Study on screw rotor thermal machining method of single screw compressor

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Abstract. Single screw compressor (SSC) is a type of rotary compressor with excellent performance. However, under high temperature conditions, the hot deformation of the screw rotor and the star wheel cause the change of the gap of the meshing pairs, which seriously degrades the compressor performance. In order to solve the problem of the gap variation of the meshing pairs, a new hot-state machining method is proposed to study the deformation characteristics of the screw rotor in the hot-state machining process, which provides some reference data for the pre-deformation of the rotor in the machining process. Numerical calculation model of thermal machining process for screw rotor was established by using finite element method. With the validated model, the deformation characteristics in the process of hot working were studied by changing the number of heating holes, diameter of heating holes and temperature of heating holes. Results show that screw rotor deformation will increase with the increase of heat source temperature and diameter, and the deformation distribution of the screw rotor is not significantly affected by the heat source temperature and diameter, but will be more uniform with the increase of heat source quantity. The research work in this paper can provide theoretical basis for hot machining of screw rotor for SSC.

1. Introduction

The single-screw compressor (SSC) was invented by the French engineer Zimmern in the 1950s [1], which is composed of a screw and two symmetrically arranged star wheels as shown in the figure1. SSC has the advantages of small volume, good force balance performance, high volume utilization rate, has been widely used in refrigeration and air conditioning, aerodynamics, process gas compression and other fields. Nowadays, with the rapid development of contemporary society, the carbon emissions are constantly rising, resulting in increasingly serious environmental problems [2-4], improving energy efficiency is of great significance to alleviate the environmental problem. In recent years, in order to improve energy efficiency, low temperature heat-pump, mechanical vapor recompression (MVR) system have been rapidly developed [5-8]. Considering the great mechanical
property and wide operation range, single screw compressor (SSC) has received increasing attention in these fields. As shown in figure 1, SSC relies on the meshing movement between the star-wheel and the screw rotor to form a periodically changed working chamber to achieve gas suction, compression and discharge. So the meshing pair is the core working component of the SSC. However, the axis of the star-wheel and the screw rotor is spatially perpendicular, which makes the meshing profile characteristics become very complex. The thermal deformation of SSC during operation causes the deviation of the center position of the star wheel and screw, which has a complex influence on the mating position of the meshing pair, directly affects the meshing relationship of the meshing pair, and reduces the reliability of the meshing pair. Therefore, it is of great significance to study the thermal deformation mechanism of screw rotor under hot machining condition.

![Figure 1. The structure of a single screw compressor](image)

In order to research the thermodynamic deformation mechanism of meshing pair tooth profile under the action of multiple coupling fields, a series of studies have been carried out for the deformation characteristics theoretical analysis, deformation predict and the deformation compensation design on the compressor by the scholars at home and abroad. Diao and Yang et al. calculated the thermal and force deformations of oil-free twin screw compressors, the research results show that the force deformations were much smaller than the thermal deformations \([9,10]\). Hsieh et al. proposed a mathematical model and a calculation procedure to efficiently calculate the temperature distributions in the male and female rotors of the oil-injected screw compressors. The temperature distributions of the screw rotor is calculated in their study \([11]\). Mustafin et al. analyzed the formation and factors influencing the profile clearances of screw compressors \([12-15]\). As for the single screw compressor, Zhou comprehensively analyzed the working process of the single screw compressor, and calculated the temperature field and thermal deformation of the main components of single screw compressor by using the boundary element numerical technology. Based on research results, the influences of thermal deformation on the leakage and on the fit clearance of the compressor under the working state were simulated \([16,17]\).

According to the above literatures, scholars at home and abroad have analyzed the factors causing the thermal deformation of the compressor, but have not compensated for the change of the clearance caused by the thermal deformation, resulting in the thermal deformation of the compressor has not been well controlled. To this end, this paper present a thermal machining method of screw rotor for single screw compressor. Which use the simulation of the screw rotor under the hot processing...
condition, the deformation of the screw rotor was obtained to compensate for the gap change of the mesh pair caused by the hot deformation under the load condition of the single screw compressor, so as to improve the hot meshing characteristics of the single screw compressor.

2. **Theoretical basis of thermal expansion**

In this paper, the single screw steam compressor used in high temperature heat pump has been selected as the physical model to investigate the thermal machining process of the screw rotor. The material property of the screw rotor are shown in table 1.

**Table 1.** Material properties of brass

| Parameter                        | Brass (Analytical model) | QT600-3 (Validation model) |
|----------------------------------|--------------------------|---------------------------|
| Coefficient of expansion /K⁻¹    | 1.85×10⁻⁵                | 1.2×10⁻⁵                  |
| Modulus of elasticity /GPa       | 90                       | 170                       |
| Density /kg·m⁻³                  | 8600                     | 7300                      |
| Poisson ratio                    | 0.36                     | 0.27                      |
| Thermal conductivity /W·m⁻¹·K⁻¹  | 120                      | 35.5                      |

2.1 **The geometry model**

The geometry model of the screw rotor hot machining process used in finite element method (FEM) is show in figure 2 (take the hot machining model with 3 heat sources for example). In this paper, the geometry model of the screw rotor hot machining process was modified with different thermal machining parameters as follows:

1) Adding 1, 2, 3 and 4 heat sources to the screw rotor model separately.
2) Changing the diameter of heat sources to 10mm, 12mm, 14mm, 16mm, 18mm and 20mm.
3) The heat sources established in (1) was loaded with thermal loads of 160°C, 180°C and 200°C respectively.
4) Adding a PATH channel.

![Figure 2. The position of three heating holes in the screw rotor](image-url)
Figure 3 show the meshing diagram of the screw rotor with three heating holes of 18mm diameter. Because of the complex structure of these components, the tetrahedral mesh has been chosen. Different mesh sizes are numerically checked for the grid dependency of temperature of lines on the screw rotor. Considering the calculation data, cost of simulation time and the grid independence test, the final selected element numbers of screw rotor are 259846, the minimum size is 2.5mm. The average grid cell mass of screw rotor is 0.805. And the mesh pass the grid independence test. So the element quality meets the calculation requirements.

![Meshing diagram](image1)

![Grid independence test](image2)

**Figure 3.** Mesh details

### 2.2 Boundary conditions

When the temperature load is applied to the screw rotor, the thermal deformation of the screw rotor will be induced. In the prototype, the screw rotor and the screw shaft were fitted through interference mode. The screw rotor can be fixed and supported axially by two angular contact ball bearings installed on the shaft in exhaust side. But in the suction side, the screw rotor can be fixed and supported by the cylindrical roller bearing, the screw shaft can freely adjustable in the axial. Therefore, the screw rotor should be constrained on the exhaust end with fixed constraint, and be constrained on the section end with the axial displacement of the constraints, keep the axial degree of freedom. In this paper, two different thermostatic heat sources are set on the surface of the screw rotor heating hole and the whole screw rotor, so that a constant temperature is obtained on the surface of the heating hole, and the screw rotor is thus heated. The screw rotor with three heat sources was taken as an example. The surface temperature of the heating hole was set at 180℃ and the ambient temperature was set at 22℃, as shown in the figure 4.

![Boundary conditions](image3)
3. Result and discussions

3.1 The parameters of the SSRC

Combining with the geometric model of the screw rotor thermal machining process and the thermal deformation analysis model of screw rotor describing the thermal processing characteristics of the SSC, the Numerical calculation model used to analysis the thermal machining process of the SSC can be set up. In order to solve and verify this model, a typical single screw compressor with the structure parameters as shown in table 2 was developed in this paper as an example for the theoretical and experimental study. By using this FEM, the thermal processing characteristics of the SSC are investigated and the influence of the thermal machining parameters on the preset thermal deformation characteristics are also discussed in this section.

Table 2 Structure parameters of the SSC with MEMP

| Structure parameters             | Value   | Structure parameters             | Value   |
|---------------------------------|---------|---------------------------------|---------|
| Screw rotor diameter /m         | 0.181   | Suction seal angle $\alpha_s$/rad| -0.681  |
| Screw rotor length /m           | 0.1557  | Central distance /m             | 0.1448  |

3.2 The Path deformation analysis

By using the verified model, the thermal machining characteristics of the SSC with the structure parameters shown in table 2 were studied. For investigating the influences of the thermal machining on the thermal machining characteristics, further researches are presented to evaluate the effects on the thermal deformation of the screw groove profile. The concentrated heat load, quantity loaded and the diameter of the heat source were selected as the main operating parameters to be examined.

Figure 5 shows the thermal deformation of different heat sources under the condition that the heat source temperature is equal to 180°C and the heat source diameter is equal to 20mm. As shown in the figure 5, the thermal deformation near the inlet and outlet ends is large, and the minimum deformation
is in the middle. It can be seen from the variation tendency of the thermal deformation along the path from the inlet end to the outlet end that a deformation peak is reached quickly, and then the deformation begins to decrease until the intermediate position reaches the minimum value, and then begins to rise to reach the second peak and also the maximum deformation near the outlet end, and then there is a downward trend before reaching the outlet end. By changing the number of heat sources, the deformation distribution of the screw rotor did not change much, but with the increase of heat source, the deformation increased, but the thermal deformation is more uneven.

Figure 5. The deformation of the path of the screw rotor with different heat sources

Figure 6 shows the deformation of different heat source diameters when there are three heat sources and the heating temperature is equal to 180℃. As shown in this figure, the deformation near the inlet and outlet ends is large, and the minimum deformation is in the middle. It can be seen from the variation tendency of the thermal deformation along the path from the intake end to the outlet end that, the thermal deformation variation tendency with different heat source diameters is the same with each other. By changing the heat source diameters of the screw rotor thermal machining process, the Uniformity of the thermal deformation of screw rotor did not change greatly. But the thermal deformation value of the screw rotor increased with the increase of the heat source diameters. When the heat source is doubled in diameter, the deformation increases by 43%.

Figure 6. Deformation of the path of screw rotor with different heating hole diameters

Figure 7 shows the deformation at different heat source temperature when there are three heat sources and the heating hole diameter is equal to 20mm. As shown in the figure 7, the variation tendency of the thermal deformation along the path from the intake end to the outlet end under different heat source temperature is the same with each other. By changing the heat source temperature of the screw rotor, the deformation distribution of the screw rotor changed little, but with the increase of heat source temperature, the deformation increased, When the heat source temperature be increased by 25%, the deformation will be increased by 30.5%. By comparing the influence of heat
source diameter and temperature on thermal deformation, the influence of heat source diameter on thermal deformation is greater than that of heat source temperature.

![Figure 7. The deformation of the path of the screw rotor with different heat source temperature](image)

The uniformity of the thermal deformation of the screw groove at the same star wheel rotation angle is an important standard to measure the thermal machining characteristics. So the thermal deformations of the screw rotor groove profile along the circumference were analyzed. The results are as follows:

Figure 8 and figure 9 shows the thermal deformation under different heat sources when the heat source temperature is equal to 180°C and the heat source diameter is equal to 20mm. As shown in the figure 8 and figure 9, when there is one heat source, the side of the screw groove with the heat source has the maximum deformation, but the other part of the screw rotor without heat source basically does not have the deformation. When there are two heat sources, the maximum deformation is located near the plane composed of the central line of the screw rotor axial and the central line of the heat source. The deformation near the two heat sources is roughly the same. The deformation is distributed symmetrically along the axis with the central line of the heat source. When there are three and four heat sources, the maximum deformation also occurs near the installation location of heating source, and the deformation is roughly rotational symmetry. When there are multiple heat sources, the deformation decreases rapidly from the heat source installation location until the farthest distance from the heat source reaches the minimum, and then begins to increase to the position of the next heat source. The deformation is distributed symmetrically on the axis of the heat source. At the same time, the heat source is different, the place with the greatest deformation is all outside the heat source. By changing the heat source number acted on the screw rotor, the deformation distribution of the screw rotor did not change much, but with the increase of heat source, the deformation increased.

![Figure 8. The deformation of the spiral groove of the screw rotor with different heat sources](image)
Figure 9. The contour of the spiral groove of the screw rotor with different heat sources

Figure 10 shows the thermal deformation of the screw rotor with different heat source diameters when there are three heat sources and the heating temperature is equal to 180°C. As shown in the figure 10, the deformation was mostly located near plane composed of the central line of the screw rotor axial and the central line of the heat source, and outside the heat source. The deformation is distributed symmetrically on the axis of the heat source. By changing the heat source diameter acted on the screw rotor, the deformation distribution of the screw rotor did not change greatly, but the deformation increased with the increase of the heating hole diameters. The curves in figure 10 were also compared and analyzed to research the effect of the heat source diameter on the thermal deformation uniformity of the screw rotor during the thermal machining process. By contrast of the curves in figure 9, the amplitude variation range of thermal deformation increases gradually with the increase of the heat source diameter. So the thermal deformation uniformity of screw rotor during the thermal machining process will be increased with the increase of the heat source diameter.

Figure 10. Deformation of the spiral groove of screw rotor with different heating hole diameters

Figure 11 shows the thermal deformation of the screw rotor at different heat source temperature when there are three heat sources and the heating hole diameter is equal to 20mm. As shown in the figure 11, the thermal deformation distribution of the screw rotor changed little when the heat source temperature of the screw rotor increased, but with the increase of heat source temperature, the thermal
deformation of the screw rotor increased. The contrast of the curves in figure 11 shows that the amplitude variation range of thermal deformation remain nearly constant with the increase of the heat source temperature. So the thermal deformation uniformity of screw rotor during the thermal machining process will be remain nearly constant when the heat source temperature increases.

![Figure 11. The deformation of the spiral groove of the screw rotor with different heat source temperature](image)

4. Conclusion

In this paper, Numerical calculation model of thermal machining process for the screw rotor in SSC was established, and the thermal deformation law of screw rotor and the effect of thermal machining parameters on the deformation characteristics of the screw groove profile were investigated for SSC. Through analysis, the following conclusions can be drawn:

1) The heat source number has influences on the thermal machining characteristics of screw rotor. The thermal deformation and its uniformity along the peripheral direction increases gradually with the increase of the heat source number. But the thermal deformation is more uneven along the screw rotor axis when the heat source number increases.

2) The heat source diameter is a factor that affects the machining characteristics of screw rotor. The thermal deformation value of the screw rotor increases with the increase of the heat source diameters. When the heat source is doubled in diameter, the deformation increases by 43%. The amplitude variation range of thermal deformation increases gradually with the increase of the heat source diameter. So the thermal deformation uniformity of screw rotor during the thermal machining process will be increased with the increase of the heat source diameter.

3) The heat source temperature is also an important factor affecting the machining characteristics of screw rotor, the deformation increased with the increase of heat source temperature. When the heat source temperature be increased by 25%, the deformation will be increased by 30.5%. The amplitude variation range of thermal deformation remain nearly constant with the increase of the heat source temperature. By comparing the influence of heat source diameter and temperature on thermal deformation, the influence of heat source diameter on thermal deformation is greater than that of heat source temperature.

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