The heat treatment effect on the surface characteristics of 9310 steel gear

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Abstract. Gear is one of the key parts of aviation industry. With the rapid development of the aviation industry, the design and precision of gears, in particular 9310 steel ones, are permanently improved. This paper focuses on the heat treatment effect on the surface performance of 9310 steel gear. The heat treatment simulation of aviation gear is carried out the DEFORM-3D software. The effects of quenching and tempering temperature on the surface hardness and residual stress of gear are analyzed, which provides a theoretical basis for the heat treatment improvement of 9310 steel gear.

1. 9310 steel gears used in helicopter drive system

The gear studied is used in the planetary gear mechanism of the helicopter main reducer, whose input is the sun wheel and output are the planet carrier as shown in figure 1 and 2. The ring gear is fixed, the sun wheel is an active part and rotates clockwise, while the star carrier is a passive part. The rotation of the planetary carrier driven by the sun wheel is still the largest gear driven by the pinion, which is a kind of deceleration movement and has the largest transmission ratio. The quality of gear tooth surface directly affects the performance, reliability, maintainability, supportability and life cycle cost of helicopter [1-3]. Table 1 shows the parameters of the planetary gear set. Gear is a transmission part, and gear material needs to have high hardness, toughness and wear resistance. 9310 steel has good hardness and toughness after overheating treatment, and it has been used more and more as gear material.

|                | Number of teeth | Modulus  | Face width |
|----------------|----------------|----------|------------|
| Sun wheel      | 38             | 2.822    | 52         |
| Planet gear    | 47             | 2.822    | 50         |
| Ring           | 138            | 2.822    | 42         |
2. 9310 steel gear heat treatment process and heat treatment simulation

2.1. Heat treatment process

The mechanical properties of 9310 steel after quenching can reach high strength and toughness, and the repeatability is very good [4-7]. Some researchers have found that the flow stress and peak strain of 9310 steel decrease with the increase of deformation temperature and the decrease of strain rate, indicating the change of stress [8]; after tempering at 150-250 ℃, the fine ε carbide disperses and precipitates in the lath martensite matrix, so 9310 steel has the best combination of strength and toughness [9-11]. The gear material 9310 steel is studied in this paper. The chemical composition and mechanical properties of 9310 steel are shown in the table 2.

Table 2. Chemical composition of 9310 steel (mass fraction, %).

|    | C   | Mn   | Si   | Cr   | Ni   | Mo   | P    | S     |
|----|-----|------|------|------|------|------|------|-------|
|    | 0.08~0.13 | 0.45~0.65 | 0.150~0.40 | 1.00~1.40 | 3.0~3.5 | 0.10~0.05 | <0.025 | <0.025 |

The gear heat treatment process of 9310 steel material is normalizing, quenching, tempering, carburizing, cryogenic treatment and low temperature tempering (Table 3).

The purpose of the process before carburizing is to improve the grinding performance of the parts, so three processes of normalizing, quenching and tempering are added. Carburizing is one of the most widely used chemical heat treatment methods in the mechanical manufacturing industry at present. The so-called carburizing is that the workpieces made of low-carbon steel or low carbon alloy steel are placed in the carbon rich active medium, heated to 850 ~ 950 ℃ for a period of time, so that the carburizing medium produces the active carbon atoms on the surface of the workpieces, and then infiltrates into the cladding of the workpieces through surface absorption and diffusion, so as to make the carbon content of the layer is more than 0.8%. Carburizing is to make the surface layer of low carbon steel have high hardness and wear resistance, and the central part of the workpiece still maintains the toughness and plasticity of low carbon steel.

After carburizing, the retained austenite can be decomposed by high temperature tempering. The carbon and alloy elements in carburizing layer are precipitated in the form of carbide. Carburizing is used to improve the strength, impact toughness and wear resistance of parts, so as to extend the service...
life of parts. Cryogenic treatment is beneficial to the transformation of retained austenite to obtain stable structure and properties, thus further improving the surface hardness and wear resistance. After low-temperature tempering, the surface layer is tempered martensite, secondary cementite, and retained austenite, which has better wear resistance, while the center part is low-carbon tempered martensite and free ferrite. Because the grains have been refined by quenching, the toughness and strength are better.

| No. | Process       | Equipment | Parameter                                                                 |
|-----|---------------|-----------|---------------------------------------------------------------------------|
| 1   | Normalizing   | Double    | 930 ± 14 ℃, heat preservation 1.5 ~ 2H, air cooling                      |
| 2   | Quenching     | Rotary    | 820 ℃, 1.5-2h, hot oil cooling                                           |
| 3   | Tempering     | Parallel  | 450 ℃, 2.5-3h, air cooling                                              |
| 4   | Carburization | Controlled| 927 ℃, 0.9% carbon potential for 9h, 5h high-temperature tempering       |
| 5   | Tempering     | Carburizing| 600 ℃, heat preservation for 3 ~ 3.5H, nitrogen cooling                  |
| 6   | Quenching     | Parallel  | 820 ℃, 1.5h, hot oil cooling                                            |
| 7   | Tempering     | Rotary    | 450 ℃, heat preservation for 4h, air cooling                            |

2.2. Heat treatment simulation

Using the DEFORM-3D software with special heat treatment module to simulate the heat treatment process of gear parts, the influence of heat treatment parameters on the integrity of gear surface is obtained. In this paper, the sun gear in the planetary gear mechanism is selected as the research object, and its parameters are shown in table 2.

The main processes of gear heat treatment of 9310 steel are normalizing, quenching, tempering, carburizing, tempering, quenching, cryogenic treatment and tempering. Model the above process in DEFORM-3D software, as shown in figure 3.

![Figure 3. Heat treatment process flow of 9310 steel gear in DEFORM-3D software.](image-url)
The material parameters, heat treatment medium parameters, process parameters and boundary conditions are set in DEFORM-3D. In the simulation analysis of heat treatment, the medium of each heat treatment process is different, such as heating, carburizing, oil cooling, air cooling and nitrogen cooling. Different media have different heat transfer coefficient and surface deformation coefficient. The general heat treatment scheme is shown in figures 5 and 6.

The simulation calculation process is completed in DEFORM-3D, and the heat treatment simulation results of 9310 steel gear are obtained. Take the martensite content diagram of gear as an example, as shown in figure 7.

3. Analysis of simulation results
The quenching temperature of 9310 steel is in the range of 780-840°C. In this paper, the simulation model of gear heat treatment under different quenching temperature is established by DEFORM-3D. The influence of quenching temperature on the residual stress and hardness of gear surface is studied under the premise of the remaining technology unchanged.
3.1. Effect of quenching temperature on gear hardness

In this study, a point p1 on the tooth surface and two points P2 and P3 along the depth direction are selected to study the effect of quenching temperature on the hardness, stress and deformation of these three points. Finally, the following results are obtained.

Select several groups of points randomly on the tooth surface, and take the average value of hardness as the research object. Figure 8 shows the change of gear hardness along the direction of tooth thickness at different quenching temperatures. With the increase of quenching temperature, the hardness of gear increases continuously. At 820°C, the surface hardness reaches the maximum value of 62.1 HRC, and then the change of hardness tends to be stable. The reason is that with the increase of quenching temperature, the carbides of alloy elements in the material dissolve gradually, and the uniformity of carbon in austenite also increases slowly. After quenching, the saturation of carbon in martensite is also increasing, so the hardness of gear is increasing with the increase of quenching temperature, and then the change of hardness of gear surface tends to be gentle with the gradual saturation of carbon in martensite.

![Figure 8. Effect of quenching temperature on hardness.](image)

3.2. Effect of quenching temperature on gear residual stress

Several groups of points are randomly selected on the tooth surface, and the average value of residual stress is taken as the research object. Figure 9 change of residual stress along the direction of tooth thickness under different quenching temperatures. With the increase of quenching temperature, the residual compressive stress decreased gradually, and after reaching 820°C, the change tended to be gentle. The reason is that with the increasing of quenching temperature, the thermal stress in the gear is increasing, because the thermal stress will lead to tensile stress on the surface of the material, so with the increasing of quenching temperature, the residual compressive stress on the surface of the material is decreasing. When the quenching temperature continues to rise, the transformation stress of the material increases, and neutralizes with the thermal stress, which makes the residual stress on the surface of the material tend to be stable.

![Figure 9. Effect of quenching temperature on residual stress.](image)

3.3. Effect of tempering temperature on gear hardness

The tempering process is mainly to eliminate or reduce the residual stress, refine the structure of the material, and improve the performance of the material. After tempering, the microstructure is mainly tempered martensite, and the hardness is slightly smaller than that of quenched martensite. In the tempering process, the influence of tempering times and temperature on the microstructure and properties of materials is more obvious than that of tempering time. A simulation model of gear heat treatment under different tempering processes is established to study the influence of tempering process on the hardness and microstructure and properties of gear surface.
The rest of the process remains unchanged. Figure 10 shows the hardness distribution of 9310 steel at different tempering temperatures. With the increase of tempering temperature, the hardness of tooth surface increased, and the hardness of tooth surface reached the maximum value of 61.1 HRC at 400 °C. As the tempering temperature continues to increase, the hardness of the tooth surface decreases to 54.3 HRC at 550 °C. The reason for the above phenomenon is that: with the increase of temperature, the martensite in the structure decomposes, but at this time, the retained austenite transforms to the bainite, and the hardness of the lower bainite is higher than that of the retained austenite, so the hardness of the material increases; when the temperature exceeds 400 °C, the speed of martensite decomposition is faster than that of the formation of the lower bainite, and the hardness of the material decreases obviously.

![Figure 10. Effect of quenching temperature on hardness.](image1)

![Figure 11. Effect of tempering times on residual stress.](image2)

3.4. Effect of tempering times on gear residual stress

The influence of tempering times on the residual stress of tooth surface was studied by using the original heat treatment process. Figure 11 shows the residual stress curve of 9310 steel under different tempering times. With the increase of tempering times, the deformation of material structure gradually recovers, the residual compressive stress of tooth surface decreases, and the residual stress inside the gear is effectively released, which shows that the stability of material structure is enhanced, which is helpful to improve the mechanical properties of the gear.

4. Analysis of the influence of gear surface heat treatment process on gear surface

According to the difference of the causes of the internal stress in heat treatment, the internal stress in heat treatment can be divided into the thermal stress caused by thermal expansion and contraction and the organizational stress caused by different phase transformation.

Quenching cooling is in the initial stage, because the surface cooling speed is relatively fast, at this time, the core is still in a relatively high temperature range, so the shrinkage of the surface will be resisted by the core, so the surface will generate tensile stress, and the core will generate compressive stress. In the process of continuous cooling, the surface temperature has not decreased as fast as the core temperature, and the core has a larger shrinkage than the surface, which makes the surface tensile stress and the core compressive stress tend to reduce until all disappear, but at this time, there is still a temperature difference on the tooth section, and in the process of continuous cooling, the core shrinkage is still greater than the surface At this time, the contraction of the core will be restrained, so that the gear core will generate tensile stress and the surface will generate compressive stress.

The microstructure stress of gear during quenching is mainly caused by the temperature difference between the surface layer and the center of the steel, which results in the different transformation of martensite. During quenching, when the surface temperature of gear is lower than the martensitic transformation temperature MS, the martensitic transformation occurs, and the temperature of the core is still above Ms. the expansion due to the martensitic transformation of the surface will be resisted by
the core without martensitic transformation, which will result in the formation of compressive stress in the surface and tensile stress in the core. In the process of continuous cooling, when the core temperature drops below Ms and martensite transformation occurs, because the surface layer has been transformed into martensite with high strength and low plasticity, plastic deformation can no longer occur, so the expansion of the core will be restrained by the surface layer, so that the internal stress of the gear will reverse, the surface layer will generate tensile stress, and the core will generate compressive stress.

5. Conclusion

In this paper, the influence of heat treatment process on the surface hardness and residual stress of 9310 steel gear is studied. The heat treatment process of gear workpiece is simulated by heat treatment module of DEFORM-3D software, and the simulation results of heat treatment are obtained.

The distribution law of hardness and residual stress on the surface of gear under different quenching temperature is analyzed. The influence of different tempering temperature on the hardness of gear surface and the influence of tempering times on the distribution of residual stress are analyzed. The distribution curve of hardness and residual stress is obtained. The results obtained provide a theoretical basis for the heat treatment process of 9310 steel gear.

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