Finite Element Simulation of Hot Shrink-fit Process for Reactor Coolant Pump Rotor-can

LI Rui Qin[a] , ZHANG Li Wen[b*] , ZHANG Chi[c] , SHEN Wen Fei[d]

School of Material Science and Engineering, Dalian University of Technology

Dalian 116024, Liaoning, China

commat@mail.dlut.edu.cn

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Abstract. In this paper, based on finite element (FE) software MSC.Marc, a two-dimensional nonlinear thermo-mechanical coupled model is established to investigate the hot shrink-fit process for the reactor coolant pump rotor-can. By using this model, the limited time and temperature evolution for hot shrink-fit process are calculated. The residual stress and contact force after shrink-fit are analyzed. The results indicates hot shrink-fit time, the contact force and residual stress decreased with the increase of interference. For the sake of expanding the shrink-fit limit time and improving success ratio, a kind of insulation layer is designed. With the increasing of thickness of insulation layer, the limit time for hot shrink-fit is linear increased. The results show the necessary time for the shrink-fit processing is increased to 85s when the thickness of insulation layer is 2.00mm.

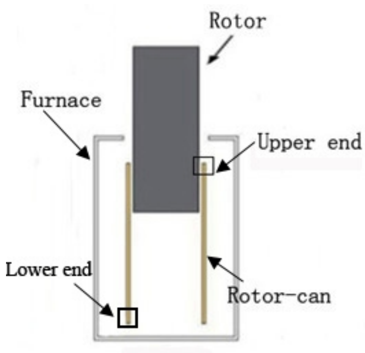
Introduction

The reactor coolant pump (RCP) rotor is required safety work for a long time[1]. But yet the rotor is corroded by coolant easily so as to reduce the active time. Rotor-can is one of the key components that shrink on the surface of rotor to prevent the rotor made of silicon steel being corroded by coolant in RCP. It is made of Hastelloy C-276 which has good mechanical and physical properties and resistance in a wide variety of corrosive environments[2]. The precision manufacturing and assembling quality for the rotor-can have strict standards. Hot shrink-fit processing plays an important role in the assembling procedure.

The rotor-can with huge length-diameter ratio and thin thickness cylinder structure bring difficulty in the hot shrink-fit processing such as buckling and bulge. The height of the rotor-can is more than three meter which led to non-homogeneous distribution of the thermal stress during the shrink-fit processing. The upper end of the rotor is shrunk once the rotor inserts into the rotor-can while lower end is shrunk at the last. It is usually happened that the end of the rotor-can is shrunk on the middle of the rotor in advance due to the quickly reducing of temperature of rotor-can. The rotor-can has to be cut from the rotor and rotor is severe destroyed. The residual stress after the process is inevitable owing to the interference fit for hot shrink-fit process. Stress corrosion and potential fatigue failure due to tensile residual stress are bad for rotor long time working[3]. There are few literature introducing RCP rotor-can hot shrink-fit process. The objective of this paper is to study the hot shrink-fit processing and design the insulation layer to improve the success ratio.

FEM model of hot shrink-fit processing

Geometrical model. A 2-D thermo-mechanical coupled axis-symmetric model is established based on MSC.Marc. Fig.1 present the shrink-fit process for rotor-can of RCP. Upper end of rotor-can is shrunk at first time during the whole hot shrink-fit process. Once the upper end of rotor-can canned on the rotor, the process is judged to be finished. Hence, it is proper to simplified modeling to upper end of rotor-can shrunk evolution as shown in Fig.2. In this model, the four-node axis-symmetric quadrilateral elements are used.



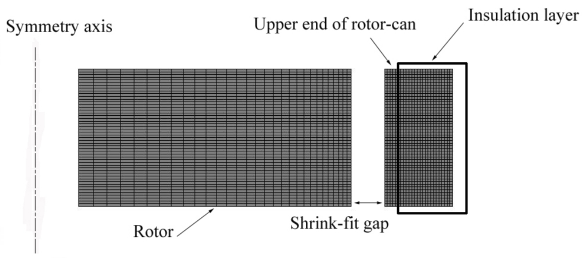


Fig.1 The shrink-fit process for rotor-can of RCP.

Fig.2 Finite element mesh with the simplified model.

Boundary condition and initial condition. During the hot shrink-fit process, the heat transfer between rotor-can and furnace is a single radiation heat transfer process. The heat flux is utilized as Eq.1 relationship:

$$q_r = \varepsilon_r \sigma_r F (T_a^4 - T^4) \,. \tag{1}$$

where ε_r is the surface emissivity, σ_r is the Stefan-Boltzmann constant, T_a and T are temperature of hot air and insulation layer surface, respectively F is the radiation view factor which is calculated by the Monte Carlo method and Mac.Marc read the view factor automatically.

A set of transient heat exchange experiments of Hastelloy C-276 and silicon steel were conducted before[4]. The holding temperature were 100˚C, 200˚C, 300˚C and 400˚C and the narrow gap were 0.0mm, 0.2mm, 0.4mm, 0.8mm and 1.2mm, respectively. The transient thermal conductance follow an exponential decay function as Eq.2 relationship:

$$h_p = \mathrm{A} \exp(-\frac{d_{gap}}{\mathrm{B}}) + \mathrm{C}. \tag{2}$$

where h_p is the peak value of the transient thermal conductance, δ_{gap} is the dimension of the air gap between the test surfaces, A, B and C are the material constants. Then the transient heat exchange is defined and inputted into the finite element model via user subroutine FILM of MSC.Marc.

The initial temperature of rotor-can is 400˚C, the rotor is 20˚C.The initial stress of rotor and rotor-can is 0MPa.

Results and analysis

Hot shrink-fit time. Fig.3 shows the simulation results about upper end radial displacement and temperature evolution during hot shrink-fit process. In this model the rotor-can is 400˚C with the 0.125mm interference and 1.225mm shrink-fit gap. The radial displacement is 1.225mm and the temperature is 69˚C for upper end of rotor-can after 20s. The temperature decreased slowly at the beginning and then reduced quickly with transient heat exchange rapidly raised. In other words, only if the process time less than 20s, hot shrink fitting process will success otherwise the rotor-can canned on the rotor so earlier as to failure. It is difficult for device that using in the shrink–fit process. Hence the longer limit time will benifit to hot shrink-fit process.

Effect of rotor-can manufacture accuracy on hot shrink-fit process. The rotor-can manufacture accuracy is one of the most important factors on shrink-fit process. It directly influences the interference then impacts on the shrink-fit gap and the limit time for shrink-fit process. Fig.4 presents the distribution of residual stress and contact force. The residual stress is tensile stress on circumference, which is bad for the rotor-can to a long active time because of the potential fatigue failure[5]. Besides, the rotor-can is working on the corrosion medium and easily corroded as a result of residue stress. Frictional force stimulate the rotor-can loosened owing to little contact pressure. Fig.5(a) shows the effect of interference on shrink-fit time at 400˚C. With the increasing of interference, shrink-fit time reduced obviously and meanwhile contact force and residual stress increase as investigated in Fig.5(b). Considering the actually manufacture accuracy and working environmrnt of rotor-can, 0.08-0.16mm interference is advised.

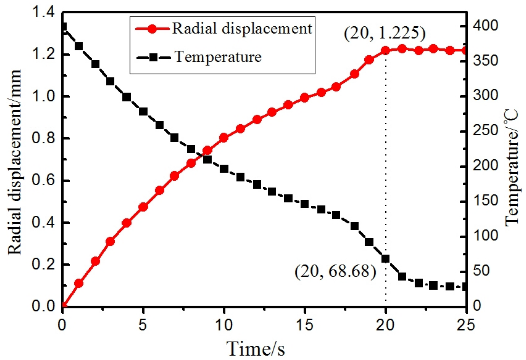


Fig.3 Change of radial displacement and temperature of upper end with time during the processing.

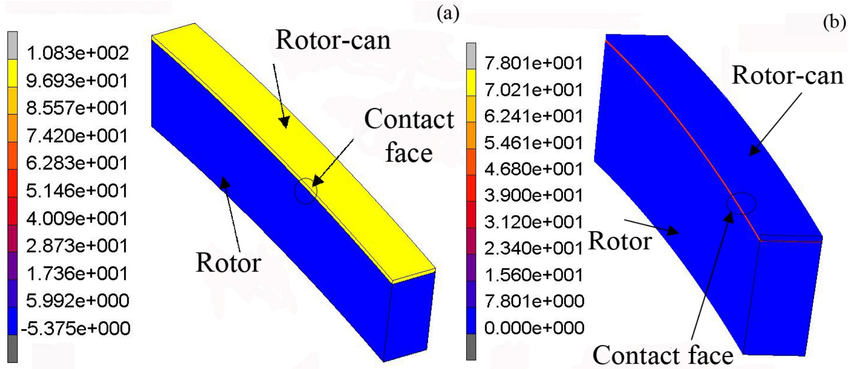


Fig.4 The distribution of (a) residual stress/MPa and (b) contact normal force/N

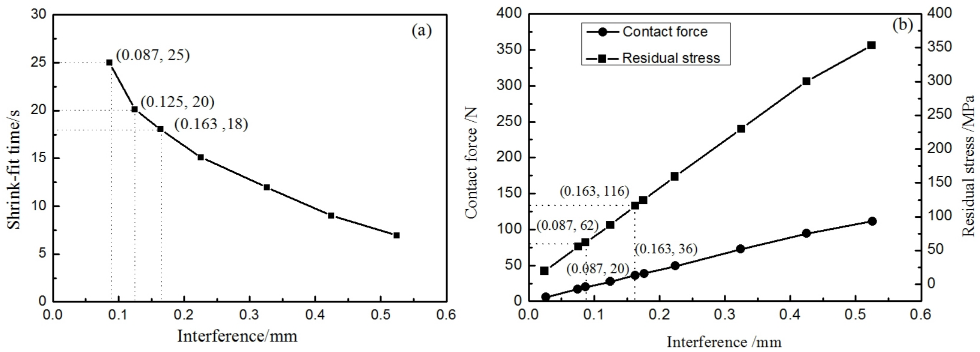


Fig.5 Change of the (a) limited time for hot shrink-fit process and (b) residual stress and contact normal force with interference.

Effect of temperature and insulating layer on hot shrink-fit process. The hot shrink-fit temperature is the another essential factor. Fig.6(a) indicates the higher temperature for shrink-fit process with 0.125mm interference, the bigger shrink-fit gap and the longer shrink-fit time. There are carbide or intermetallic compound in alloy at 650-1090˚C which make the difference of the mechanical and corrosion resistance performance[6]. Hence the shrink-fit time shouldn't higher than 500˚C. In order to increase the hot shrink-fit time, reusable insulation layer made of Hastelloy C-276 is designed. Because of the heat transfer from insulation layer to rotor-can, rotor-can temperature decreasing rate become slowly. In addition, the insulation layer can't affect the stress distribution of rotor-can.

Fig.6 (b) shows the change of hot shrink-fit time with insulation layer thickness. The gap is 1.225mm at 400˚C, thickness of 0.00mm, 0.50mm, 1.00mm, 1.50mm, 2.00mm, 3.00mm, 4.00mm and 5.00mm is designed. The fitting time follow the linear function with the layer thickness. The simulation results show that, when layer is changed from 0.00mm to 5.00mm, the fitting time expand from 20s to 178s, respectively. Thickness layer with 1.00-2.00mm is advised for high fabrication efficiency.

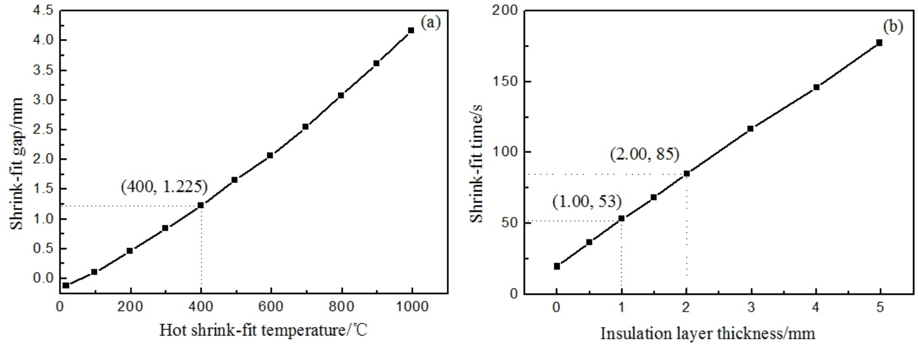


Fig.6 Effects of (a) shrink fitting temperature and (b) insulation layer on the processing.

Conclusion

A two-dimensional thermal-mechanical coupled finite element model was developed to simulate the shrink-fit processing of rotor-can using MSC.Marc. A set of transient heat exchange was tested and inputted into the finite element model via user subroutine FILM of MSC.Marc. As results, the hot shrink-fit time and upper end of rotor-can temperature are calculated and analyzed. The effects of rotor-can manufacture accuracy is investigated. The simulation results indicate the contact force and the residual stress is increased with the increment of interference while the hot shrink-fit time is reduced. Furthermore, the effects of temperature and thickness of insulation layer is studied. The hot shrink-fit time efficiently increased with increasing of layer. Taking the fabrication process into consideration, the rotor-can with 0.08-0.16mm interference and 1-2mm insulation layer at the temperature of 400-500˚C for the shrink-fit process is recommended.

Acknowledgements

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