Design and analysis of the swage for swage autofrettage with a center hole

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Abstract: The design of tungsten carbide swage with a center hole is proposed, the interference between the cylindrical mandrel and the inner hole of the tungsten carbide swage is performed by thermal expansion and contraction to form a combined swage. The stress and displacement of the combined swage are simulated and analyzed by ABAQUS finite element software under different interferences and compared with the displacement of high-speed steel swage and solid tungsten carbide swage under working conditions. The results show that the combined swage can not only meet the requirements of autofrettage, but also can reduce the manufacturing difficulty of tungsten carbide swage with a large diameter.

1. Introduction

Swage autofrettage process is when a swage with a diameter slightly larger than that of the thick-walled cylinder is pressed inside the thick-walled cylinder with mechanical or hydraulic power, so that it can produce a plastic deformation and beneficial residual stress to increase their fatigue lives and load bearing capacity. In the process of swage autofrettage, the swage is the key, and it is difficult to manufacture tungsten carbide swage (called TCS) with a large diameter. Using tungsten carbide as the material of the swage is recommended in the actual process, sometimes using high-speed steel instead. In order to minimize the impact on the autofrettage effect of the thick-walled cylinder due to the compressive deformation of the swage, the swage material needs to have a good resistance against deformation. The TCS made of tungsten carbide and cobalt by powder metallurgy process has the elastic modulus of 590 GPa. Good compression, wear resistant and high elastic modulus make tungsten carbide with cobalt suitable as the material for swage [1,2,3,4].

With the increase of the tungsten carbide volume, the tungsten carbide with the same material is more difficult to manufacture due to the volume effect. The tungsten carbide volume increased, it is difficult to remove the forming agent, and the phenomenon of high carbon in the core and low carbon on the surface is easily produced. In order to ensure sufficient sintering of the large diameter tungsten carbide, a higher sintering temperature and a longer time are often used, which intensifies evaporation and migration of cobalt in liquid-phase sintering, resulting in a compositional gradient, increasing the internal stress of the swage or reducing the resistance of the surface. The uniformity of all parts’ density also increases as the volume increases, which reduces performance and lifetime[5].

Based on the above reasons, this paper proposes the design of combined swage, the interference between the cylindrical mandrel and the inner hole of the TCS was performed by thermal expansion and contraction. The combined swage structure shown in Figure 1, consists of two parts: TCS with a hole and cylindrical mandrel, in the axial, swage consists of three parts: front cone, cylinder and tail cone [6]. It greatly reduces the sintering time and guarantees the quality of large size tungsten carbide.
The cylindrical mandrel used tool steel which acted as a seal during the swage autofrettage process driven by hydraulic force.

Figure 1. Combined swage structure.

2. Theoretical analysis of swage autofrettage

Figure 2 shows the contact diagram of the swage autofrettage. The friction between the swage and the thick-walled cylinder in the autofrettage process is not counted here.

Parameters and symbols explained (reference hereinafter):

- $P_1$: contact pressure among the front cone and the thick-walled cylinder;
- $P$: contact pressure among the cylinder and the thick-walled cylinder;
- $P_2$: contact pressure among the tail cone and the thick-walled cylinder;
- $\delta$: radial interference between the swage and the thick-walled cylinder;
- $\alpha$: angle between the axis and the forward taper of the swage;
- $\beta$: angle between the axis and the rear taper of the swage;
- $a$: inside radius of the thick-walled cylinder;
- $b$: outside radius of the thick-walled cylinder.

In this paper, the wall ratio $wb = 2.2$, the percent overstrain $k = \rho - a / b = 100\%$, now, the plastic radius $\rho$ of the thick-walled cylinder is equal to the outside radius $b$, and the thick-walled cylinder is fully plastic. According to the literature [7]:

$$\delta = \frac{\Phi(a_i)}{2E} \left[ 2(1 + \mu) + 3(1 - 2\mu) \left( \frac{F^2}{w^2} + \frac{1}{F^2} \right) \right] + \left[ \left( 1 - 2\mu \right) \frac{F^2}{w^2} + \frac{3}{F^2} \right]$$

$$\cdots + \frac{(1 - \mu_m) \Phi(a_i)}{E_m} \left( 1 - \frac{F^2}{w^2} + \ln F^2 \right)$$

(1)
Where: \[ \Phi(a_i) = \sigma_s \left( \sqrt{3} \sqrt{1 + 3a_i^4 / \rho^4} \right)^{-1} \]
\[ F = \rho / a = k(w-1) + 1 \]

\( \sigma_s \) - yield stress of the thick-walled cylinder;
\( a_i \) - cylinder radius of the swage;
\( \mu_m, E_m \) - poisson ratio and elastic modulus of the swage;
\( \mu, E \) - poisson ratio and elastic modulus of the thick-walled cylinder.

Known the cylinder radius of swage: \( a_i = a + \delta = 76.26 \), \( F = 2.2 \), \( \rho = b = 2.2a \), \( \mu = 0.27 \),
\( \mu_m = 0.22 \), \( E = 2.06 \times 10^5 \text{ Mpa} \), \( E_m = 5.9 \times 10^5 \text{ Mpa} \), \( \sigma_s = 1120 \text{ Mpa} \).

So \( a = 74 \), \( b = 162.8 \), \( \delta = 2.26 \).

The pressure \( P \) between the cylinder of the swage and the inner surface of the thick-walled cylinder [7]:

\[ P = \frac{2}{\sqrt{3}} \frac{\sigma_s}{\sqrt{1 + 3a_i^4 / b^4}} \ln \frac{b}{a_i} \quad (2) \]

The pressure value is used as the stress boundary condition of the combined swage for analysing.

3. Finite element analysis of combined swage

In this paper, ABAQUS finite element analysis software was used, the shape and load of the combined swage have symmetry, therefore, the axisymmetric model was used as shown in Figure 3. The parameters of the TCS [8] and the cylindrical mandrel are shown in Table 1.

| material grade | density \( \rho \) (g/cm\(^3\)) | elastic modulus \( E \) (GPa) | poisson ratio \( \mu \) | expansion coefficient \( \alpha \) (10\(^{-6}\)·k\(^{-1}\)) | yield strength \( \sigma_s \) (MPa) |
|----------------|-------------------------------|-------------------------------|-----------------|-----------------|-----------------|
| TCS YL10.2     | 14.6                          | 590                           | 0.22            | 5.6             | 1900            |
| tool steel     | 4Cr5MoV1Si                    | 7.8                           | 210             | 0.3             | 9               | 1450            |

The TCS inner hole and the cylindrical mandrel are assembled by thermal expansion and contraction. The interference \( \delta_y \) between them is adjusted by the TCS heating and cooling of the cylindrical mandrel, the minimum temperature of the cylindrical mandrel is reduced to -190°C, and the TCS is heated to 500°C [8]. In order to facilitate the fitting, a certain relative radial clearance is required between the cylindrical mandrel and the inner hole of the TCS in the radial direction when the combined swage is assembled, relative radial clearance \( e = k \delta / r \). The fitting coefficient is generally 0.55-2.5, and 0.6 is taken here. The sum of the cold shrinkage of the cylindrical mandrel and the expansion of the TCS should be:

\[ r \alpha_1 \Delta t_1 + r \alpha_2 \Delta t_2 = (1 + k) \delta_y \quad (3) \]

\( r \) : radius of the inner hole;
\( k \) : fitting coefficient;
\( \delta_y \) : interference of the radial direction;
\( \alpha_1 \) : linear expansion coefficient of the cylindrical mandrel;
\( \alpha_2 \) : linear expansion coefficient of the TCS;
\( \Delta t_1 \) : temperature change of the cylindrical mandrel;
\( \Delta t_2 \) : temperature change of the TCS.

The following assumptions are made on the contact pressure between the swage and the thick-walled cylinder when it is under working conditions (Figure 4):

(1) The cylinder of the swage is subjected to uniform pressure \( P \);
(2) The \( P_1 \) and \( P_2 \) are reduced at linear pace along the taper of the conical surface. The \( P_1 \) and \( P_2 \) are zero without contact.

Figure 3. Axisymmetric finite element model.

Figure 4. Pressure load distribution.

4. Results and analysis of finite element calculation

According to the engineering experience, the inner hole diameter of the TCS is 68mm. The maximum mises stress of the combined swage under working conditions changes with the interference \( \delta \) as shown in Figure 5. The maximum mises stress of the cylindrical mandrel increases with increasing interference, and the maximum mises stress of the TCS with a hole has a minimum value at the interference of 0.06 mm.

Figure 6 is the mises stress pattern of the combined swage under working conditions when the interference is 0.06mm. Due to different \( \alpha \) and \( \beta \), the lengths of the front cone and the tail cone, the mises stress of the combined swage hits the maximum at the inner hole surface on the part corresponding to the intersection of the cylinder and the front cone under the working load.

Figure 5. Maximum mises stress change of the combined swage with increasing interference.

Figure 6. Mises stress distribution of the combined swage with the interference of 0.06mm.

Figure 7 and Figure 8 show that at the maximum mises stress position of the combined swage under working conditions, along the radial direction of the combined swage, the radial stress and hoop stress change under different interferences. For the same interference, the radial stress and the hoop stress of the cylindrical mandrel are equal and there is little change in the radial direction. Minimal change of radial stress occurs at the assembly interface. The radial stress of the TCS with a hole increases in the radial direction when the interference is less than 0.06mm, it decreases in the radial direction when the interference is greater than or equal to 0.06mm, and it is equal to the working pressure on the outer surface. The hoop stress has a large stress gradient at the assembly interface of
the combined swage, when the interference is 0.06mm, the stress gradient is the smallest. The hoop stress of the TCS with a hole decreases in the radial direction when the interference is less than 0.06mm, and it increases in the radial direction when the interference is greater than or equal to 0.06mm.

Under the same working conditions, Figure 9 shows the cylinder displacement of the high-speed steel swage, the cylinder displacement of the TCS and the cylinder displacement of the combined swage. The cylinder displacement of the combined swage has little change with increasing interference, and it is almost the same as the cylinder displacement of the solid TCS, and it reduces by 55.1\% compared to the cylinder displacement of the high-speed steel swage. Figure 10 shows displacement pattern of the combined swage with the interference of 0.06mm under working conditions.

**5. Conclusions**

The design of TCS with a center hole was proposed, in addition, the variation of displacement, maximum mises stress, radial stress and hoop stress of the combined swage with increasing interference under working conditions was developed by finite element simulation analysis.
According to the analysis results of the combined swage, three conclusions can be given as following:

1) When the interference is 0.06mm, the maximum mises stress of the TCS with a hole is the smallest, so the interference is determined to be 0.06mm.

2) Under the working conditions, the interference $\delta_1$ has negligible impact on the cylinder displacement of the combined swage.

3) The cylinder displacement of the combined swage is only increased by 0.017mm compared with that of the solid TCS, which poses no effect on the autofrettage effect of the thick-walled cylinder. Therefore, the design of the combined swage not only satisfies the requirements of swage autofrettage, but also greatly reduces the difficulty in manufacturing the TCS and the internal defects of the TCS. So this is a feasible solution in the project.

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