A Study on Forging Process of New Aluminum Alloy

ChaoFeng1*, Weike Liu1, Xianhui Cao1, Yunlai Deng2, Jun Wang1, Yi Xie1
1State Grid Hunan Electric Power Company Limited Research Institute, Changsha 410007, China
2Changsha University of Science and Technology, School of Electrical and Information Engineering, Changsha 410007, China
*676459812@qq.com

Abstract: This paper employs the isothermal compression method to study the forging process of new aluminum alloy and analyzes its law of thermal deformation behavior at the temperature of 400~550℃ and the strain rate of 1~10^-3s^-1. It is found that flow stress is correlated with the temperature and strain rate and that the stress level decreases with the increase of temperature and the decrease of strain rate. This reveals the evolution law of the microstructure of the aluminum alloy in thermal deformation and lays a foundation for the subsequent studies and optimization of the forging process.

1. Introduction
Because of its light weight, aluminum alloy can replace steel materials in many fields and achieve the goal of being lightweight. The strength of aluminum is low, generally 80~200MPa. By adding copper, zinc, manganese, magnesium, silicon and lithium to aluminum for alloying, the strength of aluminum alloy thus formed can reach 300~800MPa or even higher[1-2]. The main alloying elements added in the 6000 series aluminum alloy are Mg and Si. By adding them according to the proper proportion, the Mg2Si precipitation strengthening phase will be formed. This series of aluminum alloy has good comprehensive properties: high specific strength and corrosion resistance, good formability, low cost, etc. It has been widely used in the fields of national defense, military industry, rail transit, ground vehicles, surface ships, construction, electric power and electronics. The forged aluminum alloy can improve its microstructure and mechanical properties. While in terms of the cast aluminum alloy, after hot working deformation and subsequent treatment, the microstructure of castings undergo deformation, recrystallization and precipitation strengthening, so that the original coarse dendrites and columnar grains become microstructure of the forging flow line. The original metallurgical defects such as segregation, porosity, gas hole and slag inclusion in the ingot are compacted and welded. In this way, the strength, ductility, and toughness can be improved to obtain higher comprehensive properties[3-5].

2. Study plan
The first step is to determine the composition of the 6000 series aluminum alloy, whose performance index meets the requirements, find out its forging process performance and study the manufacturing process of the clamps for the transmission line. On this basis, the tests on the strength of aluminum alloy materials and the performance of clamps under simulated load conditions are then carried out.
3. Results and conclusions

3.1. Constitutive model for thermal deformation of 6000 series aluminum alloy

The constitutive relation of aluminum alloy can accurately describe the effect of material characteristics, such as strain rate, forming temperature, strain and work hardening behavior on deformation resistance. In accordance with the objectives of the project, an Al-Mg-Si-Mn alloy was designed and prepared, and the composition is shown in Table 1.

| Element | Si    | Mg    | Mn    | Fe    | Ti    | Zn    | Cu    | Al     |
|---------|-------|-------|-------|-------|-------|-------|-------|--------|
| Content | 1.17  | 0.966 | 0.520 | 0.316 | 0.026 | 0.043 | 0.021 | Bal    |

Table 1 Composition of the HD6X70 alloy (wt.%)

The isothermal compression method was adopted to study the thermal deformation behavior of this alloy and the constitutive equation of this new aluminum alloy was set up in accordance with the true stress-strain curve. Furthermore, the quasi-SEM-EBSD method was applied to discuss the recrystallization mechanism in the whole forging process, providing a basis for the formulation of the actual forging process.

Figure 1 shows the true stress-strain curves of the HB6X70 aluminum alloy at the temperature of 400°C, 450°C, 500°C and 550°C, strain rate of 0.001, 0.01, 0.1 and 1s⁻¹ and true stress of 0.9 obtained by the isothermal compression experiments. The curves indicate that the thermal deformation temperature and strain rate significantly affect the flow behavior of the HB6X70 aluminum alloy. Generally speaking, at the given strain rate, the flow stress decreases with the increase of temperature. Meanwhile, at the given temperature, the flow stress tends to decline with the decrease of strain rate.

Figure 1 also suggests that, at the initial stage of deformation, the flow stress rapidly increases with the increase of stress and shows a tendency of yield decline under the condition of a high strain rate. The specific dynamic softening mechanism may be different. The typical performance under most...
experimental conditions is: the flow stress gradually decreases after the peak value until the high strain, showing dynamic flow softening. Deformation-induced flow softening is caused by different mechanisms such as deformation heating, strengthened dynamic recovery (DRV), sub-grain coarsening, dynamic recrystallization (DRX), dynamic precipitation and dissolution, and precipitation phase coalescence/growth.

The effect of deformation heating on flow softening is very important. After the flow softening, flow stress near the steadystate occurred at the end of the experiment. This suggests that the flow stress remains relatively constant and does not increase with strain. Secondly, there is little flow softening when it is directly hardened to the steady state. This is the characteristic of DRV-dominated deformation behavior, which can be obviously seen in Figure 1-a and Figure 1-b. In addition, the flow stress continuously increases with the increase of strain, namely obvious continuous work hardening. The maximum flow stress is reached at the end. Under this condition, dynamic softening is insufficient enough to offset the work hardening effect in the thermal deformation process. This flow behavior can be obviously observed from Figure 1-c. The last one is relatively complicated. As shown in Figure 1-d, the peak stress is quickly reached after work hardening when the strain rate is 1s−1. Then dynamic softening occurs and subsequently, the flow curve goes up and down repeatedly, revealing that alternate hardening and softening continuously occur at this time.

Typically, the shape of the flow curve is decided by the competitive results of simultaneous work hardening and dynamic softening. What’s more, the rate of the work hardening and the dynamic softening is decided by the temperature and the strain rate. At the beginning of the deformation, work hardening caused by the intense proliferation, accumulation and interaction of dislocations leads to the rapid increase of flow stress. At this stage, the softening caused by DRV is relatively less obvious. In other words, in the work hardening area, the dislocation generation rate is higher than the dislocation annihilation rate caused by DRV. With the increase of temperature or the decrease of strain rate, the work hardening amount decreases.

3.2. Constitutive model for thermal deformation of 6000 series aluminum alloy
The hot working diagram is widely applied to determine the conditions for the hot working of the alloy materials. The hot working diagram of the HB6X70 aluminum alloy can be established according to the dynamic material model. The total input power \( P \) is divided into plastic deformation dissipation power \( G \) and microstructure transformation dissipation power \( J \), as shown in formula (1).

\[
P = \sigma \dot{\varepsilon} = G + J = \int_0^\varepsilon \sigma d\dot{\varepsilon} + \int_0^\sigma \dot{\varepsilon} d\sigma
\]

\[
J = \int_0^\sigma \dot{\varepsilon} d\sigma = \frac{m}{m+1} \sigma \dot{\varepsilon}
\]

\[
\eta = \frac{J}{J_{\text{max}}} = \frac{m/(m+1)}{1/2} = \frac{2m}{m+1}
\]

where, \( m \) denotes the strain rate sensitivity index of the alloy and is defined as:

\[
m = \frac{\partial J}{\partial G} = \frac{\dot{\varepsilon} d\sigma}{\sigma d\dot{\varepsilon}}
\]

The dissipation efficiency parameter \( (\eta) \) can be expressed with the formula 3-4. \( J_{\text{max}} \) represents the power consumption under the ideal linear conditions \( (m=1, J_{\text{max}} = \sigma \dot{\varepsilon}/2) \). When \( J \) or \( \eta \) changes, defects such as voids and cracks may appear due to unstable deformation. These unstable areas can be marked on the hot working diagram. In a study on the hot working diagram, the value of the dimensionless parameter is adopted as the basis for the determination. The deformation instability occurs when such value is smaller than zero, as shown in the red area in Figure 2. When the temperature is lower than 480°C, the deformation conditions corresponding to the temperature in this area are prone to cause cracking. When the temperature is 500–550°C or the strain rate is low (for example, between 0.1–1s\(^{-1}\)), the power consumption efficiency is the highest, indicating that the alloy has good hot working performance, and there are almost no unstable areas in the hot working diagram.
3.3. Evolution law of microstructure of the 6000 series aluminum alloy in thermal deformation

3.3.1. Effect of the temperature on microstructure

Figure 3 shows the change of alloy microstructure with temperature. In the figure, the red zone (GOS>7.5) represents the deformed grain, the blue zone (GOS<1) represents the dynamically recrystallized grain and the yellow zone (1<GOS<7.5) represents the sub-grains. It can be seen from the IPF diagram that the grain structure after isothermal compression can be divided into two types. One is the large fiber particles which are about 20μm wide and has many sub-particles inside. The other is equiaxed recrystallized grains distributed along the grain boundary. The temperature has a great effect on the morphology of these grains. At a lower temperature of 400~450℃, the original banding grain is extruded into the fiber grain with a width of fewer than two sub-grains. The deformation is serious. As indicated by the arrows in the figure, many tiny equiaxed grains are formed in the fiber grain and distributed along the grain boundary. On the whole, at the temperature of 400~450℃, the distribution of fiber grains becomes uneven and the size of both equiaxed grain and sub-grain grows. At 550℃, the grains completely recover, recrystallize and grow, with almost all the original banding microstructures transformed into equiaxed grains.

It can be seen from the GOS diagram that, within the range of 400~450℃, the deformation of the test samples is serious and the recrystallized grains, the sub-grains and the deformed microstructures are mixed together. Those marked by the white box in Figure 5-1 can clearly reflect these characteristics. With the increase of temperature, the number of recrystallized grains increases obviously and the size of the deformed microstructure decreases gradually. When the temperature is between 500℃ and 550℃, due to dynamic recrystallization and recovery, there is almost no deformed microstructure, but there are a large number of recrystallized grains and some sub-grains.
3.3.2. Effect of the deformation rate on microstructure

In addition to temperature, strain rate also has a significant effect on the grain morphology. As shown in Figure 4, when the strain rate is $10^{-3}\text{s}^{-1}$, almost all of them are equiaxed recrystallized grains, indicating a lower strain rate. The work hardening caused by deformation has enough time to be offset by the softening mechanism of the alloy, and the recrystallized grains also have enough time to grow. With the increase of the deformation rate, the recrystallization rate decreases and the grains are refined. When the strain rate is $10^{-2}−10^{-1}\text{s}^{-1}$, the original grains are mixed with HAGBs and LAGBs, indicating that the recrystallization mechanism is CDRX. When the strain rate is $1\text{s}^{-1}$, as shown in Figure 4(b), the softening effect caused by recovery and recrystallization is not enough to offset the work hardening caused by deformation, resulting in inclusion deformation and recrystallized grains in the fine grain microstructure.

4. Conclusions

In this paper, we prepared the samples for studying the forging process principle of the 6000 series aluminum alloy with the isothermal compression method, and carried out studies on the thermal deformation behavior of such aluminum alloy at the temperature of 400−550°C and the strain rate of $10^{-3}\text{s}^{-1}$. We have the following main conclusions:
(1) The flow stress of the alloy is correlated with the temperature and strain rate. The flow stress reduces with the rise of temperature and the decrease of strain rate. Based on the experimental data, it is found that the apparent activation energy of thermal deformation of such alloy is 171.91kJ/mol. We then established the constitutive relation of thermal deformation of the alloy, laying a foundation for the subsequent studies.

(2) In the process of thermal deformation, the main recrystallization mechanism is CDRX, accompanied by GDRX at high lnZ. After heat treatment, the recrystallization mechanism is similar to that of heat treatment. Grain growth during discontinuous recrystallization occurs in the form of grain boundary migration driven by energy storage.

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