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Effects of process parameters on vacuum hot bulge forming process on reactor coolant pump rotor-can with ring-shaped outward defect

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Abstract. Rotor-can is one of the key components of the canned reactor coolant pump to protect the rotor from corrosion damage in nuclear industry. It demands high dimension precision, posing great challenges to the processing technology. Vacuum hot bulge forming process is a potential technique to control the manufacture precision. In this paper, a 2-D nonlinear thermal-mechanical coupled finite element model (FE model) was established to simulate vacuum hot bulge forming process of rotor-can with ring-shaped outward defect. The displacement field of rotor-can and the height of ring-shaped outward defect after vacuum hot bulge forming process were calculated. The effects of process parameters, including holding time, holding temperature and bulging clearance, on vacuum hot bulge forming process of rotor-can with ring-shaped outward defect were analyzed. Results showed that to ensure the radius of the rotor-can can meet the requirement, when bulging clearance is fixed, holding temperature should also be fixed. The residual height of ring-shaped outward defect is decreasing with the decreasing of bulging clearance and increasing of holding temperature.

1. Introduction

Rotor-can is one of the key parts of canned reactor coolant pump in nuclear industry, and is canned out of the rotor to separate the rotor from coolant in the primary loop of nuclear power plant. It is a thin thickness cylinder usually made by Hastelloy C276 via the methods of clipping, rolling circle and welding [1]. In particular, the radius of the rotor-can in this paper has reached 276.875mm, and the thickness of rotor-can is only about 0.5mm. Thin thickness and large radius/thickness ratio of rotor-can posing great challenges to the processing technology. The manufacturing quality of rotor-can has large influence on the whole reactor coolant pump [2]. Defect usually occurs during manufacturing process on rotor-can, and ring-shaped outward defect is one of common defects occurring in welding process. The shape of ring-shaped outward defect is shown in Fig.1.

Vacuum hot bulge forming process is widely used for precise forming of thin-walled workpiece, and can be used to ensure the dimension and shape of rotor-can [3-5]. The difference of thermal expansion coefficients between workpiece and die is utilized in this technique [6,7]. The thermal expansion coefficient of die is larger than that of the workpiece. When heated, the die will expand faster than the workpiece, and the workpiece will be formed into the required dimension and shape by the thermal expansion force caused by the die.

In this paper, a 2-D nonlinear thermal-mechanical coupled FE model is established to study the effects of processing parameters on vacuum hot bulge forming process of rotor-can with ring-shaped

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outward defect. The displacement field of rotor-can with ring-shaped outward defect during vacuum hot bulge forming process with different holding time, holding temperature and bulging clearance is simulated, and further suggestions of choice of processing parameters have been given in terms of the calculated values.

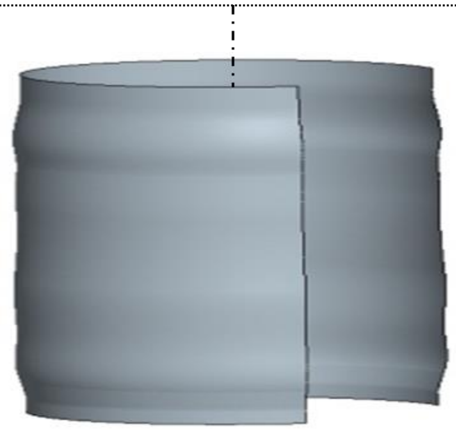

Figure 1. Rotor-can with ring-shaped outward defect

2. Finite Element Model

A 2-D axial symmetry FE model is established using MSC.Marc. The model includes vacuum furnace, water-cooled vacuum chamber, Mo heating element, thermocouple, all-metal heat shields, rotor-can and die, and is shown as Fig. 2. The initial temperature of die and rotor-can is 20 ℃. The die and rotor-can are heated by Mo heating element during the vacuum hot bulge forming process. The Time-Temperature curve of Mo-heating element is shown in Fig.3. The area inside the furnace is vacuous, therefore only radiation heat transfer is considered. The length of die and rotor-can is 200mm, the thickness of rotor-can is 0.5mm, and the inner radius of rotor-can is 276.2mm. There is a ring-shaped outward defect on the rotor-can. The width of the ring-shaped outward defect is 32mm, and the height of the ring-shaped outward defect is 0.4mm. Type 10 element, a type of four-node axis-symmetric quadrilateral element, is used in this FE model. The materials of rotor-can and die in this model are Hastelloy C276 and 1Cr18Ni9Ti respectively.

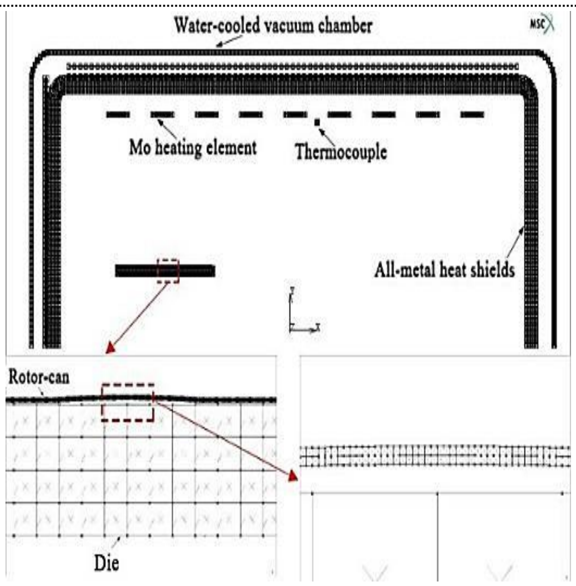

Figure 2. FE model of vacuum hot bulge forming

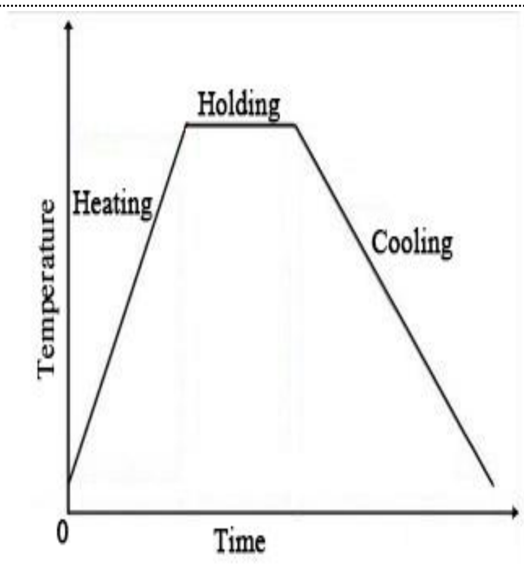

Figure 3. Time-Temperature curve of Mo heating element

3. Results and discussion

3.1. Stress field and displacement field of rotor-can with ring-shaped outward defect

When heated, the rotor-can and the die will expand, and the die will expand faster than the workpiece. The rotor-can and the die will contact with each other at some points during heating stage, and then expanding force will occur in rotor-can. Creep strain and plastic strain will occur in rotor-can because of the stress in the rotor-can caused by the die. Fig. 4 shows the stress distribution on rotor-can with ring-shaped outward defect at the beginning of holding stage. It can be seen that stress out of the defect area is much larger than that inside the defect area. The non-homogeneous distribution of stress leads to non-homogeneous deformation around the defect. Therefore, bulging dimension inside the defect is smaller than that out of the defect, and the height of ring-shaped outward defect on the rotor-can after vacuum hot bulge forming process is smaller than the original height of ring-shaped outward defect.

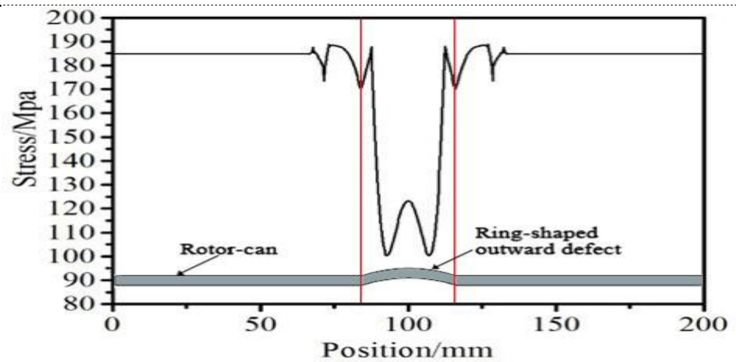

Figure 4. Stress distribution of rotor-can with ring-shaped outward defect at the beginning of holding stage

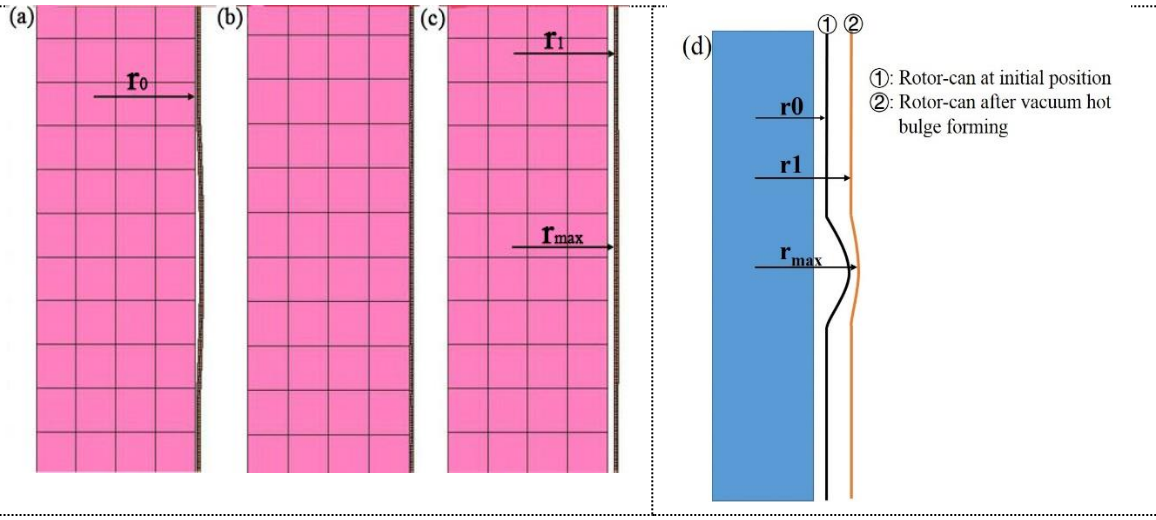

Figure 5. Evolution of shape of rotor-can and die. (a): initial position (b): holding stage (c): after vacuum hot bulge forming process (d): schematic illustration of vacuum hot bulge forming process

The evolution of shape of rotor-can is shown in Fig. 5, where r_0 is the original inner radius of rotor-can, r_1 is the inner radius of rotor-can after vacuum hot bulge forming process, and r_{max} is the radius of the centre of defect after vacuum hot bulge forming process. It can be seen that at holding stage, rotor-can is in contact with die completely. After vacuum hot bulge forming process the rotor-can and die separate from each other, and a ring-shaped outward defect occurs on the rotor-can again. r_1-r_0 is the bulging dimension of vacuum hot bulge forming, and $h=r_{max}-r_1$ is the residual height of defect after vacuum hot bulge forming process. The inner radius of rotor-can after vacuum hot bulge forming process should be within the range of 276.875±0.038mm.

3.2. Effects of holding temperature and bulging clearance on radius of rotor-can and height of ring-shaped outward defect

The radius of rotor-can after vacuum hot bulge forming process is related to holding temperature and bulging clearance [8]. With the increasing of holding temperature and decreasing of bulging clearance, the inner radius of rotor-can after vacuum hot bulge forming process will decrease. To ensure the radius of the rotor-can can meet the requirement, when bulging clearance is fixed, holding temperature should also be fixed. When the holding temperature is higher than 900℃, carbide precipitates in Hastelloy C276 will precipitate, and will affect the corrosion resistance of the rotor-can [9]. Therefore, the holding temperature should be smaller than 900℃. Table 1 shows the values of holding temperature at different bulging clearances when the radius of rotor-can can meet the requirements after vacuum hot bulge forming process. Fig. 6 and Fig. 7 show the values of inner radius of rotor-can, maximum inner radius of rotor-can and residual height of defect after vacuum hot bulge forming process with different bulging clearances and temperatures. It can be seen that the condition with 800 ℃ for holding temperature and 0.2mm for bulging clearance is the optimum process.

Table 1. Values of holding temperature at different bulging clearances

Bulge clearance(mm)	0.1	0.2	0.3
Holding temperature (°C)	600	800	900

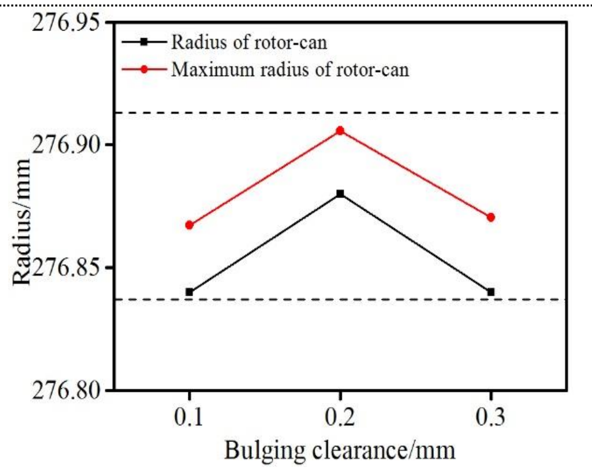

Figure 6. Effects of bulging clearance on radius of rotor-can

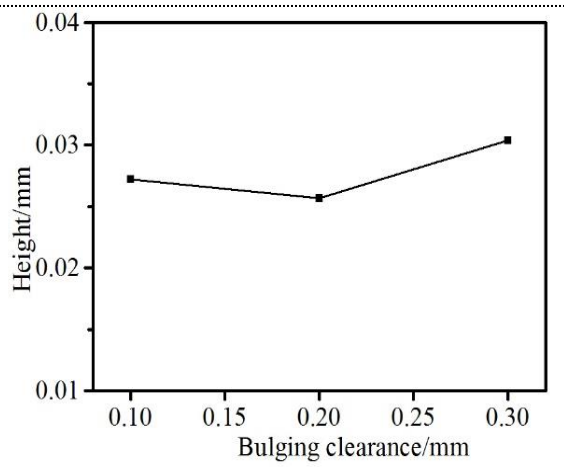

Figure 7. Effects of bulging clearance on residual height of defect

3.3. Effects of holding time on radius of rotor-can and ring-shaped outward defect

To research the effects of holding time, a set of FE models were established to simulate vacuum hot bulge forming process with different holding time. Fig. 8 shows the inner radius and maximum inner radius with holding time of 1-5h under the condition of 800℃ for holding temperature and 0.2mm for bulging clearance. With the increasing of holding time, more elastic strain is transformed into creep strain, therefore the inner radius and maximum inner radius of rotor-can after vacuum hot bulge forming process are increasing with the increasing of holding time. When holding time reaches 2h, the inner radius and maximum inner radius can correspond to required dimension. Creep rate is decreasing with the increasing of holding time. When holding time is longer than 3h, creep strain reaches the maximum value, and the radius of rotor-can hardly changes. Fig. 9 shows the residual height with the increasing of holding time under the condition of holding temperature for 800℃ and bulging clearance for 0.2mm. The simulated results indicate that the residual height of defect decreases with the increasing of holding time rapidly when the holding time is less than 3h. When the holding time is longer than 3h, residual height of defect reaches a stable value. Taking these factors into account, the optimal holding time for vacuum hot bulge forming process of rotor-can with ring-shaped outward defect is 3h.

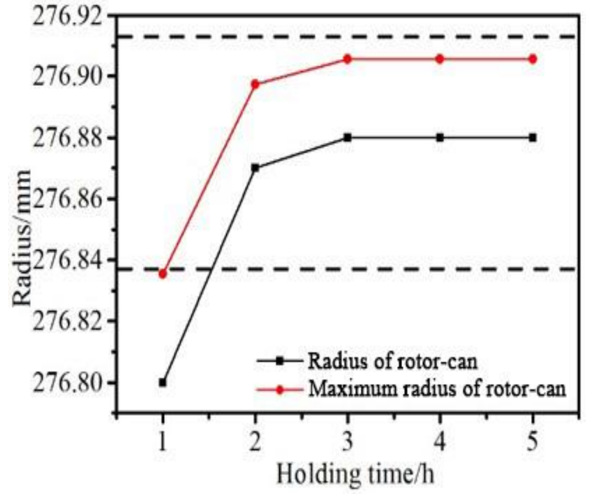

Figure 8. Effects of holding time on radius of rotor-can

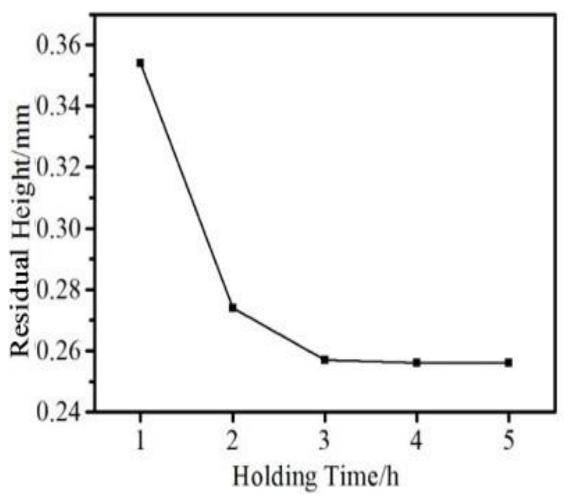

Figure 9. Effects of holding time on residual height of defect

4. Conclusions

A 2-D nonlinear thermal-mechanical coupled FE model is established to simulate the vacuum hot bulge forming process of rotor-can with ring-shaped outward defect. Using this model, the effects of process parameters on vacuum hot bulge forming process for reactor coolant pump rotor-can with ring-shaped outward defect is investigated, and conclusions can be drawn as following:

1) The dimension error of the rotor-can can be modified through hot bulge forming process. The height of ring-shaped outward defect after vacuum hot bulge forming process is smaller than the original height of ring-shaped outward defect.

2) The residual height of ring-shaped outward defect is decreasing with the decreasing of bulging clearance and increasing of holding temperature.

3) To ensure the radius of the rotor-can can meet the requirement, when bulging clearance is fixed, holding temperature should also be fixed. In this paper, the radius of rotor-can is within the range of 276.875±0.038mm. When the bulging clearances of rotor-can is 0.1mm, 0.2mm and 0.3mm, the holding temperatures should be 600℃, 800℃ and 900℃ respectively. The condition with 800℃ for holding temperature and 0.2mm for bulging clearance is the optimum process.

4) When the holding time is less than 3 hours, the residual height of the defect decreases with the increase of the holding time. When the holding time is longer than 3 hours, the residual height of defect hardly changes with the increase of the holding time.

Acknowledgement

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