Numerical Simulation of Radial Compression and High-temperature Creep of Metal Elastic Elements

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Abstract: With the help of the numerical calculation method—Finite Element Method, the numerical simulation and result analysis of a kind of metal elastic element-knitted spring are carried out, mainly focusing on the radial compression and high temperature creep behaviours of the spring. The purpose of this study is to analyse the previous with numerical simulation and explain the influence of configuration parameters on its mechanical properties and to provide data support for design, manufacture and application of the prepared material as an elastic component.

1. Introduction

With the development of high-speed aircraft, it is vital to study the high-temperature sealing technology and high-temperature metal elastic elements. Since the shape reinforced skeleton is often used with other high-performance materials to prepare various seals for specific technological functions [[1]-[2]]. Therefore, to achieve these particular requirements and understand the mechanical behaviour of elastic material and prevent seal leakage [3], several actual configurations and material tests were performed[4]-[5], especially the high-temperature performance of elements[6][7]. However, mechanical modelling, performance prediction, and parametric design of components employing numerical analysis can replace expensive material tests in a certain extent and make it cost-effective. The research content includes the influence of geometric configuration parameters, boundary constraints, and high temperature creep on the resilience performance of metal elastic elements. The adjustment in a geometric configuration, boundary constraints, and working environment led to the optimized value. However, the listing of commonly used high-temperature metal flexible elements is as follows: inclined coil spring, knitted spring, helical spring, and cutting spring (Figure 1). Each configuration has multiple configuration parameters, which determine the mechanical behaviour of the elastic elements.

The main problems discussed in this work are: (1) combining the material constitutive model and the finite element model (for metal elastic element). (2) To establish a relationship between the main mechanical performance parameters i.e. force-displacement relationship, high temperature creep
characteristics, and resilience energy, and the geometric configuration characteristic parameters of elastic elements, obtained through different geometric configurations of numerical simulation. (3) The testing and analysis of typical structural samples, design, manufacture, and application of high-temperature metal elastic elements data. (4) While for knitted winding spring, ABAQUS is used to carry out numerical simulation and describe the finite element modeling process.

![Figure 1](image1.png) **Figure 1**: configuration of common elastic elements

2. Finite element calculation model and material parameters

Knitted spring is a new type of spring (Figure 2), which is widely used by NASA and other departments in the United States. Through flexible winding, design the spring can be made relatively superior in rebound performance. The same feature unit spirally winds the spring, with various geometric parameters, as shown in Figure 3.

![Figure 2](image2.png) **Figure 2**: knitted winding spring

![Figure 3](image3.png) **Figure 3**: feature unit and parameters of knitted spring

The spring has a flexible configuration; the radius of the arc section of the feature element is:

$$ r = c \frac{\pi D}{2npt} $$

npt (needles per turn) is the number of elements per turn, c is defined as the radius adjustment constant of the feature element which in the range of $0 < c < 1$. Its value changes with the diameter $D$ of the knitted spring tube. However, we selected the constant value for $c$ is equal to 0.8, here in this work.

Besides, when modeling with CAD, the feature units are offset correspondingly in the radial
direction to avoid the mutual penetration of the adjacent coil (Figure 4a). Then the CAD model is imported into the finite element software ABAQUS, and the simulation analysis of the radial compression and resilience process can be carried out after meshing, setting the boundary and loading conditions. The final finite element simulation model is shown in Figure 4b. The lower rigid plate is fixed, and the stiff upper plate is pressed down to an absolute displacement for radial loading. Because friction has little influence on the displacement-load characteristics of the radial compression, therefore the self-contact and the friction between the rigid plate and the spring are ignored.

![Figure 4](image)

Figure 4. Finite element simulation model for radial compression of knitting spring

The Superalloy K4169 is used in the design of spring while setting the material parameters at 25°C, 600°C, 700°C in Table 1.

| $T^a$ (°C) | $E^b$ (GPa) | $\mu^c$ | $\sigma_y^d$(MPa) | $\sigma_b^e$(MPa) | $\delta^f$(%) |
|-----------|------------|--------|-----------------|-----------------|--------------|
| 25        | 199.6      | 0.2903 | 1123.9          | 1365.2          | 21           |
| 600       | 166.4      | 0.2768 | 989.6           | 1142.6          | 15.44        |
| 700       | 159.0      | 0.2913 | 933.6           | 1014.4          | 8.56         |

$^a$ $T$ is temperature.
$^b$ $E$ is Young's modulus.
$^c$ $\mu$ is Poisson's ratio.
$^d$ $\sigma_y$ is Yield strength.
$^e$ $\sigma_b$ is Tensile strength.
$^f$ $\delta$ is Elongation.

Table 1. Parameters of Superalloy K4169 elastic plastic material

3. Calculation results of radial compression process

3.1. Influence of length and end effect
The listing for various designs of the springs is in Table 2, and the result of the simulation is shown in Figure 5, and Figure 6. These results are consistent with the experimental and simulation results obtained by NASA [3] and other relevant researchers. The load increases linearly with the downforce displacement in a broad range, and the spring stiffness increases significantly when the movement of downforce exceeds about 45%. The whole displacement-load characteristic curve is bilinear. Figure 5 shows the maximum stress of different length springs under the same pressure displacement, so the end effect has little effect on the stress inside the spring. When the pressure displacement reaches 51%, the maximum Mises stress in the spring is close to the yield strength of 1460 MPa.

Compared with the displacement-load curve in Figure 6, it can be seen that the length and end effect have little effect on the stiffness of the knitted spring. Therefore, we can obtain the exact solution just by simulating two coil length springs, not to consider the actual length of the springs in
the simulation analysis.

Table 2. Simulation parameters of knitted spring (different lengths)

| No. | $L^a$ (mm) | $p^b$ (mm) | $d^c$ (mm) | $d_w^d$ (mm) | npt$^e$ | $LD^f$ (loops/mm$^2$) | $T^g$ (°C) |
|-----|-----------|-----------|-----------|--------------|--------|------------------------|----------|
| L4.2 | 4.2       | 2.1       | 10.5      | 0.3          | 15     | 0.217                  | 25       |
| L6.3 | 6.3       | 2.1       | 10.5      | 0.3          | 15     | 0.217                  | 25       |
| L10.5| 10.5      | 2.1       | 10.5      | 0.3          | 15     | 0.217                  | 25       |

$^a$ $L$ is the length of spring.

$^b$ $p$ is the screw-pitch.

$^c$ $d$ is Diameter.

$^d$ $d_w$ is Wire diameter.

$^e$ npt is Needles per turn.

$^f$ LD is Loop Density.

$^g$ $T$ is Temperature.

Figure 5. Simulation results with different length of knitted spring

Figure 6. Radial compression displacement-load curve with different length of knitted spring

3.2. Influence of wire diameter
The wire diameter is 0.2, 0.3, and 0.4mm, respectively, and the length is 8.4mm. Other parameters, such as the placement-load curve, are the same as in Table 1 and Figure 7. The wire diameter has a significant influence on the stiffness of the knitted spring. The larger the wire diameter is, the higher is the spring stiffness.
Figure 7. displacement-load curve of knitted spring with different wire diameters

Figure 8. Influence of wire diameter on the stiffness of knitted spring

A linearly fitted curve is drawn in Figure 7, taking the slope value of the fitting line as the stiffness K of the knitted spring. The drawing of the wire diameter-stiffness curve is shown in Figure 8, shows that the stiffness of the knitted spring is directly proportional to the fourth power of the wire diameter, that is:

$$ k = ad^4 $$  \hspace{1cm} (2)

where $a$ is a constant number. It can be seen that the spring with different stiffness can be obtained by changing the wire diameter in a small range, which is of great reference value for the design of knitted spring.

4. Effect of high temperature creep on resilience performance

The simulation calculation and analysis of high-temperature creep are carried out according to the creep data of superalloy K4169 at 600°C and 700°C, which are fitted with time hardening model as follows:

$$ \dot{\varepsilon}^{cr} = A\overline{q}^n t^m $$  \hspace{1cm} (3)

Where $\dot{\varepsilon}^{cr}$ is equivalent to creep strain rate, $\overline{q}^{cr}$ is equivalent to deviator stress and $t$ is the time. Since the curve obtained from the creep test is the creep deformation-time curve, therefore the above formula expressed by the strain rate must be integrated. The integration result is as follows:

$$ \overline{\varepsilon}^{cr} = \frac{A}{1 + m} \overline{q}^n t^{1+m} $$  \hspace{1cm} (4)

Where $n > 0$, $0 \geq m > -1$. Then, the test data can be fitted with the above-mentioned integral formula to obtain the appropriate three parameters A, n and m, as shown in Table 3.

| $T$  | $A$     | $n$      | $m$     |
|------|---------|----------|---------|
| 600°C| 4.569E-19 | 3.608    | -0.3361 |
| 700°C| 3.647E-36 | 10.381   | -0.24347|

The calculation results of high temperature creep at different temperatures are shown in Figure 9.
and Figure 10. It can be seen that at 600°C, the spring can rebound after 10 hours creep at 50% compression, and the rebound rate is close to 100%. At 700 °C, the rebound performance decreases obviously after 1 hour creeps at 50% compression, and the spring tube height decreases compared with the full rebound height after complete unloading. The ratio between the reduction height and the full rebound height is defined as the height reduction, as shown in Figure 11, to quantitatively measure the impact of high temperature creep on the radial compression rebound performance of spring tube.

![Figure 9](image-url)  
(a)600°C  
(b)700°C  
**Figure 9.** Creep results of knitted spring at 600/700 °C (50% compression, 3600s creep)

![Figure 10](image-url)  
(a)600°C  
(b)700°C  
**Figure 10.** Creep results of knitted spring at 600/700 °C (50% compression, 36000s creep)

![Figure 11](image-url)  
**Figure 11.** Definition of rebound height reduction of knitted spring

Figure 12 shows the comparison of the height reduction after creep at 600 °C and 700 °C, from which it can be seen that the height reduction after creep at 600 °C for 1 hour and 10 hours is basically zero, while at 700 °C, the height reduction is as high as 2% and 5% for 1 hour and 10 hours respectively. It can be seen that if K4169 alloy is used to make knitting spring, effective heat insulation measures should be taken to avoid the spring tube directly bearing the high temperature above 600 °C.
Figure 12. The height reduction of knitted spring after creep at 600 °C and 700 °C

Figure 13. The resilience-the radial compression displacement curve of knitted spring under high temperature creep at 600 °C and 700 °C

Figure 13 shows the influence of high temperature creep at 600 °C and 700 °C on the radial compression and resilience characteristics of knitted winding spring. It can be seen that the resilience has no visible attenuation after creep at 600 °C for 1 hour or 10 hours, the loading and unloading lines almost coincide. While creep at 700 °C for 1 hour, there has apparent attenuation that the resilience force becomes to zero when the rebound reaches about 2% compression displacement. After 10 hours of creep, the mitigation of resilience is more serious, and the horizontal intercept is about 5%.

Figure 14. Maximum creep strain at 600 °C and 700 °C

It is evident that the maximum creep strain (Figure 14) at 600 °C is much lower than that at 700°C, the magnitude increases from 1e-6 for 1h to 1e-4 for 10h. Compared with that at 700 °C for 1h i.e., 1E-3, the creep rate at 600 °C is relatively slow. The creep strain is the fundamental reason that influences the resilience performance of elastic elements on high-temperature creep, along with that, the main factors include temperature, time, and stress. In other words, different temperatures, different creep time, and different radial compression displacements (different stress) will affect the resilience of elastic elements. The above content has made a detailed analysis of the influence of temperature. It can be seen that the creep effect at 600 °C in a short time (less than 10 hours) has no apparent impact on the resilience of the knitted spring, while the creep effect at 700 °C can significantly change the strength of the knitted spring within 1 hour.

The influence of creep time on the resilience performance of knitted spring is analyzed, and the simulation results are shown in Figure 15, and in Figure 16a with the reduction of resilience height. It can be seen that under 50% compression and half an hour of creep at 700°C, there is a noticeable
influence on the resilience performance, where the maximum creep strain reached 1E-3 from Figure 16b. While in Figure 17, the effect of creep time on the characteristic curve on the resilience and the radial compression displacement is mentioned in detail.

![Figure 15](image15)  
**Figure 15**. the reduction of resilience height of knitted spring under different creep time

![Figure 16](image16)  
**Figure 16**. the reduction of resilience height and maximum creep strain under different creep time

![Figure 17](image17)  
**Figure 17**. the resilience-the radial compression curve of knitted spring under different creep time

In Figure 18, Figure 19 and Figure 20, the influence of different radial compression displacement under high temperature creep on the resilience performance of knitted spring is analyzed and compared the results under 50% and 40% compression. It has little effect on rebound performance when creeping one hour under 40% compression, but it has a noticeable impact on rebound performance after 10 hours of creep. Under 50% compression, it has an evident effect on rebound performance after 10 hours of creep. Under 50% compression, just one hour of creep has an evident impact on resilience, more significant after 10 hours, especially.

It can be seen that no matter whether the variable is temperature, creep time, or radial compression when the maximum creep strain reaches the order of 1E-3, the apparent decrease of rebound height and resilience can be observed. That is, when the maximum creep strain reaches the order of 1E-3, the effect of high temperature creep on the resilience performance of knitted spring becomes clear.

![Figure 18](image18)  
**Figure 18**. resilience height of knitted spring under different radial compression (creep 1h and 10h)

![Figure 19](image19)  
**Figure 19**. the reduction of resilience height and maximum creep strain under different radial compression (creep 1h and 10h)
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5. Summary

Based on the above simulation results, the following are the main conclusions:

1) compared with other types of springs, although the structural characteristics of knitted springs are more complicated. There are many variable characteristic parameters, the displacement-load features of radial compression are relatively simple, and the load increases linearly with the increase of compression.

2) The total length of the spring has little effect on the stiffness of the winding spring per unit length, so the influence of the end effect can be ignored.

3) The wire diameter has a significant impact on the stiffness of the knitted spring. The larger the wire diameter is, the higher the stiffness is, and the stiffness is proportional to the fourth power of the wire diameter. The radial compression stiffness required by design can be easily obtained by changing the wire diameter.

4) Determining the effect of high temperature creep on the resilience properties of elastic elements lies in the magnitude of creep strain, and the main factors affecting creep strain are temperature, time, and compression. Different temperatures, different creep time, and different compression (different stress) will change the rebound performance of the elastic element.

5) it can be seen that if K4169 alloy is used to make knitted spring, effective thermal insulation measures should be taken to prevent the spring tube from directly bearing the high temperature above 600°C.

Acknowledgment

There are no conflicts to declare. This work is supported by the National Natural Science Foundation of China (No.11704244 and U1733130); CALT Foundation (No.201707); Shanghai Natural Science Funding (Grant No. 17ZR1441000); Basic Research Field of Shanghai Science and Technology Innovation Program (No.16JC1401500); Science and Technology Innovation Special Zone Program (No.18-163-13-ZT-008-003-06); Cross Research Fund of Biomedical Engineering of Shanghai Jiao Tong University (YG2016MS70). The Instrumental Analysis Center of Shanghai Jiao Tong University and Xi'an Respro Applied Materials Science and Technology Co., Ltd. are sincerely acknowledged for assisting with the relevant analyses.
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