Simulation research on high speed centrifugal residual stress homogenization of turbine disk

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Abstract. At present, problems such as excessive residual stress, local stress concentration and machining deformation are common encountered in the production and processing of turbine disk. In order to further improve the machining quality and performance of turbine disk components, a high speed centrifugal stress homogenization and strengthening method with in-depth research and application value is proposed in this paper. The simulation research on the centrifugal stress homogenization effect of turbine disk forging blank is carried out, and the distribution of residual stress at different speeds is obtained, the influence of rotating speed on stress homogenization effect is summarized.

Keywords: Turbine disk, Residual stress, High speed rotation.

1. Introduction

The aero-engine is the core component of the aircraft, and its performance has an important impact on the aircraft's key performance indicators (such as flight speed, ceiling, range), safety and reliability. The turbine disk, which is the most important hot end component and key rotating part of aero-engine, is used to fix the turbine blades and transmit power[1]. In the working state of the engine, on the one hand, the turbine disk will be impacted by high temperature and high pressure gas. On the other hand, it will suffer the centrifugal load of the turbine blade and itself at high speed operation. In addition, there may be stress concentrations at the grooves, openings, installation blade edges and other structures of the turbine disk[2], which will further affect the service life and performance of the whole turbine disk. Nickel base superalloy is often used as the material for aero-engines turbine disk, due to its excellent comprehensive properties such as fatigue resistance, creep resistance, corrosion resistance and oxidation resistance under the severe service environment [3-5].

The machining accuracy and high temperature mechanical properties of turbine disk determine the performance and reliability of the aero-engine. The stress homogenization technology in the machining process is of great significance to the control of machining deformation and the improvement of mechanical properties[6-7]. The current common stress homogenization methods include thermal aging, vibration aging, and ultrasonic aging[8]. Although they are widely used, it is difficult to homogenize the residual stress of turbine disk parts due to its complicated structure. In this paper, a high speed centrifugal residual stress homogenization method is proposed to homogenize the machining residual stress of the turbine disk, and the influence of rotating speed on stress homogenization effect is studied.

2. Principle of residual stress homogenization by centrifugal stress

Residual stress is defined as the self-balanced stress that exists inside the part when it is not subjected to external load. Residual stress can be released by introducing plastic strain to the workpiece under external loads. The high speed rotating disc workpiece will be subjected to a certain centrifugal action, resulting in a centrifugal stress regularly distributed along the radius, and this centrifugal stress field will form a plastic deformation zone extending from inside to outside at a certain speed. Therefore, through the plastic deformation formed in the disc workpiece by the centrifugal stress field, the residual stress homogenization of the disc workpiece can be realized. In this process, the load applied to the material is the inertial centrifugal load of the material itself. As a typical disk part, turbine disk has the following characteristics in achieving the homogenization of residual stress by using this method.

First, the working state of the turbine disk is under the combination of high speed centrifugal load, high-temperature thermal load and vibration load. The inner edge connected with the main shaft is a dangerous section under centrifugal load. During the processing of turbine disk, centrifugal load is applied in advance to reduce the amplitude of residual stress at the inner edge, which can effectively reduce the failure risk of turbine disk in the working process.

Second, due to the forming characteristics of disc-shaped workpiece, significant stress concentration effect at the inner edge will be appeared in the forging process of turbine disk, which further increases the failure risk of the inner edge under the working state of turbine disk. The plastic zone formed by the residual stress homogenization method of high speed centrifugation extends from inside to outside, which can effectively release this part of residual stress, and thus stress concentration at the inner edge will be solved.

Third, the stress distribution of centrifugal stress field changes along the radius direction, which is matched with the disc workpiece. In contrast, the effect of dynamic stress of vibration aging and other methods on the workpiece depends on the vibration source position and the vibration mode of the workpiece, and the effect on the disk workpiece does not have a radial law.

3. Model establishment

In this paper, the turbine disk material is GH4169. The analysis of high speed centrifugation of turbine disk is based on the simulation results of forging process, and the simulation steady-state solution results of forging process are introduced as the initial residual stress field.

High speed centrifugal simulation of forged turbine disk is a small deformation process. Abaqus/Standard solver is selected and implicit algorithm is used to solve the problem.

The process of high speed centrifugation includes three stages of acceleration, uniform speed and deceleration. Considering the driving capacity of deceleration driving equipment in reality, the time scale of acceleration and deceleration stage is on the order of tens of seconds, and the dynamic effect of acceleration and deceleration has little influence on the stress field, which can be simulated as a steady-state process approximately. Therefore, the simulation analysis of high speed centrifugal stress homogenization process only considers the steady-state stress field of forged turbine disc, and the analysis step type is Static, General.

The main load of high speed centrifugal process simulation of forged turbine disc is that the centrifugal force formed by inertia acts on each position in the workpiece during high speed rotation. ABAQUS/ Standard solver can directly couple to solve various kinematics, dynamics and structural stress-strain problems. Therefore, after giving the fixed axis rotation angle speed, the comprehensive solution result including rigid body rotation is obtained. At the same time, there is no degree of freedom of motion rotating around the axis of symmetry in the analysis of the axisy-symmetric model of ABAQUS, and this rigid body degree of freedom is not needed for this problem. In this paper, the stress field under centrifugal load is only investigated, and the rotational motion is not concerned. Therefore, Rotational Body Force is selected for loading, and the whole workpiece is selected for loading scope.

For the setting of boundary conditions, in order to ensure the smooth passage of critical speed, reduce the transverse load of drive shaft and realize self centering rotation at high speed, the elastic clamping method shall be adopted for turbine disk. Correspondingly, in the ideal case, the radial elastic constraint should be established in the simulation model, and the axial rigid body displacement of the workpiece should be limited. The coupling constraint between the inner edge surface and the reference point is established, the axial and in-plane torsional degrees of freedom of the reference point are constrained, and the radial spring constraint is added to equivalent the radial clamping stiffness.

4. Solution results of high speed centrifugal process of turbine disk

In the case of centrifugation at different speeds, the corresponding stress changes and distribution results are obtained after solving. As shown in Figure 1, the Mises equivalent stress distribution cloud diagram of the initial forged turbine disk without high speed centrifugation is shown. 100 nodes were taken along the radius of the middle layer of the turbine disc, and the stress of the nodes was extracted respectively.

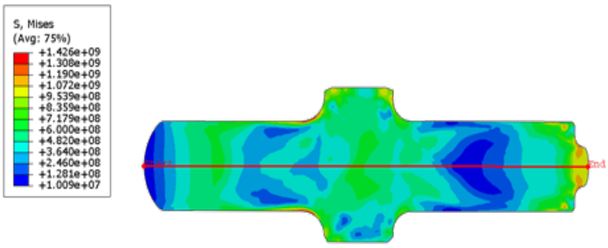

Figure 1: Schematic diagram of stress extraction path

Figure 2 and figure 3 show the Mises equivalent stress distribution of the interlayer nodes taken after centrifugation at different speeds. It can be seen that the stress difference is large at the position close to the inner edge, while the stress difference is small at the position close to the outer edge at different speeds, and the difference gradually decreases from the inside to the outside. On the other hand, with the increase of rotating speed, it can be seen that the stress distribution curve moves down as a whole, and the first peak on the inner side moves outward. According to the distribution law of centrifugal stress during rotation within the elastic range, the inner edge is a dangerous point for workpieces such as turbine disk rotating at high speed. Therefore, it is ideal to reduce inner edge stress as much as possible after high speed centrifugation. Therefore, it can be seen from the results in the figure that the Mises stress at the inner edge is the smallest and close to zero at the speed of 1800 rad/s. Although the peak value is slightly higher than that at the speed of 2000 rad/s, the innermost stress rises again at the speed of 2000 rad/s or higher.

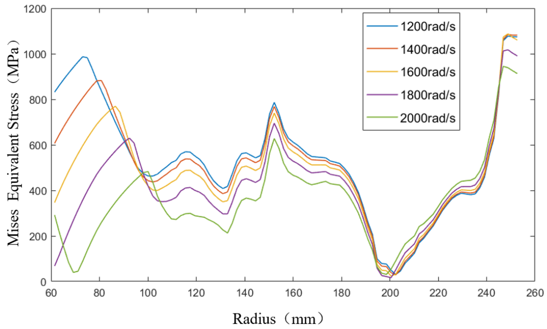

Figure 2: Mises equivalent stress distribution along radius

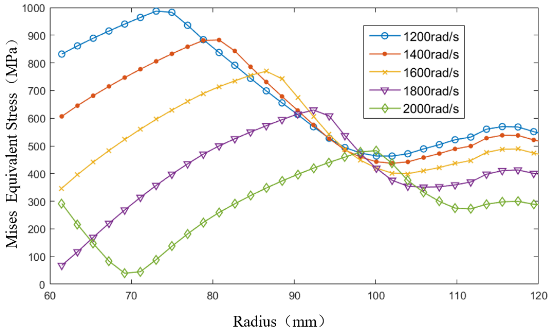

Figure 3: Mises equivalent stress distribution along radius (local)

Figure 4 and figure 5 show the distribution of the radial stress of the middle layer node after centrifugation at different speeds. It can be seen from the figure that its distribution law is similar to the Mises equivalent stress. With the increase of speed, the curve gradually moves down near the inner edge, while there is little difference at different speeds on the side near the outer edge. However, the stress at the innermost point of radial stress has little difference at different speeds.

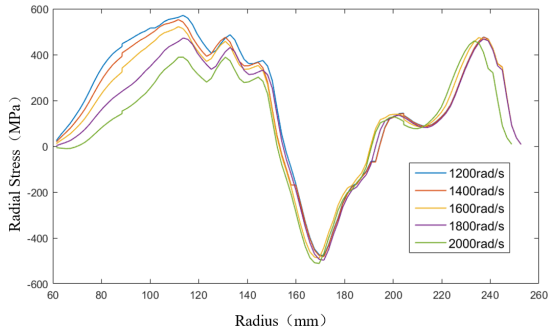

Figure 4: Radial stress distribution along radius

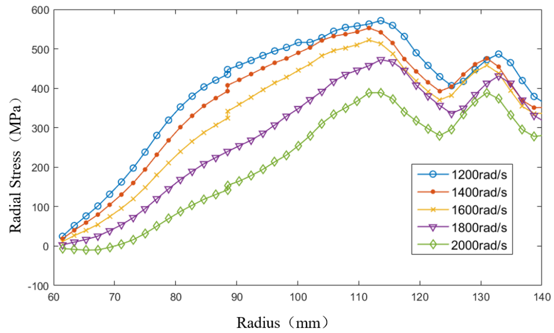

Figure 5: Radial stress distribution along radius (local)

Figure 6 and figure 7 show the axial stress distribution of the selected middle layer nodes. Since the axial stress of the centrifugal stress field formed by high speed centrifugation is almost zero, it has little effect on the axial stress distribution of the turbine disk itself, and only slight changes due to stress coordination under the action of radial and tangential stresses.

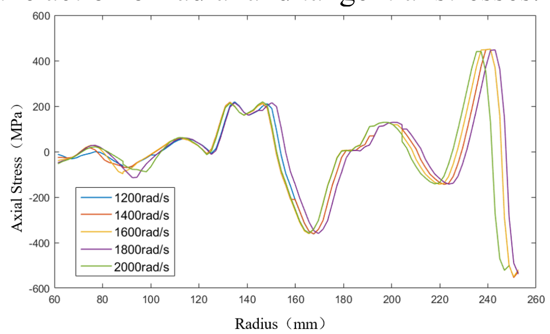

Figure 6: Axial stress distribution along radius

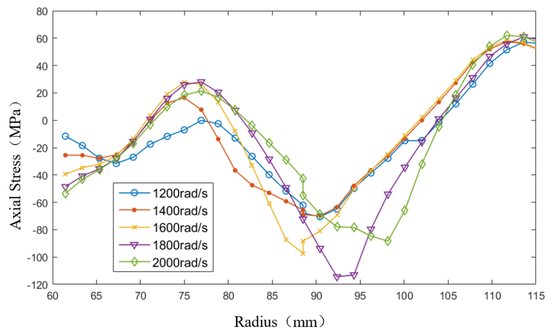

Figure 7: Axial stress distribution along radius (local)

Figure 8 and figure 9 show the circumferential stress distribution of the nodes in the middle layer. In the three-dimensional stress, the circumferential stress amplitude is the largest, which is also the stress direction that has the greatest impact on Mises equivalent stress. After centrifugation at different speeds, it also meets the above distribution law.

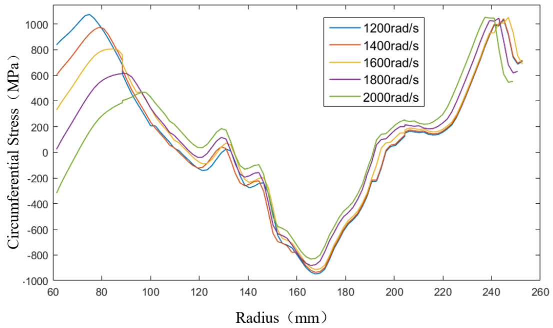

Figure 8: Circumferential stress distribution along radius

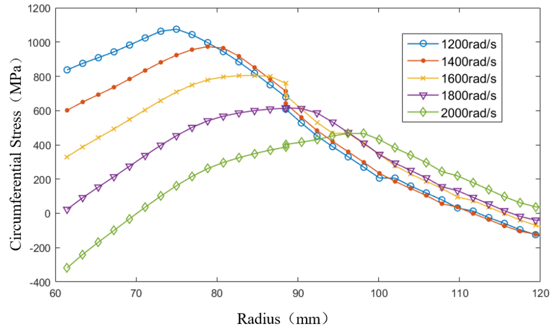

Figure 9: Circumferential stress distribution along radius (local)

According to the above law, the rotating speed of 1800 rad/s has the best homogenization effect on the residual stress of forged turbine disk. Figure 10 compares the initial treated state with the state after 1800 rad/s centrifugation. It can be seen that the Mises stress decreases significantly along the radius, and the decrease is most obvious at the dangerous point. At the same time, the magnitude of the first stress peak near the inner side decreased from 1165MPa to 630MPa, and the peak moved significantly outward. The risk of material failure at dangerous points during turbine disk operation is reduced.

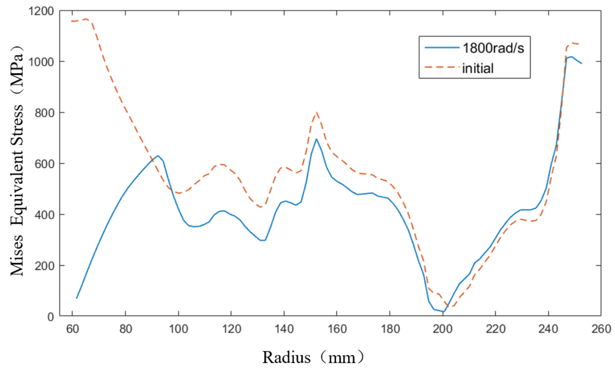

Figure 10: Comparison of Mises stress distribution before and after high speed centrifugation

5. Conclusion

In this paper, the effect of high speed centrifugal stress homogenization on the turbine disk under the stress state of blank isothermal die forging is explored. By establishing several groups of simulation analysis models with different speeds, the influence law and change trend of speed on the effect of high speed centrifugal stress homogenization of turbine disk are determined.

From the stress distribution of the forging blank of the turbine disk, it can be known that the inner edge is prone to stress concentration in the forging process and failure risk in the working state. From the stress distribution of the turbine disk after high speed centrifugation, the following conclusions can be obtained. First, the high speed centrifugation process can effectively reduce the stress at the inner edge of the forging blank of the turbine disk, and the stress drop is related to the centrifugal speed. Secondly, with the increase of centrifugal speed, the stress amplitude at the dangerous point of turbine disk, that is, at the inner edge, decreases first and then increases, and there is the best centrifugal speed.

It can be seen from this paper that the high speed centrifugation method has positive significance for stress homogenization of the blank forged by turbine disc, which is of great value for reducing the deformation in subsequent processing and improving the dimensional stability of parts, and is also of value for further practical research.

Acknowledgments

We acknowledge financial supports from Defense Industrial Technology Development Program (JCKY2020601C004) and National Natural Science Foundation of China (52005018).

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