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THE USE OF EXPERIMENTAL DESIGN FOR THE SHRINK-FIT ASSEMBLY OF MULTI-RING FLYWHEEL

Yujin WANG
Shanghai Jiao Tong University
ShangHai, People's Republic of China
Email: battlestar@sjtu.edu.cn

DeZhong WANG
Shanghai Jiao Tong University
ShangHai, People's Republic of China
Email: dzwang@sjtu.edu.cn

Junlian YIN
Shanghai Jiao Tong University
ShangHai, People's Republic of China
Email: jlyin@sjtu.edu.cn

Yaoyu HU
Shanghai Jiao Tong University
ShangHai, People's Republic of China
Email: huyaoyu@sjtu.edu.cn

ABSTRACT

The flywheel of latest coolant pump provides high inertia to ensure a slow decrease in coolant flow to prevent fuel damage after the loss of power. Flywheel comprises a hub, twelve tungsten alloy blocks and a retainer ring shrink-fit assembled on the outer surface of blocks. In the structural integrity analysis, the shrinkage load due to shrink-fit and the centrifugal load due to rotation are considered, so the wall thickness of retainer ring and the magnitude of shrink-fit are key variables. In particular, these variables will change the flywheel running state. This paper considers the influence of these variables, we employ Latin hypercube design to obtain the response surface model and analyze the influence of these variables. Finally we obtain the magnitude of wall thickness of retainer ring and the range of shrink-fit.

INTRODUCTION

In order to prevent fuel damage after loss of power of reactor coolant pump motor, the flywheel is designed to provide sufficient inertia for the pump to work for a short time in order to remove the residual heat from the reactor core [1].

In 1989, Westinghouse Electric Corp. designed a high inertia flywheel for AP600, the flywheel is comprised of a heavy metal disk made of a uranium alloy with a stainless steel ring enclosing the heavy metal [2]. After about 10 years, Westinghouse Electric Corp improved the design of the flywheel for AP1000 RCP, the uranium alloy blocks are replaced by tungsten alloy blocks. To minimize the volume of flywheel, the flywheel of the canned pump has a multi-ring structure with two metals, as shown in Fig. 1. The hub is made of stainless steel, the middle ring is heavy metal blocks, the outer ring called retainer ring is made of maraging steel, the material allowable stress ($[\sigma]$) is 1G Pa. The retainer ring is heated at high temperate and shrink-fit assembled outside surface of heavy metal blocks. In particular, adequate shrink-fit is needed to ensure a structural safe life for a given operating condition. Compared with the shaft sealing pump, the power loss of the pump associated with the flywheel resulting from pumping surround fluid is greater than the shaft sealing pump [2]. The power loss is proportional to the square of the radius of flywheel, so the volume of flywheel of canned pump is designed to be smaller than the shaft sealing pump.

From the view of engineering, structural integrity must be considered in the design of flywheel.The structural integrity of the flywheel attracts considerable attraction from U.S nuclear regulatory commission (USNRC). USNRC considered that the safety consequence could be significant because of possible damage to the reactor coolant system, the containment or other equipment of systems, and stipulated the flywheel regulatory for

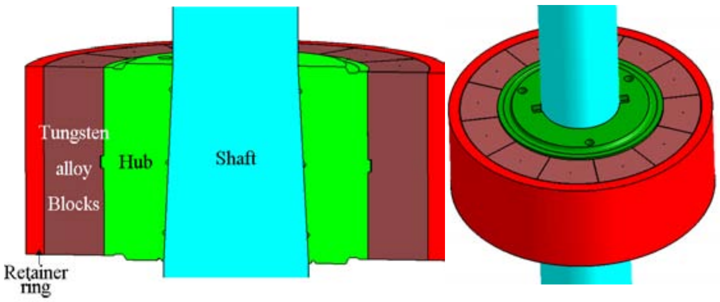


FIGURE 1: THE STRUCTURE OF MULTI-RING FLYWHEEL

avoiding structural failure of flywheel [1, 3].

The residual stress resulted from the shrink-fit promises that the contact status between tungsten alloy blocks and inner hub is closed when the rotational speed is close to the design speed. In the flywheel design, the shrink fit should be chosen in a range, the lower limit of this range is determined by the contact pressure of the inner hub, and the upper limit is decided by the hoop stress of the retainer ring. If the residual stress is greater than the material yield stress, the retainer ring will fail. In addition, if the centrifugal load under design rotational speed is enough to open the contact, the flywheel will be delaminated.

A number of comprehensive detailed reviews of flywheel kinetic storage have been published [4–6], the important parameters of flywheel(i.e. shrink-fit, thickness, material property and load condition, etc) are discussed and analyzed, and Genta provided the analytical solution for hoop stress and radial stress, and presented the failure criterion for the stress analysis and fatigue for single disk and multi-ring disk. Park adopted finite element method (FEM) to develop a program for the stress analysis and fracture mechanics evaluation of shrink-fit flywheel, and considered the ductile and non-ductile fracture of RCP flywheel [7]. Arvin explored press-fit filament wound of the multi-ring composite flywheel, in the conclusion of his paper, residual stress should be small, or else the structural integrity will be damaged by a small fault [8]. Ozturk.F employed FEM to analysis the shrink-fit assembly, the maximum stress is at the contact area and decreases through the outer disk thickness [9]. Jiang analyzed the mechanism of shrink-fit toolholder with FEM, there are two operation stages, when the rotational speed is relatively low, the contact pressure is the principal variable, but as the rotational speed grows faster, the centrifugal force will be greater than the contact pressure [10]. Antoni considered the contact states of rotating multi-ring flywheel, in his analytical modeling, the contact separation and failure rotation speeds are analyzed, and a range of rotational speed can be extracted from the results of the model [11]. To sum up, these studies focused on the failure conditions of the flywheel, but the design method of the multi-ring heavy metal flywheel was not included, so we need a novel method for the special flywheel.

In this paper, the wall thickness of retainer ring, shrinkage load due to shrink-fit and centrifugal load due to rotational speed are considered for the structural integrity of multi-ring heavy metal flywheel. We employ the experimental design method to analyze the influence of these design variables, and obtain the response surface model of contact pressure of hub and maximum hoop stress of retainer ring, finally the response surface model is used to determine the magnitude wall thickness and range of shrink-fit.

STRESS ANALYSIS MODEL

In the flywheel assembly, it is assumed that the inner end of the hub and outer end of the retainer ring are free and unconstrained, and the problem is assumed to be plane stress. Figure. 2 shows the 1/4 FEM model of multi-ring flywheel with 12 tungsten blocks .

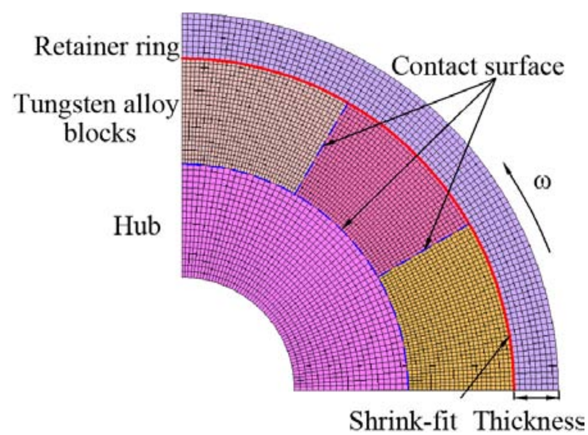
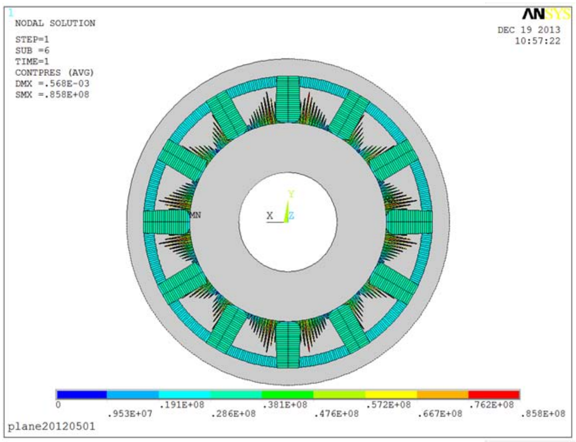


FIGURE 2: FINITE ELEMENT MODEL OF MULTI-RING FLYWHEEL

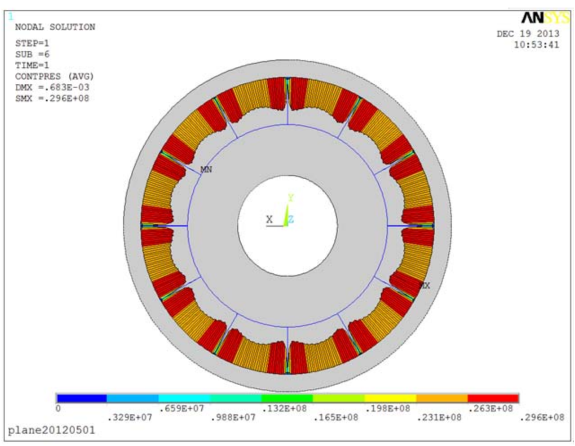
Considering the influence of rotational speed and shrink-fit, the structural integrity of multi-ring flywheel depends on two constraints, one is the contact pressure between hub and heavy blocks.

Under low rotation speed, the residual pressure is greater than the centrifugal load, the tungsten blocks are together by the retainer ring, as shown in Fig. 3(a). Otherwise, under high rotational speed the contact pressure is lower than allowable contact pressure (0MPa), contact will separate under high rotational speed, as shown in Fig. 3(b),

Another constrain condition is the hoop stress of retainer ring, under low rotational speed, if the magnitude of shrink-fit beyond the allowable value, the retainer ring will failure, as shown in Fig. 4(a). And under high rotational speed, because the contact statuses of components change, the stress of the retainer ring will redistribute, the maximum hoop stress is located in the contact region of two tungsten blocks, as shown in Fig. 4. In our analysis, the contact pressure and hoop stress will be consider as two observation variables for the structural integrity of the flywheel.

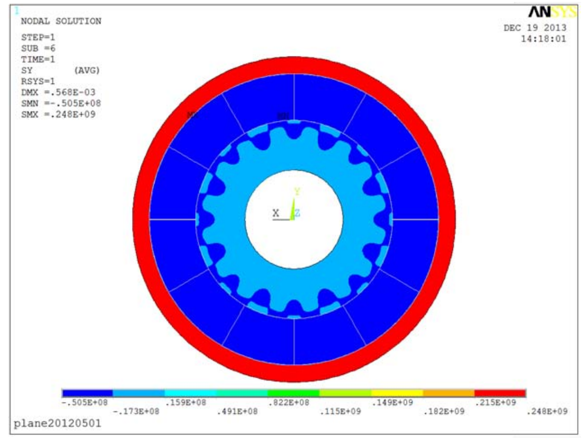


(a) LOW ROTATIONAL SPEED

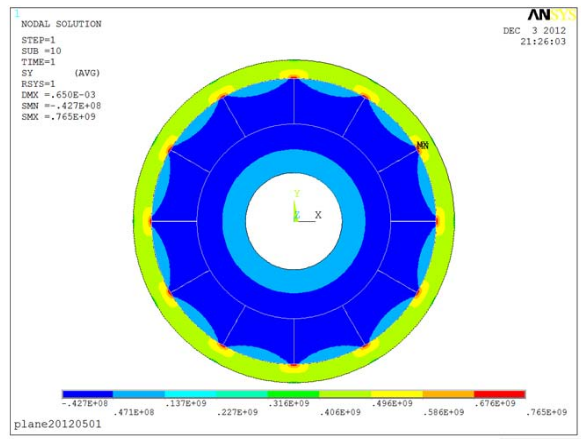


(b) HIGH ROTATIONAL SPEED

FIGURE 3: THE CONTACT PRESSURE UNDER DIFFERENT ROTATIONAL SPEED



(a) LOW ROTATIONAL SPEED



(b) HIGH ROTATIONAL SPEED

FIGURE 4: THE HOOP STRESS UNDER DIFFERENT ROTATIONAL SPEED

EXPERIMENTAL DESIGN

Experimental design is used to obtain the response surface models of hoop stress and contact pressure, which will help us to find a better designation in a short time. Experimental design needs a large amount of data, and the data points must cover the space we need to analyze. But for the structure of flywheel, it's hard to get these data by field experiments. In this paper, we adopt the computer experiment method to analyze. For computer experiment, space-filling designs are very popular. Latin hypercube designs (LHD) is one of space-filling designs, whose samples can be obtained as follows. The range of each design input variable is divided into n intervals, and one observation is made in each interval using random sampling [12, 13]. There are two parameterized design variables in this paper, wall thickness of retainer ring (T), magnitude of shrink-fit (D), and two observation variables, hoop stress of retainer ring (σ_{Hoop}) and contact pressure of outer surface of inner hub ($P_{Contact}$), as listed in Table. 1. In addition, the rotational speed (ω) is another variable considered in the experimental design.

In this procedure, a response surface is constructed by using 400 sampling data points generated by random Latin hypercube design.

TABLE 1: VARIABLES OF EXPERIMENTAL DESIGN

	Design variables		Observation variables	
	T (m)	D (m)	$P_{Contact}$ (MPa)	σ_{Hoop} (MPa)
Range	0.025∽0.04	0.0002∽0. 00125	>0	<1000

RESULTS AND DISCUSSION
RESPONSE SURFACE MODEL

Based on the LHD, two fourth-order response surface models corresponding to contact pressure and hoop stress are formulated as in Eqn. (1) and Eq. (2).

$$\begin{aligned} P_{contact} = {} & A_1 + A_2T + A_3D + A_4\omega + A_5T^2 + A_6D^2 + A_7\omega^2 \\ & + A_8TD + A_9D\omega + A_{10}\omega T + A_{11}T^3 + A_{12}D^3 \qquad (1) \\ & + A_{13}\omega^3 + A_{14}T^4 + A_{15}D^4 + A_{16}\omega^4 \end{aligned}$$

$$\begin{aligned} \sigma_{hoop} = {} & B_1 + B_2T + B_3D + B_4\omega + B_5T^2 + B_6D^2 + B_7\omega^2 \\ & + B_8TD + B_9D\omega + B_{10}\omega T + B_{11}T^3 + B_{12}D^3 \qquad (2) \\ & + B_{13}\omega^3 + B_{14}T^4 + B_{15}D^4 + B_{16}\omega^4 \end{aligned}$$

Where, A_i, B_i represent regression coefficients, which are listed in the appendix A.

The average approximation error of contact pressure is 9%, and average approximation error of hoop stress is 10%.

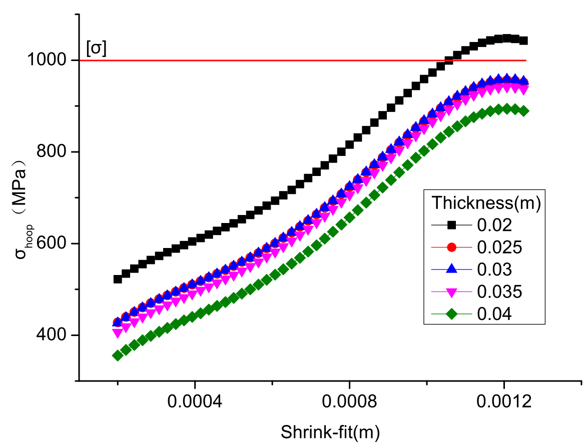
WALL THICKNESS OF RETAINER RING

In order to analyze the influence of shrink-fit, wall thickness of retainer ring is one of important aspects. In Arnold's study, the thicker retainer ring could fail by delamination due to excessive tensile radial stress, and thinner retainer ring could be failure by the shrink-fit, and wall thickness will affect residual stress due to shrink-fit [5]. In our study, we obtain the same conclusion as Arnold. In addition, selecting a proper wall thickness of retainer ring is investigated in this paper.

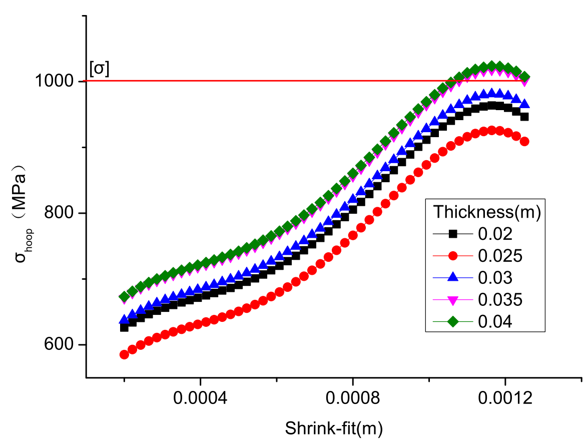
Firstly, two service conditions are analyzed for the structural integrity. In the first service condition, the rotational speed is assumed to be 0 rpm, so it could be considered as non-rotating condition. The retainer ring is under the residual stress without centrifugal load, so the hoop stress grows as the magnitude of shrink-fit, and the thinner one is easy to be fail, as shown in Fig. 5(a). The other service condition is considered as design rotational speed, the rotational speed is close to 2250 rpm, the distribution of hoop stress changes with rotational speed, as shown in Fig. 4(a) and Fig. 4(b). The maximum hoop stress occurs at the contact zone between retainer ring and two tungsten alloy blocks because of the fillet of tungsten alloy blocks, the stress concentration is illustrated in Fig. 4(b). Besides that, the thicker ring are stiffer than the thinner ones, so the local stress concentration is greater than those of the thinner ones, as shown in Fig. 5(b).

So the proper wall thickness of the retainer ring should be consider under the two service conditions. For the lower limit, initial shrink-fit should be considered without centrifugal load, and the upper limit, the design rotational speed need to be considered. In this paper, the range of wall thickness is determined to be 0.03m.

Figure. 5 only suggests that the hoop stress under certain magnitude of shrink-fit is lower than the allowable stress, whether the contact pressure due to residual stress is enough to keep tungsten blocks together under design rotational speed is still unknown.



(a) 0rpm



(b) 2250rpm

FIGURE 5: HOOP STRESS OF DIFFERENT WALL THICKNESS RETAINER RING

RANGE OF SHRINK-FIT

When the wall thickness is determined, the next step is to select a proper range of shrink-fit. Based on the response surface model, the response surface figures could be obtained readily. Figure. 6(a) shows the response surface of contact pressure from Eqn. (1). If the flywheel is delamination under design rotational speed, contact pressure will decrease to 0 Pa, so the isoline (Contact pressures=0 MPa) can be extracted from this figure, and has a intersection with the design rotational speed line, from the intersection obtained, move vertically to down and read the value of shrink-fit, the value is considered as the lower limit of range of shrink-fit.

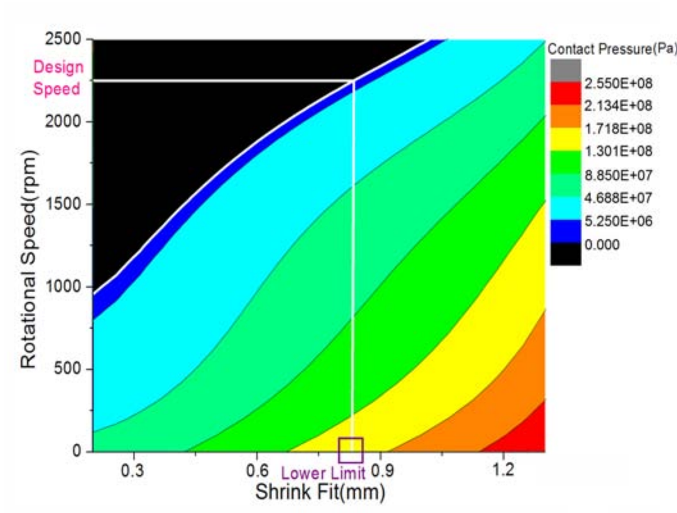
Figure. 6(b) obtained from Eqn. (2) is used to determine the upper limit of range of shrink-fit. There are two intersection that should be considered for structural integrity. One is the intersection of the design rotational speed(2250 rpm) and isoline(Hoop stress=1000 MPa), another one is the intersection of static(0 rpm) and isoline(Hoop stress=1000 MPa). So we can obtain two values of shrink-fit after projection, the smaller one is selected to be the upper limit of range.

Finally, we obtain the range of shrink-fit (0.7∽ 1.2 mm) from Fig. 6.

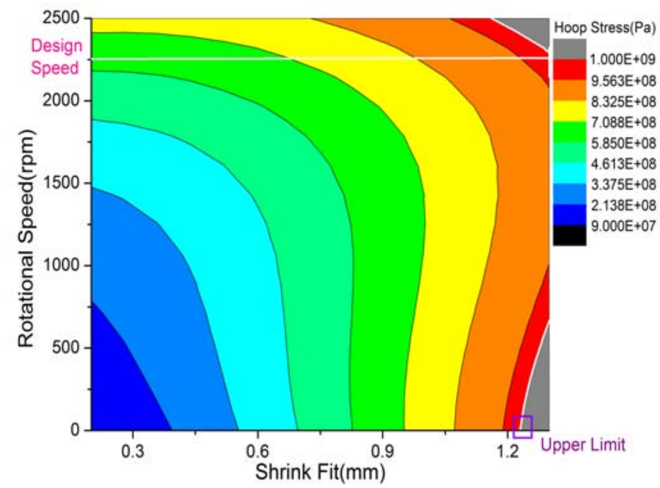
CONCLUSION

In this paper, the wall thickness of retainer ring and the range of shrink-fit are discussed in order to present a proper design method for the structural integrity of multi-ring heavy metal flywheel. The article includes three parts. Firstly, we employ the LHD method to get two response surface models, one is the contact pressure between hub and tungsten alloy blocks ($P_{contact}$), another one is the hoop stress of retainer ring (σ_{hoop}). Secondly, the wall thickness of retainer ring is determined with considering the material allowable stress. Thirdly, after determining the wall thickness of retainer ring, the range of shrink-fit is obtained from Fig. 6(a) and Fig. 6(b).

From the view of engineering, if we can obtain a high precision response surface model from enough data points, the experience design method could be replaced by this design method with high precision. And the design method based on the response surface model has some advantages, we can design a flywheel for a special purpose in a short time and optimize the structure of a poorly-designed flywheel.



(a) RESPONSE SURFACE OF CONTACT PRESSURE OF HUB



(b) RESPONSE SURFACE OF HOOP STRESS OF RETAINER RING

FIGURE 6: DETERMINATION OF RANGE OF SHRINK FIT

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Appendix A: Coefficients of response surface model

A1	360750535781785	B1	274393404481147
A2	135810. 415396477	B2	883149. 066404986
A3	−2. 99881518920769e+015	B3	−2. 29410860500422e+015
A4	−1205226116927. 59	B4	1341386125239. 35
A5	0. 279274797442204	B5	416. 123464777708
A6	9. 34765896466826e+015	B6	7. 19204737720769e+015
A7	25257271213976. 6	B7	−2. 8388046865703e+015
A8	−257800. 018798429	B8	−1974464. 1739041
A9	−14940884. 8001844	B9	−383372301. 082803
A10	2410147216762. 27	B10	980980889833. 863
A11	−0. 00527142214504885	B11	−0. 222696185456818
A12	−1. 29494880765318e+016	B12	−1. 00201793202768e+016
A13	1. 31989854487976e+017	B13	3. 08567843525419e+018
A14	1. 73647550350061e−006	B14	5. 27449014164645e−005
A15	6. 72686396971366e+015	B15	5. 23475507239172e+015
A16	−6. 77377071489127e+019	B16	−1. 02475744160318e+021