Microstructure Evolution Simulation of GH4169 Fasteners in Forging Process

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Abstract. This paper mainly calculated the microstructure evolution characteristics of GH4169 alloy fasteners during hot forging deformation. The constitutive equation and the microstructure evolution models of the material were embedded in the finite element software. By analysis, the grain size and dynamic recrystallization volume fraction were calculated, and the key points on the fastener in forging process were analyzed. As a result, the microstructure evolution of the GH4169 alloy fastener during the hot forging deformation process was obtained. The results show that, through the plastic deformation by the hot forging process, the grain size on the fastener’s head is gradually refined, the minimum average grain size is reduced from the initial 100 μm to less than 10 μm. During the deformation process, the splinted part of the fastener begins to undergo dynamic recrystallization first. After that, dynamic recrystallization volume fraction gradually increases from the central region to the edge, with the highest value of 60%. These results provide a basic data reference for GH4169 fastener forging process development and parameters optimization.

Key words: GH4169; fastener; forging; microstructure; numerical simulation.

1. Introduction
Superalloy GH4169 is a main material as wrought superalloys due to its high strength, oxidation resistance and corrosion resistance. It is widely used in advanced aeroengines and aircraft at home and abroad. In terms of aero-engine fasteners, GH4169 alloy bolt fasteners account for more than 70% of the total bolt demand, and is also an indispensable high-strength load-bearing fastener material for aircraft. The main purpose of the forging process is to form and modify. Forming is a basic requirement, and the performance of the forgings should be maximized as far as the shape requirements are reached. GH4169 alloy fasteners work under high temperature and high pressure, which have extremely high requirements on microstructure and mechanical properties of the material, and need to withstand bending and shear stress caused by alternating load during service. Therefore, so great performance is also required such as fatigue resistance and wear resistance. However, GH4169 alloy fasteners may undergo a variety of microstructure evolution during the hot forging process, including dynamic recrystallization, grain growth and so on. The recrystallization process directly affects the change of the grain size in the forging process, which could affects the mechanical and structural properties of the
material. By numerical simulation, the microstructure evolution of the GH4169 fasteners in forging process could be studied, and the parameters of the forging process could be optimized. Therefore, this work has great significance for optimizing process parameters and improving product quality and performance.

In this paper, the microstructure evolution characteristic of GH4169 alloy fasteners during hot forging deformation was calculated. The constitutive equation and the tissue evolution model of the material were embedded in the finite element software, and the grain size and dynamic recrystallization volume fraction of forging process were obtained. The key points on the fasteners were analyzed, and the microstructure evolution law of GH4169 alloy fasteners during hot forging deformation was obtained, which provided the basic data reference for the formulation and parameters optimization of GH4169 fastener in forging process.

2. Numerical modelling of the fasteners in forging process
For the hot forging process simulation of GH4169 alloy fasteners, firstly, the shape and size of the initial blank and the forging dies need to be determined, and the three-dimensional assembly model should be established. As shown in Fig. 1(a), according to the spatial geometric relationship between the blank and the upper and lower dies, the model is initially positioned and assembled. The upper and lower dies are set as rigid bodies, and the blank is elastic-plastic. And the initial mesh is discredited by absolute meshing method. Finally, there are 61,969 nodes, 45,600 polygons and 225,364 tetrahedral on the initial blank, as shown in Fig.1 (b). During the simulation analysis, the meshes were attached to the material, and the material is easily deformed due to excessive deformation of the corresponding mesh shape during the flow process. The calculation process may be interrupted by the distortion. Therefore, it is very important to ensure that the analysis can continue after the material has undergone a large deformation in the simulation process, but the results still have enough accuracy. After the mesh distortion reaches to a certain level, the distorted mesh is automatically redeveloped, and the new high-quality meshes are generated.

![3D modeling of the fastener in forging process](image)

Fig. 1 3D modeling of the fastener in forging process (a-assembly, b-blank mesh)

3. Material definitions
Since the forging process is a plastic deformation process, involving the flow and plastic deformation of the material, the GH4169 material model should be defined in the numerical simulation model. And all the material properties including the high temperature flow stress parameters, elastic modulus, Poisson's ratio, thermal expansion coefficient, thermal conductivity, specific heat are all need to be input.
In order to study the microstructure evolution of the fastener in forging process, the constitutive and microstructure evolution models of the material should also be defined as following:

- Critical strain and peak strain models:
  \[ \varepsilon_c = 0.83 \varepsilon_p \]  
  \[ \varepsilon_p = 0.004659 \varepsilon^{0.1238} \exp\left(\frac{49520}{RT}\right) \]  

- Static recrystallization models:
  \[ X_{srex} = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{0.3}\right] \]  
  \[ t_{0.5} = 3.16 \varepsilon^{-0.75} \exp\left(\frac{74790}{RT}\right) \]  
  \[ d_{srex} = 678 \exp\left(-31694/RT\right) \]  

- Meta-dynamic recrystallization models:
  \[ X_{mrex} = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)\right] \]  
  \[ t_{0.5} = 5.04 E - 9 \varepsilon^{-1.42} \varepsilon^{-0.408} \exp\left(\frac{196000}{RT}\right) \]  
  \[ d_{mrex} = 4.85 E 10 \varepsilon^{-0.41} \varepsilon^{-0.028} \exp\left(-240000/RT\right) \]  

- Dynamic recrystallization models:
  \[ X_{drex} = 1 - \exp\left[-0.693\left(\frac{\varepsilon-0.8 \varepsilon}{\varepsilon_{0.5}}\right)\right] \]  
  \[ \varepsilon_{0.5} = 5.043 E - 9 \varepsilon^{-1.42} \varepsilon^{-0.408} \exp\left(196000/RT\right) \]  
  \[ d_{drex} = 4.85 E 10 \varepsilon^{-0.41} \varepsilon^{-0.028} \exp\left(-240000/RT\right) \]  

- Grain growth models:
  \[ d_g = d_{g0}^2 \exp\left(-390753/RT\right) \]

The equations of (1)–(12) are all embedded into the numerical analysis model for the stress, strain and microstructure evolution calculation.

### 4. Grain size calculation results

The calculation results of the average grain size change during the forging process of GH4169 alloy fasteners are shown in Fig. 2. The initial billet is homogenized, and the average grain size is 100 μm. By the hot forging plastic deformation process, the grain on the fastener head is gradually refined, and the minimum average grain size is reduced from the initial 100 μm to less than 10 μm. Due to the small plastic deformation of the central area, the grain size is thicker than other areas, and more than 85% of the deformation area is refined by hot forging plastic deformation, which helps to improve the application performance of fasteners.
Fig. 2 Average grain size during forging of GH4169 alloy fasteners

Fig. 3 Grain size of different regions on GH4169 alloy fastener in forging process

Select the key points (P1~P6) in different areas of the central axis section on the fastener to analyze the average grain size. As shown in Fig. 3. With the deformation of the material during the forging process, the grain size of each point are gradually refined. Among them, the P3, P4, and P5 first enter the grain refining process. When the forging is completed, the average grain size value of the P4 is the smallest, which is refined from 100 μm to 42 μm.

5. Dynamic recrystallization calculation results
The calculation results of the dynamic recrystallization volume fraction of the GH4169 alloy fastener in forging process are shown in Fig. 4. During the deformation process, the spine portion of the fastener head begins to undergo dynamic recrystallization first, and then the dynamic recrystallization volume fraction increases with the deformation process from the central region to the edge, with a maximum of 60%.
The dynamic recrystallization volume fraction of different regions in the forging process of GH4169 alloy fasteners was selected as shown in Fig. 5. The calculation results show that the fasteners complete the dynamic recrystallization softening after the forging process is completed, and the softening degree of the peripheral region is higher than that of the core. The highest value of the dynamic recrystallization volume fraction is approximately 60%.

**Fig. 5 Dynamic recrystallization volume fraction of different regions on GH4169 alloy fastener in forging process**
6. Conclusion
The calculation results of microstructure evolution of GH4169 alloy fasteners during the forging process show that the grain deformation on the fastener head is gradually refined by hot forging plastic deformation, and the minimum average grain size is reduced from the initial 100μm to less than 10μm. The calculation results of dynamic recrystallization volume fraction show that the dynamic recrystallization on the head of the faster occurs first, and then the dynamic recrystallization volume fraction gradually increases from the center area to the edge, with a maximum value of 60%. The microstructure evolution characteristics of different parts on the fastener head during forging deformation were analyzed by data comparison. The microstructure evolution of GH4169 alloy fasteners during the forming process were given, which could provide data reference for the forging process parameters optimization.

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