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Simulation and prediction of microstructure in hot forming of metals①

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[Abstract] The evolution of microstructure seriously influences the forming processes and the quality of forgings in metal hot forming processes, it is therefore desirable to gain information on the microstructure evolution of a process by means of computer simulation, not by conventional trial and error method that is time consuming, expensive and does not always lead to optimum results. Models for microstructural simulation and prediction were set up according to the evolution of microstructure during hot forming and cooling processes. The expanding-extrusion complex hot forming and cooling processes, as an example, were simulated.

[Key words] metal hot forming; microstructural simulation; quality prediction
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1 INTRODUCTION

In recent years, there has been growing need in the metal forming industry to improve quality and decrease costs of products. Effective control of mechanical properties and quality of products can be achieved by the understanding of deformation conditions and microstructural changes during hot deformation. But during industrial forming process, workpieces are generally subjected to complex temperature-time-strain-strain rate histories and inhomogeneous distribution of deformation occurred, which make it unrealistic to investigate the influence of all possible variables on the microstructure of the material by means of industrial trial on the spot. However, the constantly expanding capacities of modern computers make it possible to simulate the forming process with even great accuracy. The finite element method has been proved to be the most suitable numerical method for accurate prediction of these parameters. Many researches have predicted the microstructure during deformation and the final mechanical properties of steel after hot deformation[1~6]. Most of these models are based on the work of Sellars[1]. Kopp et al has presented an model for integrated process and microstructural simulation in hot forming, used FEM for multilevel simulation of hot compression and predicted the grain size of 50CrV4 steel and improved microstructure in forging of a connecting rod by means of finite element simulations successively[3~5]. Xu et al[6] simulated the microstructure in the ring rolling of hot steel, which is a steady-state process. In this paper, simulation models for dynamic recrystallization in the non-steady state process and static recrystallization after deformation are presented by analyzing the evolution of microstructure during hot forming and cooling processes. The microstructural changes of the retaining ring during the expanding and extrusion complex hot forming[7] and air cooling processes are simulated.

2 SIMULATION OF DYNAMIC RECRYSTALLIZATION PROCESS

2.1 Dynamic microstructural changes during hot forming

Hot forming is characterized by work hardening due to increasing dislocation density, which is simultaneously relieved by dynamic softening processes. The dynamic stress-strain curve is shown in Fig.1. Following initial work hardening, the stress-strain curve attain a peak associated with dynamic recrystallization. At this maximum, a small proportion of the structure has already recrystallized, so that the strain for the onset of dynamic recrystallization ε_c is lower than ε_p. In this process, existing grain boundaries represent preferred nucleation sites, at which the ratio of process energy to surface energy permits nucleation once ε_c is attained. Recrystallization continues by means of repeated nucleation, so that the initial grain boundaries are quickly saturated and the boundaries between the non-recrystallized and the recrystal-

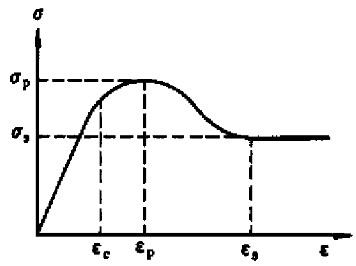

Fig.1 Dynamic stress-strain curve

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lized zones become nucleation sites. The result is an inward cascade growth of transformed zones into the grain interior, until these meet in the center of the former grains. This point coincides with attainment of the strain for steady-state stress ε_s. Because zones which have already recrystallized will renucleate, the flow stress levels are steady value.

The kinetics of dynamic recystallization can be described by the following Eqn.:

$$\varphi_d = 1 - \exp k_1 \left[\frac{\varepsilon - \varepsilon_c}{\varepsilon_s - \varepsilon_c} \right]^{k_2} \quad (1)$$

where φ_d is the dynamically recystallized volume fraction.

The equivalent strain ε_c and ε_s characterizing the recystallization process may be described by the following Eqns.:

$$\varepsilon_c = k_3 \varepsilon_p \quad (2)$$

$$\varepsilon_s = k_4 d^{k_5} Z^{k_6} \quad (3)$$

where Z is the Zener-Hollomon parameter, d is the grain size.

$$\varepsilon_p = k_7 d^{k_8} Z^{k_9} \quad (4)$$

In the steady-state range, the grain size d_d is a function of Z, and not dependent on the original grain size. It may be described by the following Eqn.

$$d_d = k_{10} Z^{k_{11}} \quad (5)$$

The coefficients $k_1 \sim k_{11}$ must be determined empirically.

Using the Eqns. given above, the characteristic variables for recrystallization of a steel can be determined. By integrating these models in a plastic-mechanical simulation model (FEM), it is possible to determine the beginning and degree of dynamic recrystallization and the size of steady-state grain.

2.2 Simulation model for dynamic recrystallization

When dynamic recrystallization occurs, there are strain hardening and recrystallization. The degree of recrystallization and grain size are changing, therefore, it is difficult to describe this complex process. In order to simplify the simulation process, the growth process of recrystallized grain is neglected. This means that the recrystallized grain has the steady-state grain size when dynamic recrystallization occurs.

After recrystallization initiated, the primary microstructure is subdivided into volume fractions differing in residual stress, effective strain, grain size etc from the matrix they derived from. Eqn.(1) can be used to determine the dynamically recrystallized volume fraction φ_{ij}. Here the index i characterizes the strain increment and j is the number of the element. Therefore, the volume fraction $\Delta \varphi_{ij}$ of a newly recrystallized structure can be calculated by

$$\Delta \varphi_{ij} = \varphi_{ij} - \varphi_{(i-1)j} \quad (6)$$

and the corresponding newly grain size is

$$\Delta d_{ij} = k_{10} Z^{k_{11}} \quad (7)$$

Therefore, the mean grain size in element j can be obtained by weight mean of the volume fraction and its corresponding grain size

$$d_{ij} = \sum_{1}^{i} \Delta d_{ij} \Delta \varphi_{ij} + d_0 (1 - \varphi_{ij}) \quad (8)$$

It is assumed in the simulation that if the effective strain lies below the critical effective strain for onset of dynamic recrystallization, or the recrystallized fraction is smaller than $\varphi_{min}(1\%)$, there is no recrystallized structure. If both the newly recrystallizing and the non-recrystallized fractions of the structure are larger than the given value φ_{min}, two separate structure are then considered. The non-recrystallized structure continues to work harden, whereas the newly recrystallized structure is completely softened and have the steady state grain size. If the fraction of the structure not recrystallized during an increment is less than φ_{min}, the recrystallization is regarded as completed. The next increment is restricted to the newly recrystallized structure.

3 SIMULATION OF STATIC RECRYSTALLIZATION PROCESS

3.1 Static microstructure changes after hot deformation

The metal structure undergoes work hardening and dynamic recovery/recrystallization determined by effective strain and the Zener-hollomon parameters during hot forming process. The microstructure occurred in this process is non-steady, and the "static" changes will take place during cooling process after deformation or between deformation steps. As a result, the stored energy has been released. These static processes include static recovery/recrystallization, meta-dynamic recrystallization and grain growth. When the effective strain of deformation structure is lower than the onset strain of the static recrystallization ε_{cs}, the static recovery will take place, otherwise, the static recrystallization will take place after deformation. The meta-dynamic recrystallization, that is a special static recrystallization process, will take place in the dynamic structure. In a word, the recrystallization bahavior after deformation is of great influence on the metal structure, the softening of the material in different degree, and the final structure and property of products.

3.2 Simulation model for static recrystallization

The static recrystallization is a process by which a large number of dislocation is simultaneously annihilated. The recrystallization kinetics are well described by the Avrami Eqn. and the recrystallized fraction is determined using the Eqn.:

$$\varphi_s = 1 - \exp[-0.693 (\frac{t}{t_{0.5}})^n] \quad (9)$$

where φ_s is the volume fraction recrystallized in time t, n is the time exponent and $t_{0.5}$ is the time for recrystallized 50 %.

Similar to simulation of the dynamic recrystallization process, the static recrystallization process was simulated by using the integrated process for simulation model. But its integrated variable is time other than strain in the dynamic recrystallization simulation model. The static recrystallization time is divided into several steps. At each step, the temperature is considered to be constant. Thus, the recrystallized volume fraction after a time interval Δt is calculated as

$$\varphi_i = 1 - \exp[-0.693(\frac{t_{i-1} + \Delta t}{t_{0.5}(T_i)})^n] \quad (10)$$

The static-recrystallized grain size is given by

$$d_i = f(d_d, \varepsilon) \quad \varepsilon \leqslant \varepsilon_c$$

or

$$d_i = f(Z) \quad \varepsilon > \varepsilon_c \quad (11)$$

During simulation of the static recrystallization process, the grain growth will take place when the static recrystallized volume fraction is larger than 0.95. Therefore, the time necessary to achieve the recrystallized volume fraction of 0.95 in isothermal conditions at that temperature is t'_i and is given as

$$t'_i = \left[\frac{1}{0.693}\ln\frac{1}{1-0.95}\right]^{\frac{1}{n}} \times t_{0.5}(T_i) \quad (12)$$

If $t'_i < t_i$, the recrystallization is completed and the grain growth occurs, otherwise, the iterative procedure is repeated until the total time reaches the given time or until the recrystallized volume fraction reaches 0.95.

Although the static recrystallization removes the relatively high internal energy imparted by the hot deformation, the structure is still meta-stable. Further reduction in the overall internal energy occurs by a reduction of the total grain boundary area. It is apparent that high temperature growth starts immediately after the completion of recrystallization in the short time. The dependence of grain growth on time and temperature is written as

$$d^{10} = d_S^{10} + At\exp(-Q_{gg}/RT) \quad (13)$$

where A and Q_{gg} are constants determined by experimental data.

4 EXAMPLE OF MICROSTRUCTURE SIMULATION

The microstructure changes of Mn18Cr18N steel[8] in the expanding-extrusion complex forming and cooling processes were simulated by using the above recrystallization models. The process data and ring blank dimensions are listed in Table 1.

Table 1 Process data and ring-blank dimensions

Name	Value	Unit
Outer radius of ring blank	400	mm
Inner radius of ring blank	110	mm
Axial height of ring blank	868	mm
Initial grain size	250	μm
Velocity of punch	150	mm/s
Friction coefficient	0.35	
Forge reduction	1.3	
Original temperature of ring blank	1 250	℃
Temperature of dies	200	℃

The results of simulation are as follows:

The distribution of grain size d and dynamic recrystallization volume fraction φ_d after hot forming of ring are shown in Fig.2(b). It can be seen that dynamic recrystallization in ring is very unevenly distributed, which is similar to that of the distribution of strain in Fig.2(a), that shows the distribution of effective strain and temperature in the formed ring. The greater the strain, the larger the volume fraction and the refiner the grains. All of those indicate that the refining and uniform grains can not be attained by forming of the ring.

Subsequently, control cooling after hot forming is important to the homogeneities of grain size. Fig.3 shows the distribution of grain size on the cross section of the ring at different time. In the early stage of air cooling, grain size is fined with static recrystallization process. When large strain zone is fully recrystal-

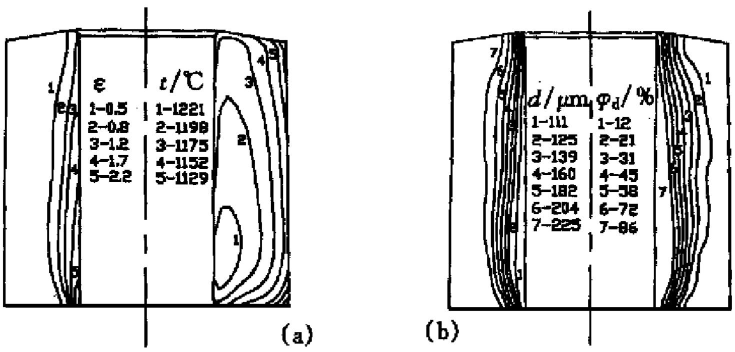

Fig.2 Parameter distributions of deforming and recrystallization in formed ring
(a) —Strain and temperature; (b) —Grain size and volume fraction of recrystallization

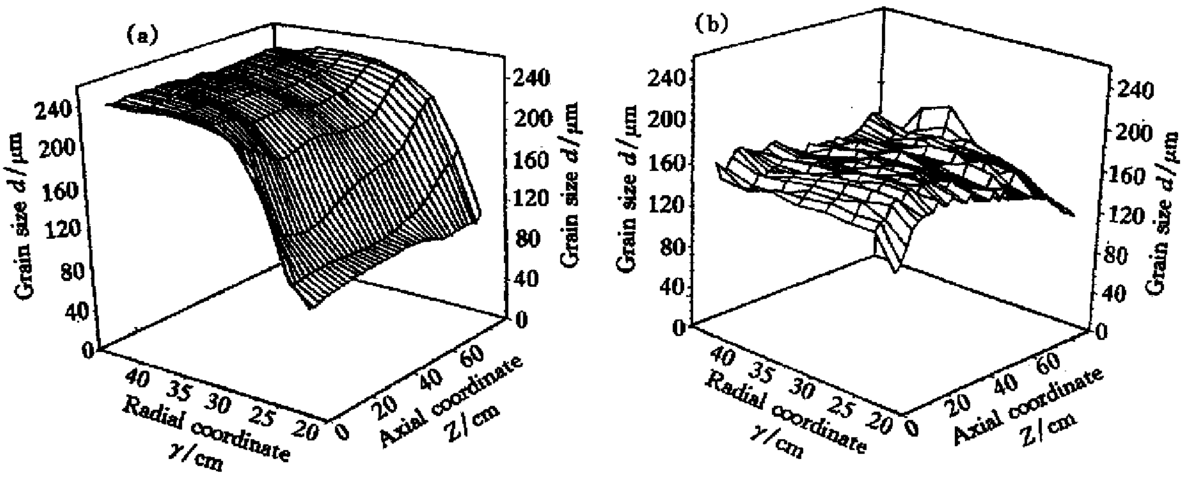

Fig.3 Grain size distribution on cross section of ring at different cooling times
(a) —0s; (b) —120s

lized, the grains begin to grow. Except of the four corners of the cross-section, grain distribution tends to be well-distributed and the mean grain size is about 150 μm by 210 s of cooling time. These agree with the experimental results[9,10] of research on control forging and control cooling of Mn18Cr18N.

5 CONCLUSION

The evolution of the microstructure of metals during hot forming can be simulated by models for microstructure simulation, which incorporates the mathematical relations obtained from laboratory tests into a coupled thermo-mechanical finite element method, and gives meaningful results on the micro-variables of the process.

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