A Study on the Physical Structure and Residual Stress of Forgings by Vacuum Induction and Atmosphere Protection

Zhaowei Dong¹, Kuikui Xu¹, Xiaohang Wan², Lihui Sun¹, Meng Liu³, Zhongqi Dong²,*

¹School of Information Technology, Hebei University of Economics and Technology, Shijiazhuang, Hebei 050061, China
²Department of Material Engineering, Hebei Vocational and Technical University of Technology, Shijiazhuang, Hebei, 050000, China
³Avic Shangda Superalloys Co.,Ltd. Technology Center, Qinghe, Hebei 054800, China

*Corresponding author: dongzhongqi@hebut.edu.cn

Abstract. GH4169 alloy was prepared by vacuum induction, atmosphere protection and vacuum self-consumption triple-smelting technology. After forging and standard heat treatment, the microstructure defects of GH4169 alloy bar were analyzed by scanning electron microscope and x ray diffraction. The change law of tissue defects was simulated by statistical analysis. Residual stress of GH4169 bar is measured by drilling method, and strain release coefficient is calibrated by finite element analysis. The experimental results show that the GH4169 alloy forgings have fine grain size, including δ phase, γ' phase, γ''' phase and mc carbide phase. The distribution of small defects near the center is dense, the distribution of large defects near the edge is sparse, but the distribution of large defects near the outermost layer is also very dense. The residual stress increases first and then decreases along the radial direction, and the residual stress shows the trend of "external pressure internal pull" on the disk surface, and the compressive stress increases greatly near the edge of the disc. The residual stress is consistent with the density of tissue defects.

Keywords: GH4169 alloy; grain refinement; Forging; heat treatment; Residual stress

1. Introduction
The nickel - iron - based high - temperature alloy GH4169 alloy has high comprehensive resistance to creep, high strength and fatigue resistance in the high temperature environment, and is widely used in aerospace, petrochemical, nuclear energy and other industries, especially in the high temperature component of aero - engine. GH4169 alloy rod preparation process has a long route, involving the technical control of chemical composition, smelting process, billet process and mold forging process. Meanwhile, GH4169 rod in the heat treatment and molding preparation process will produce residual stress, affect the service life of the material, reliability and cause processing deformation of parts. Therefore, the residual stress must be effectively controlled and reduced during the heat processing process. Therefore, this paper mainly studies the structure and defect and residual stress.
distribution rules of GH4169 alloy forging, explores the influence rules of tissue defects on residual stress, and provides theoretical guidance for practical production.

2. Test materials and methods

2.1. Test materials

The GH4169 alloy used in this paper is AVIC Superalloy Material Co., Ltd., produced using vacuum induction - atmosphere protection - vacuum self-consumption ‘triple smelting technology’ and forging process (the main components of the alloy are shown in Table 1 and the processing process is shown in Table 2). GH4169 alloy large bar forging adopts standard heat treatment: 92 furnace number (950 ℃ - 980 ℃) ± 10 ℃, 1h, water cooling 720 ℃± 5 ℃, 8h, to 50 ℃ / h to 620 ℃± 5 ℃, and 8h, air cooling.

| Table 1. Chemical composition of GH4169 alloy. |
|-----------------------------------------------|
| C | Mn | Si | Cr | P | Ni | Mo | Ti | Cu | Nb | Co | Ta | residue |
|----|----|----|----|----|----|----|----|----|----|----|----|--------|
| 0.03 | 0.03 | 0.06 | 17.94 | 0.011 | 53.34 | 2.94 | 0.42 | 0.02 | 5.37 | 0.29 | <0.03 | Fe |

| Table 2. Forging process of GH4169 alloy. |
|------------------------------------------|
| Heating number | Operation instructions | Deformation | Heating temperature (℃) | Soaking time | Open forging/final forging temperature (℃) |
|----------------|------------------------|--------------|--------------------------|--------------|------------------------------------------|
| 1              | Pper handle            | 27%          | 1100                     | 1 hour 31 minutes | 1023/907                                   |
| 2              | Press pper and and and cutting | 27%          | 1100                     | 2 hours 1 minute | 1027/918                                   |
| 3              | Pier pull              | Jumping-up 1/3 | 1100                     | 1 hour 19 minutes | 1021/                                      |
| 4              | Pier pull              | Jumping-up 1/3 | 1080                     | 1 hour 17 minutes |                                           |
| 5              | Exout                  | 33%          | 1050                     | 1 hour 10 minutes | 900                                       |
| 6              | Exout                  | 26%          | 1020                     | 1 hour 27 minutes |                                           |
| 7              | Exout                  | 26%          | 1020                     | 1 hour 27 minutes |                                           |
| 8              | Exout                  | 25%          | 1020                     | 1 hour 27 minutes |                                           |

2.2. Test methods

GH4169 alloy bar diameter φ 220mm, according to figure 1(a), a long strip of 220 mm wide 10 mm is cut from the bar end face along the diameter, and the cut strip is divided into 28 parts. The sample number from the center of the bar end to the edge is 16/28, as shown in figure 1(b).
After wire cutting, hot inlay, grinding and polishing of GH4169 alloy samples, First, the metallographic analysis of Nikon LV100ND was carried out by metallographic microscope, After that, the microstructure and phase composition of the alloy were analyzed by VEGA3SBH scanning electron microscope and energy spectrum analyzer. The X diffraction spectra of powder samples were determined by Cu-Kα target on the XRD-7000 of Shimadzu X ray diffractometer, the crystal structure of the sample was analyzed. Using 20 ml hydrochloric acid 20 ml anhydrous ethanol 1.5 g copper sulfate pentahydrate corrosion solution for chemical corrosion [3], then a metallographic analysis was carried out by metallographic microscope and scanning electron microscope. In the analysis, 12 samples were numbered according to the position order from inner diameter to outer diameter, from top to bottom, from left to right, Image-proplus software was used to record the morphology of the defects and the position on the alloy surface.

The surface residual stress of the specimen is measured by drilling method, The strain flower arrangement on the surface of the specimen is shown in Fig. 2, A spacing of 30 mm, for 4 measuring points along the radial direction Set the interval of three columns in the circumferential direction to 120, Drill diameter 1.5 mm, Drilling depth 2 mm. Building a finite element model, Using solid186 unit to establish GH4169 specimen (size 200 mm × 200 × 20 mm) and strain flower bonding model, corresponding to the fine mesh division around the variable flower and the small hole, Improve the accuracy and efficiency of the solution.

![Fig 1. Schematic diagram of sampling area of GH4169 alloy](image)

(a) section of GH4169 alloy; (b) sampling area of GH4169 alloy.

![Fig 2. GH4169 alloy specimen residual stress test site layout.](image)
3. Results and Discussion

3.1. GH4169 Structure Analysis of Alloy Forging

GH4169 alloy forgings X diffraction patterns, the results are shown in Figure 3, among them, (a) No .16, (b) No. 20, (c) No.24 and (d) No .28. Figure 3 shows that, GH4169 alloy forgings contain δ, γ', γ'' and carbon phases, And this indicates that the forging process did not change the type of phase in the GH4169 alloy, However, from the core of the bar to the edge alloy MC the peak height of the carbide phase decreases first and then increases.

Fig 3. XRD analysis of GH4169 alloys forging.

Fig 4. Defect of microstructure in GH4169 alloy forgings
(a) Heart; (b) between heart and 1 / 2R; (c) between 1 / 2R and edge; (d) edge.
Figure 4 GH4169 microstructure defects in alloy forgings. It can be seen that GH4169 alloy forgings, there are obvious differences in microstructure defects, grain boundary morphology and precipitation phase distribution along the center-to-edge of the large bar cross section. The center of GH4169 alloy (a) has triangular void (hole) defect on the crystal plane, and (b) there is a square precipitate between the center and 1/2 R. The diameter of the precipitate is about 10μm; (c) 1/2.

3.2. Analysis of residual stress of GH4169 alloy rod cross section
In order to explore the influence relationship between the GH4169 alloy forging tissue defects and the residual stress, the radial and circumferential stress analysis of the GH4169 alloy forging bar cross-section disk is done. Fig. 5 (a) shows the residual stress along the radial distribution curve from the angle of 0, 120 and 360. It shows that the main stress starts from the center and decreases along the radial direction, and part of the stress changes to negative near the edge of the disk. The residual stress shows the trend of "external pressure internal pull" on the disk, and the pressure stress near the edge of the disk. Fig. 5 (b) If the residual stress is distributed along the circumferential direction, the circumferential angle is positive clockwise, it is seen that the circumferential stress value with a radius of 30mm is significantly increased at 120 , and the stress is not evenly distributed along the circumferential direction. In order to more intuitively study the distribution of residual stress on the disk, using the polar cloud map, as shown in Fig. 5 (c), the color in the cloud map reflects the compression stress near the disk edge, the other positions are tensile stress, with large tensile stress in the area from 90 to 180 .

![Residual Stress Diagrams](image-url)

**Fig 5.** GH4169 alloy bar cross-section residual stress distribution
(a) Residual stress along radial distribution curve  
(b) Residual stress along circumferential distribution curve  
(c) Residual stress main stress distribution cloud map.
4. GH4169 Analysis of the Relationship between Alloy Tissue Defect and Residual Stress

Forging GH4169 alloy bars, the residual stress mainly comes from non-uniform plastic deformation, thermal transformation and phase transformation, the residual stress of the alloy after forging provides energy storage for the change of microstructure. GH4169 uneven distribution of cross-section defects of alloy bars may be related to the stress distribution, It can be seen from figure 6 that the residual stress at the center of the section is high and the distribution of small defects is dense, Because of the dense tissue defects in the center and the high stress, The "tensile stress" helps to promote the [4] of γ” and γ’ phases, So that the stress consumption can reduce the residual stress, But the center is deformed, limiting the stress reduction at the center, [5] the residual stress at the center of the disk during the aging process of GH4169 alloy was observed by neutron diffraction to promote the nucleation and growth of the γ” phase, and produce a higher number of core density in the matrix; The quantitative density of γ” phase is larger and the size is smaller after aging 8 h; radial residual stress decreases along the GH4169 alloy bar section, The big, sparse defect, This may be because the closer to the edge, the stronger the compressive stress, To promote the gradual precipitation in the crystal γ” the number of phases and γ’ phases is not as large as the number of central sites, At the same time, the edge is less constrained by deformation, So that near the edge of the stress reduction; The distribution of large defects near the outermost layer is also dense, The residual stress also increases, This may be due to the maximum cooling rate at the edge during heat treatment; And GH4169 alloy bars, After deformation, 980℃ solid solution, lattice distortion caused by deformation within the specimen, The micro-defects such as dislocation and sub-structure decrease gradually, resulting in a decrease in the residual stress value.

5. Conclusion

(1) the grain size of GH4169 alloy forgings is fine and contains δ phase, γ’ phase, γ” phase and MC carbide phase.
(2) GH4169 alloy forgings have dense distribution of small defects near the center, sparse defects near the edge and mainly large defects, but also dense distribution near the outermost layer.
(3) The residual stress of GH4169 alloy forgings increases first and then decreases along the radial direction, and the residual stress shows the trend of "external compression and internal tension" on the disk surface, and the compressive stress increases greatly near the edge of the disc, and the residual stress is consistent with the density of tissue defects.

Acknowledgment

Thanks to the department of S & T Program of Hebei (no.:20311007D). Science and technology research projects in Hebei Province (ZD2019125) and Hebei Institute of Technology (SKZ201802) for its support.

References

[1] Wang Di, Yang Shu-feng, Qu Jing-long, et al. Distribution of inclusions on surface of GH4169 ESR ingot [J]. Iron & Steel, https://kns.cnki.net/kcms/detail/11.2118.TF.20201204.0933.002.html.
[2] Geng P H, Qin G L, Zhou J, et al. Hot deformation behavior and constitutive model of GH4169 superalloy for linear friction welding process [J]. Journal of Manufacturing Processes, 2018, 32: 469 - 481.
[3] Prasad K, Sarkar R, Ghosal P, et al. Tensile deformation behaviour of forged disc of IN 718 superalloy at 650 ℃ [J]. Materials & Design, 2010, 31 (9): 4502 - 4507.
[4] DU Jinhui, L Xudong, DONG Jianxin, et al. Research progress of wrought superalloys in China [J]. Acta Metallurgica Sinica, 2019, 55 (9): 1115 - 1132.
[5] ZHU X M, GONG C Y, JIA Y F, et al. Influence of grain size on the small fatigue crack initiation and propagation behaviors of a nickel-based superalloy at 650 ℃ [J]. Journal of Materials Science & Technology, 2019, 35 (8): 1607 - 1617.