour and cooled by air. Then, the specimen was reheated in an induction furnace to a temperature of 1200 °C at a heating rate of 40 K/s and holding time of 20 minutes. These heat treatment resulted in uniform grain size of 80 μm before hot deformation. Then, the specimen was transported into the cam plastometer to deform it at the predefined forge reduction in diameter (56%) at strain rate of around 10 s^{-1}. Immediately after deformation the specimen was fast cooled by immersion into the tank with water. The delay time was controlled to be 1.3 s and 2.5 s. It is worth noting that during microstructure simulations, the temperature during the delay time was assumed to be unchanged.

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 E 112 standards. Fig. 2 shows the positions where austenite grain size was measured.

4. Results and Discussions

The transition of average grain size at point B (dead zone) for different values of Zc_2 is illustrated in Fig. 3. From this figure, we can see that the simulation followed the experimental measures as $Zc_2=7x10^{10}$.

Fig. 4 (a) shows the transition of average grain size distribution at point A for $Zc_1=1x10^9$. At point A, the DRX volume fraction, just after deformation was 85%, and the grain size was refined to 20 μm. The change of the grain size just after deformation is dominated by postdynamic recrystallization. Fig. 4 (b) shows transition of recrystallized fraction at point A, we can see that classical static recrystallization finished just after 0.03 s of deformation, and after then, the austenite grain boundary migration occurs due to metadynamic recrytallization. Measured and pre-

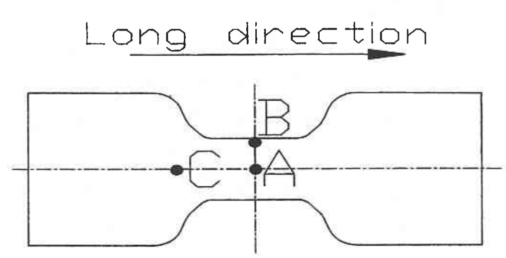

Fig. 2　Positions were grain size was measured

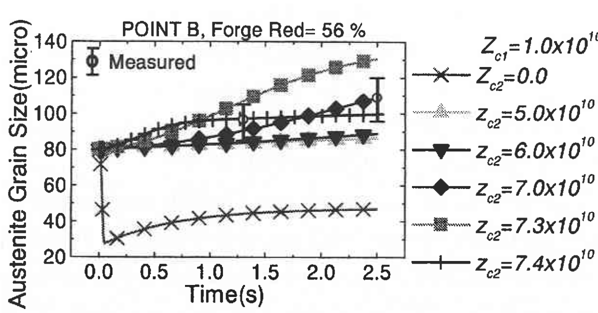

Fig. 3　Transition of average grain size at point B

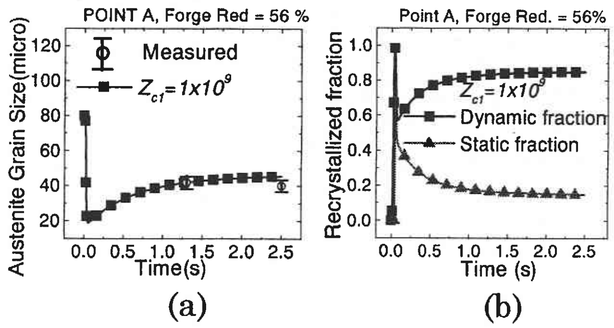

Fig. 4 (a) Transition of average grain size, and (b) Transition of recrystallized fraction at point A

dicted grain sizes agree well with each other.

Fig. 5 shows the transition of grain size at point C with $Zc_1=1x10^9$. At this point experimental measures shows some discrepancies. They could be due to the difficulty to measure the grain size at this point which is a transition zone, where the grain size shows considerable change as can be seen in Fig. 6.

Fig. 6 shows the austenite grain size distribution in longitudinal direction at 56 % of forge reduction. Predicted distributions of austenite grain size ($Zc_1=1x10^9$ and $Zc_2=7x10^{10}$) are compared with experimental measurements at three positions and different delay time. From these figures, we can see good quantitative agreement between measurements and analysis.

5. Conclusions

The applicability and versatility of the new incremental formulation for dynamic and static recrystallization has been successfully tested in hot open die forging from a round bar. The existence of a critical Zener-Hollomon parameter is a good flag to distinguish static microstructural changes during and just after hot deformation.

However, further investigation is necessary to include the temperature computation in the simulation model, and the experimental procedure has to be improved to permit the measurement of austenite grain with varied delay time.

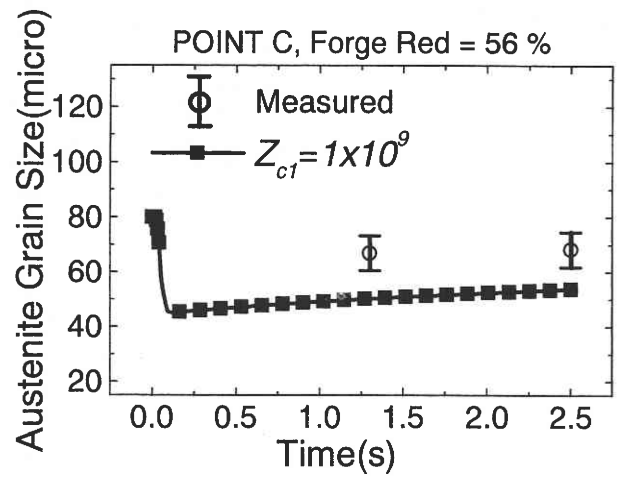

Fig. 5 Transition of average grain size at point C

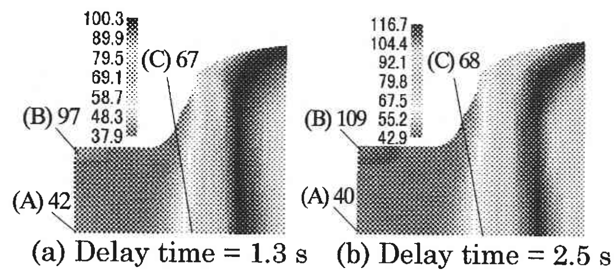

Fig. 6 Austenite grain size distribution at different delay times (a), (b)

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References

1) 柳本ほか：平成10年度塑加春講論（1998), 503.
2) 湯川ほか：48回塑加連講論（1997), 3.
3) Yanagimoto: CAMP-ISIJ, 10 (1997), 333.
4) Yanagimoto: Transaction of ASME, 120 (1998), 316.
5) Yanagimoto: Submitted to ISIJ International.
6) H. Yada et al.: J. of the JSTP, 27-300 (1986), 34.