Structural design and strength analysis of multi-ring packed flywheel with heavy metal alloy segments

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Abstract. Flywheel, as a kinetic energy storage and conversion device, has promising applications due to its high efficiency, no pollution and long lifetime. In particular, with a three-layer structure packed with heavy metal alloy middle layer, a flywheel can achieve both a large rotational inertia and a high energy density. To guarantee structural strength safety of this type of multi-ring packed flywheel operating at high temperature, structural and thermal stress analysis for a flywheel with a tungsten alloy layer sandwiched between two stainless steel layers is carried out using finite element method (FEM). Based on plane stress assumption, flywheel stress characteristic along radius under assembly force, centrifugal force and thermal loading is demonstrated. The results show that, the rise of temperature causes inconsistent thermal expansion between neighbouring layers and results in a large thermal stress. Particularly, a high circumferential tensile stress occurs in the middle layer. It is also found that, the segments of the middle tungsten alloy layer can efficiently relieve the inconsistent thermal expansion and lower the thermal stress. Moreover, the number of segments significantly influences the efficiency of thermal stress releasing and the reserved gap between adjacent segments significantly improves the contact pressure between inner hub and tungsten alloy layer. This work may provide reference for structural design of the multi-ring packed flywheels under thermal loading.

Nomenclature

\( r_1 \): Inner radius of inner hub [mm]
\( r_2 \): Outer radius of inner hub [mm]
\( r_3 \): Outer radius of tungsten alloy layer [mm]
\( r_4 \): Outer radius of outer retainer [mm]
\( E \): Elastic modulus of material [GPa]
\( \nu \): Poisson’s ratio
\( \rho \): Mass density [kg/m³]
\( \sigma_y \): Yield strength [MPa]
\( \alpha \): Thermal expansion coefficient [1/K]
\( \sigma_r \): Radial stress [MPa]
\( \sigma_\theta \): Circumferential stress [MPa]
\( \omega \): Angular velocity [rad/s²]
\( \delta \): Interference fit magnitude [mm]
\( T \): Temperature [K]
\( p \): Contact pressure [MPa]
1. Introduction

With the advantages of high efficiency, no pollution and long lifetime, flywheel has broad applications in power system, vehicles and aerospace [1-3]. The flywheel stores enormous kinetic energy at rotating condition and releases this energy when needed, e.g., it can be used to punch the workpiece in punching machine, stabilize the output power in power station, and provide the delayed flow in reactor coolant pump (RCP) system [4-6]. Theoretically, the amount of energy stored is linearly proportional to the square of rotation speed and the rotational inertia of rotor about the rotation axis [7,8]. However, when the rotation speed is fixed by machine system, a rotor with large enough rotational inertia is desired to ensure the ability of energy storage. To enhance rotational inertia of a rotor, one may design a larger geometry or select a higher density material [9]. Nevertheless, for traditional single disk rotor, the large geometry encounters high circumferential stress in inner radius and high density material often results in an overweight exceeding load-carrying ability of supporting bearings [10-13]. On the other hand, in terms of materials utilization, the single disk rotor is not efficient as the mass element adjacent to rotation axis has much less contribution to rotational inertia than the mass near outer rim. To improve such an old design, three-layer structure flywheel packed with a high density layer (middle layer) was recently proposed [14-16]. Owing to its large rotating radius and high density middle layer, this multi-ring packed flywheel can achieve not only a larger rotational inertia but also a higher energy density, which provides novel design guidance for large rotational inertia flywheels.

To date, little is known about the stress characteristics of this flywheel under thermal loading. However, in reality, during early design phase, thermal stress evaluation is very essential to guarantee safety operation under temperature effect [17-19]. With respect to this multi-ring packed flywheel, the inner layer is responsible for connecting the shaft with flywheel, and the middle layer supplies the major rotational inertia of flywheel. As for the outer layer, it plays the role of packing the inner and middle layers. The outer layer is assembled outside the middle layer using an interference fit to provide prestress to keep inner layers closed. When this flywheel operates under high temperature condition, apart from assembly prestress and rotating stress, thermal stress occurs due to strain induced by thermal expansion [20,21]. As pointed out by Lippmann [22] and Kovacs [23], temperature rising reduces the assembly prestress in the interface of interference fit and increases the risk of assembly failure. Antoni [24] considered a rotating two-cylinder assembly under thermal loading and found that the reasonable magnitude for interference fit is necessary to prevent the occurrence of separation due to temperature effect. On the other hand, the multi-ring packed flywheel confronts inconsistent thermal expansion due to mismatch in expansion coefficients between neighboring layers. You [25] showed that the mismatch in thermal deformation often causes the fiber breaks, debonds and cracks at the interfaces of fiber-reinforced composite cylinder. Clearly, effect of thermal loading needs to be studied for the multi-ring packed flywheel operating at high temperature.

In this communication, structural and thermal stress analysis for the multi-ring packed flywheel in RCP is carried out using finite element method (FEM). Two-dimensional finite element analysis (FEA) model is established through introducing plane stress assumption and the stresses along radius under assembly force, centrifugal force and thermal loading are discussed. To understand the coupling effect of these loads, load condition in the FEA process is divided into three steps: assembly, rotating and thermal loading conditions. Under assembly condition, the interference fit is studied to determine assembly prestress, while under rotating condition both the interference fit and rotational speed are considered to obtain rotating stress. Under thermal condition, the interference fit, rotating speed and thermal loading are all taken into account. For a deep understanding of the multi-ring packed structure, structural and thermal stress characteristics of the flywheel packed with a number of tungsten alloy segments middle layer is investigated. Analysis processes are accomplished in Abaqus which is specialized in simulating coupled fields and contact problems [26-29].
2. Numerical analysis

2.1. Model construction
As shown in figure 1(a), three layers are described as inner hub, heavy metal alloy layer, and outer retainer. They play the roles of connecting rotor with shaft, providing a large rotational inertia, and packing the inner and middle layers, respectively. The shaft and inner hub are made of stainless steel, and heavy metal layer is a type of tungsten alloy with twice the density of stainless steel. The outer retainer is made of high strength maraging steel so as to withstand the assembly prestress and rotating stress. Flywheel is assumed to rotate in horizontal plane, i.e., the rotating shaft is in vertical direction. Such arrangement is commonly seen in RCP system [30] and wind power generation system [31].

![Figure 1. Multi-ring packed flywheel with tungsten alloy layer: (a) structure diagram, (b) FEA model.](image)

The load consists of three parts: assembly force, centrifugal force, and the stress induced by thermal expansion. The gravity force is negligible as it has much less effect on stress relative to these forces. Considering the smaller axial thickness relative to the flywheel radial radius, we give concentration on the stress distribution along radial direction using plane stress model [32]. To further reduce calculation cost, 1/4 structure is taken to construct the FEA model due to its symmetry characteristic as used in literature [15]. As shown in figure 1(b), symmetry boundary conditions are defined, respectively. Contact relationships between the shaft, inner hub, tungsten alloy layer, and outer retainer are considered. Surface to surface contact is used, and friction coefficients are all set as 0.15 in Abaqus. Final model established is displayed in figure 1(b). Tables 1 and 2 give respectively the geometry parameters and mechanical properties for flywheel.

| Description | Value |
|-------------|-------|
| Inner radius of inner hub, $r_1$ | 150 mm |
| Outer radius of inner hub, $r_2$ | 300 mm |
| Outer radius of tungsten alloy layer, $r_3$ | 430 mm |
| Outer radius of outer retainer, $r_4$ | 500 mm |

| Components | $E$ (GPa) | $\rho$ (kg/m$^3$) | $\sigma_y$ (MPa) | $\alpha$ (1/K) |
|------------|----------|-----------------|----------------|----------------|
| Shaft, inner hub | 198 | 7900 | 275 | 1.12x10^{-5} |
| Tungsten alloy | 325 | 17500 | 520 | 4.5x10^{-6} |
| Outer retainer | 198 | 7900 | 1500~1700 | 1.12x10^{-5} |

2.2. Rotating stress
Different initial stress fields may express distinct responses to thermal loading. Here, rotating stress of this multi-ring packed flywheel is studied in advance before thermal stress analysis. To look into its
stress characteristic, the load condition is divided into two steps: assembly condition and rotating condition. Under assembly condition, the interference fit between tungsten alloy layer and outer retainer is studied to determine assembly prestress, while under rotating condition both the interference fit and rotational speed are considered to obtain rotating stress. In this paper, interference fit magnitude of \( \delta = 1.0 \) mm and rotational speed of \( n = 1800 \) rpm is studied as example. Centrifugal force is applied by defining a rotational body force with the given angular velocity in Abaqus (angular velocity, \( \omega = 188 \) rad/s\(^2\)). Since the stress keeps constant around the circumference, the radial stress, \( \sigma_r \), and circumferential stress, \( \sigma_\theta \), along the radius are evaluated.

In figure 2(a) we can see that, the radial stresses of flywheel along radius show characteristic of continuous distribution. Clearly, owing to the assembly prestress, effective contacts between layers are established. The contact pressures in three contact interfaces are defined respectively as \( p_1 \), \( p_2 \) and \( p_3 \) (see figure 3) and they show the relationship of \( 0 < p_1 < p_2 < p_3 \). The centrifugal force makes all layers expand outward releasing part of the contact pressures. Specifically, this rotating condition significantly lowers \( p_1 \) but has less impact on \( p_3 \) (see red line with circle symbols in figure 2(a)). With respect to circumferential stresses (see figure 2(b)), the inner hub and tungsten alloy layer both show low compressive stress levels rather than high tensile stress in inner radius for traditional single disk flywheel [34]. Apparently, this outer retainer plays a critical role in packing the flywheel and making inner layers stay at low stress levels.

![Figure 2](image.png)

**Figure 2.** Stress distribution along radius: (a) radial stress, (b) circumferential stress under assembly and rotating conditions.

![Figure 3](image.png)

**Figure 3.** Schematic of the contact pressures between layers.

2.3. Thermal effect

As known, thermal stress takes place due to either non-uniform temperature fields or mismatch in thermal expansion coefficients of components. Since the thermal expansion coefficient of tungsten alloy layer is about one half of that of inner layer and outer retainer, thermal stress occurs due to inconsistent thermal expansion between layers. To investigate its effect, stress analysis under interference fit
magnitude of $\delta=1.0$ mm, rotational speed of $n=1800$ rpm and constant temperature of $T=561$ K (steady temperature caused by coolant flow through the reactor core under normal working condition [35]) for RCP flywheel is carried out. Room temperature of $T=294$ K is taken as initial temperature field.

Figures 4(a) and 4(b) give the radial and circumferential stress distributions along the flywheel radius. It is seen that temperature effect leads to remarkable rising of stresses in the inner hub and tungsten alloy layer (see red lines with circle symbols). Particularly, considerable high stress turns up in the inner surface of tungsten alloy layer. In fact, considering the thermal expansion, the tungsten alloy layer has a smaller radial deformation than inner layers (shaft and inner hub) due to its smaller thermal expansion coefficient. Consequently, this inconsistent radial deformation builds an interference fit relationship between tungsten alloy layer and inner hub. As presented in figures 4(a) and 4(b), this additional interference fit results in much larger contact pressures between layers and the considerable high stress in inner surface of tungsten alloy layer. With the same mechanism, the outer retainer has a larger radial deformation than tungsten alloy layer which leads to the decrease of circumferential stress in outer retainer.

Figure 4. Temperature effect on: (a) radial stress, (b) circumferential stress distributions along radius.

3. Segment design for the middle layer

3.1. Thermal stress characteristic

To deal with the thermal stress problem pointed out, an improved design for multi-ring packed flywheel is proposed. The integrated tungsten alloy layer is replaced by 12 tungsten alloy segments evenly around the circumference (see figure 5(a)). Flywheel becomes a typical cyclic symmetric structure about the rotation axis and contact relationships between tungsten alloy segments need to be considered. Based on this symmetry characteristic, 1/12 flywheel structure is taken to construct the FEA model. Four contact pairs are established between the shaft, inner hub, tungsten alloy segments and outer retainer. To make a comparison with the integrated tungsten alloy layer, we also carry out stress analysis process under assembly and rotating conditions with $\delta=1.0$ mm and $n=1800$ rpm for this type of design. Considering that stress changes around the circumference, stress along the radial path crossing a single segment center (see $r$ in figure 5(c)) is observed. Comparing results in figures 5(c) and 5(d) with those in figures 2(a) and 2(b), we can find that two types of flywheel designs present almost the same stress distributions.

Further, to learn the thermal stress characteristics, radial and circumferential stress along the radius under temperature of $T=561$ K is given in figures 6(a) and 6(b). It can be found that, stresses in inner hub and tungsten alloy layer are both under compression and show low stress levels. Though at high temperature, they both maintain a low stress level rather than the significant rising presented in figure 4. To understand this phenomenon, firstly, we recognize that the segment design of tungsten alloy layer substantially breaks the state of high tensile stress around the circumference and thus releases the
Figure 5. Multi-ring packed flywheel with tungsten alloy segments: (a) structure diagram, (b) FEA model, (c) radial stress, and (d) circumferential stress distributions along specified radial path.

Figure 6. Temperature effect on multi-ring packed flywheel with tungsten alloy segments: (a)-(b) radial and circumferential stresses along specified radial path, (c)-(d) radial and circumferential stresses along specified circumferential path.
circumferential stress. Secondly, instead of an integrated tungsten alloy layer, those tungsten alloy segments enhance the deformation ability of tungsten alloy layer around the circumference. Thus, previously stated inconsistent thermal expansion between layers will be greatly weakened and thus thermal stress will be highly relieved. Consequently, these two factors contribute to these low stresses in inner hub and tungsten alloy layer. This improved flywheel design with tungsten alloy segments middle layer can successfully solve the thermal stress problem and maintain the low stress environment for packed inner components. However, what we need to acknowledge is that segment design break the uniform contacts between the inner hub, middle layer, and outer retainer.

Figures 6(c) and 6(d) show the radial and circumferential stresses along a specified circumferential path in the inner surface of a single segment (see figure 6(c)). It is seen that, within the single segment, pressure in middle contact area is higher than that in both sides. In terms of this non-uniform contact, effect of segment number will be studied in the following subsection.

3.2. Effect of the segment number for middle layer

Segment design of middle layer releases the high tensile stress around circumference and weakens the interference fit relationship built by inconsistent thermal expansion. To understand the segment number design for tungsten alloy layer, effect of segment number on relieving the circumferential stress is explored. Flywheel stresses with different segment numbers are studied. Similarly, making full use of the structural cyclic symmetry characteristic, stress analysis processes are carried out using FEM. In figure 7, the stress contour with N=1 represents integrated tungsten alloy layer of which high circumferential stress is displayed. When integrated tungsten alloy layer is divided into a number of segments, the high circumferential tensile stress is highly released. Specifically, it presents a fast declining with increasing segment numbers. But this decrease slows down quickly with large segment numbers. This performance reveals that different segment numbers contribute to different degrees of stress relieving in middle layer, i.e., too small a number cannot guarantee a low stress. In other words, increasing the segment number can help improve the efficiency of relieving the circumferential stress and weakening the inconsistent thermal expansion. However, we should put in mind that too large a number actually will bring difficulties during practical manufacturing and assembly process. From the curve in figure 7, it can be concluded that segment number of around 10-14 can not only contribute to a high degree relieving of thermal stress, but also maintain simplicity for manufacturing and assembly process.

![Figure 7](image)

**Figure 7.** Effect of different segment numbers (N=2, 4, 6, 8, 10, 12, 16) on relieving the circumferential tensile stress, $\sigma_\theta$, in middle layer (N=1 represents the integrated tungsten alloy layer).

In figure 7, we also noticed that segments break the uniform contacts between inner hub, middle layer and outer retainer. Stress concentration appears in the inner surface of outer retainer and the
maximum peak stress occurs in the contact area between two adjacent segments. Due to mismatch in interface deformation, interface friction force occurs. This friction force gives shear effect on the inner surface of outer retainer and hence results in non-uniform contact. Stress contour graphs with different segment numbers are given in figure 8. Based on cyclic symmetry characteristic, we look into the stress around circumference in the inner surface of outer retainer within a periodic structure. It is seen that, they all present an inverted funnel shape distribution and the maximum peak stress presents a declining trend with increasing segment numbers.

\[
\begin{align*}
\sigma_{\text{max}} / \text{MPa} \quad & \quad N=4 \\
& 496.5 \\
& 340.8 \\
& 275.4 \\
& 209.9 \\
& 144.5 \\
& 89.0 \\
& 73.8 \\
& 13.6 \\
& 12.1 \\
\sigma_{\text{max}} / \text{MPa} \quad & \quad N=8 \\
& 395.2 \\
& 330.9 \\
& 266.7 \\
& 202.3 \\
& 138.0 \\
& 75.7 \\
& 9.4 \\
\sigma_{\text{max}} / \text{MPa} \quad & \quad N=12 \\
& 382.2 \\
& 320.5 \\
& 258.8 \\
& 197.1 \\
& 135.4 \\
& 73.8 \\
& 11.0 \\
\sigma_{\text{max}} / \text{MPa} \quad & \quad N=16 \\
& 372.7 \\
& 312.5 \\
& 252.2 \\
& 191.9 \\
& 131.6 \\
& 71.3 \\
& 11.0
\end{align*}
\]

**Figure 8.** Effect of segment number on stress distribution around circumference in the inner surface of outer retainer.

### 3.3. Effect of gap dimension on thermal stress

![Diagram](image)

**Figure 9.** Effect of gap dimension on contact pressures.

Figure 9 shows the gap structure between adjacent segments. This gap actually provides space for the circumferential deformations of segments which will accommodate the thermal expansion and affect the compatible deformations between layers. To explore the effect of gap dimension (\(\delta_{\text{gap}}\)) on thermal stress, contact pressures between neighboring layer (see figure 9) and between adjacent segments (see figure 10) are studied. In figure 9, the maximum contact pressure between tungsten alloy layer and inner hub shows a fast growth with the increase of gap dimension (0–0.08 mm). Apparently, the gap enhances the contact between segments and inner hub. Compared with no gap (\(\delta_{\text{gap}}=0 \text{ mm}\)), the maximum pressure improvement rate reaches 53.5% when \(\delta_{\text{gap}}=0.08 \text{ mm}\). In figure 10, the contact pressure between adjacent segments is 0 MPa when \(\delta_{\text{gap}}=0.08 \text{ mm}\). It indicates that adjacent segments are in open state and this gap dimension completely accommodates the circumferential deformation. Thus, the contact pressure becomes stable when the gap dimension exceeds about 0.08 mm. With respect the contact pressure between tungsten alloy layer and outer retainer, it almost keeps a constant versus the gap.
dimension (see figure 10) as this contact pressure is mainly dominated by the assembly prestress between tungsten alloy layer and outer retainer.

Figure 10. Contact pressures between adjacent tungsten alloy segments under different gap dimensions: (a) $\delta_{gap}=0$ mm, (b) $\delta_{gap}=0.06$ mm, (c) $\delta_{gap}=0.08$ mm.

4. Conclusions
In this paper, structural and thermal stress analysis for a multi-ring packed flywheel composed of inner hub, tungsten alloy layer and outer retainer is carried out. Results show that, for this type of three-layer structure, temperature effect gives rise to considerable thermal stress because of different thermal expansion coefficients of neighbouring layers. Specifically, inconsistent thermal expansion causes high circumferential stress in the middle layer. Fortunately, adopting segment design for middle layer can effectively accommodate and weaken the inconsistent thermal expansion and thus relieve the high circumferential stress. Moreover, a proper segment number contributes to a high stress relieving and also a significant improvement of stress concentration induced by non-uniform contact. Reserving gaps between adjacent segments helps adapt to circumferential deformation and enhances the contact pressure, which is beneficial to keep inner layers closed. This work may provide reference for structural design of the multi-ring packed flywheels under thermal loading.

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Conflict of Interest
The authors declare that they have no conflict of interest.

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