Residual stress and deformation analysis on thermal shrink-fitted joint in the semi built-up marine crankshaft

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Abstract—Interference and deformation of the shrink fitting connection have a significant influence on the local stress state at the contact area. To improve its assembly quality, an optimized induction heating method with an arc-shaped frame coil and a cylinder type coil was developed. The effects of shrink fitting parameters such as residual contact stress and dimensional deformation were researched using finite element analysis (FEA). A thermal-structure coupling model of crankshaft shrink fitting was built, and contact stress evaluations of the measurement points in the shrinkage were obtained by numerical simulation. In addition, contact stress and deformation analysis under different interferences were also carried out to determine the range of values. The simulation and comparative analysis results show that the optimized multiple induction heating method with an arc-shaped frame coil and a cylinder type coil would be helpful to improve the uniformity and sustainability of contact.

1. INTRODUCTION

Semi built-up crankshaft where main journals or crankthrows are forged as one piece and shrink fitted together, is the most common for large marine main engines. It is well-known that the semi built-up crankshaft, when subjected to complex load in operation, may fail in their shrinkages. If it occurs, crankthrows are slipping over the main journals and/or fretting wear appears¹. The reliability of the joint depends on its interference and on the internal stresses generated during the cooling process. The residual stresses and their distribution may cause them to fail at a load level significantly lower than expected²³. Therefore, the prediction of the internal stress distribution and dimensional deformation of the thermal shrink-fitted joint is of great importance.

The induction heating device utilized in thermal shrink of semi-built-up crankshafts is shown in Fig.1, which consists of two subcomponents-a cylinder type coil and a frame type coil. This device is apt to cause uneven contact stress and dimensional deformation. To reduce the stress and residual deformation and improve the control capacity of union quality, we propose an arc-shaped frame coil and studies on the shrinkage mechanism through thermo-mechanical analysis concerning shrink-fitted joint.
2. Induction Heating Coil Description

For different types of crankthrows, the coil should have a certain flexibility. Coupled with the requirements of thermal uniformity and assembly operation, the coil is not suitable for integration. Referring to the original form (shown in Fig. 2), the improved coil is still designed as a separate-type structure. As shown in Fig. 3, the cylinder type coil is still placed in the shrink fitting hole and the arc-shaped frame one between the shrink fitting hole and the crankpin. The arc-shaped frame coil and the cylinder type coil are concentric with the hole. The relative positions between the arc-shaped coil, cylinder coil and crankthrow are kept constant with identical metal blocks. Fig. 4 shows the cross-section of arc-shaped coil and the wire inside is wound by winding.

Figure 1. Induction heating for thermal shrink fitting

Figure 2. The existing heating coil

Figure 3. The improved heating coil

Figure 4. Cross section of the arc heating coil
3. FEA MODEL

Shrink fitting is an inner cylindrical surface contact problem, and its analysis steps are shown in Fig.5. Before operation, some real constants in interference assembly contact algorithm, including normal contact stiffness factor (FKN), maximum penetration range (FTOLN), initial proximity factor (ICONT), and contact surface offset (CNOF), are needed to be defined properly, which is mainly to facilitate the definition and adjustment of the interference and clearance between crankthrow and journal model, eliminating the gap between the grids.

There are three steps to set the interference fit correctly in commercial software ANSYS:

Step 1: set KEYOPT(9) = 4. The default value of KEYOPT(9) 0 specifies that both the initial clearance caused by the geometric position of the two contact parts and the offset set in CNOF are simultaneously considered during contact analysis. After setting KEYOPT (9) = 4, the program only considers the value of CNOF when calculating. It does not consider the intrusion or gap caused by the geometric position of the contact part, and the interference is applied in ramp mode.

Step 2: set real constant ICONT. Generally, after meshing, there is a gap or interference between the target surface element and the contact surface element. If the gap or interference is within the ICONT setting error, it will be eliminated, and the program will make the target surface element and the contact surface element just in contact with each other.

Step 3: Set the interference by specifying the real constant CNOF. In step 2, through the ICONT setting, the elements above the target surface and the contact surface have just been in contact. At this time, CNOF is set again. The value of CNOF is the interference.

4. CONTACT STRESS ANALYSIS

The contact stress nephogram after six hours are finally obtained as shown in Fig. 6. It can be known that the minimum stress of the crankweb hole is 241.29 MPa. The average theoretical stress calculated by the reference stress formula in literature [4] is 194.37Mpa. The minimum stress calculated by the finite element model is much larger than the theoretical value, which meets the requirements of the connection strength of the parts. The maximum stress is located in the middle and lower part of the crankweb hole, which is caused by the asymmetry of the upper and lower surface structure of the crankthrow after installation of main journal. This asymmetrical complex structure causes unique deformation and stress. As can be seen from Table 1, the stress remained substantially constant after three hours, with a change of less than 3%. This phenomenon well illustrates that the contact stress can reach a steady state in the actual process. The yield strength of the material is 360 MPa, and the maximum stress calculated is 355.42 MPa. The maximum stress occurs at the position of the shrink fitting hole away from the crankpin.

Figure 5. Flow chart of interference fit contact analysis

Figure 6. Contact stress distribution after 6 hours


### TABLE 1. EVOLUTION OF MAXIMUM STRESS WITH TIME

| Step | Time/s | Min/MPa   | Max/MPa |
|------|--------|-----------|---------|
| 1    | 3600   | 1.8443    | 308.80  |
| 2    | 7200   | 0.2117    | 331.08  |
| 3    | 10800  | 2.80×10^{-2} | 345.08 |
| 4    | 14400  | 2.94×10^{-3} | 351.22 |
| 5    | 18000  | 4.51×10^{-4} | 354.11 |
| 6    | 21600  | 1.19×10^{-3} | 355.42 |

We take 5 points on the inner wall of the crankweb hole for the observation of residual contact stress in thermal shrink fitting process. Fig.7 shows their specific allocations. Figs.8 and 9 demonstrate the evolutions of the contact stress in the connection by the frame type coil and the arc-shaped type coil.

![Figure 7. Five measurement points](image1)

![Figure 8. Original contact stress evaluation](image2)

![Figure 9. Improved contact stress evaluation](image3)
For illustration, the original contact stress distribution are more dispersed than the latter’s. The biggest value of the original differences is 232.1MPa, in which the contact stress of some points has exceeded the yield strength of the material, and the latter is 107.4MPa.

5. CONTACT DEFORMATION ANALYSIS
Taking temperature distribution and deformation of the crankweb as the initial conditions, the original and improved displacement distributions after 6 h cooling are obtained as shown in Figs.10 and 11.

![Figure 10. Original displacement distribution of the crankweb](image)

![Figure 11. Improved displacement distribution of the crankweb](image)

In addition, Figs.12 and 13 depict the original and improved displacement distributions of the main journal in the shrinkage at the same time. Figs.14 and 15 show the original and improved displacement evolutions of the upper surface center. The component along z axis induced by journal gravity is the major displacement, which is 2.19mm and 0.392mm respectively. The improved displacement of the upper surface center is significantly smaller, which implies that it could provide better perpendicularity by the improved induction heating method with the arc-shaped frame coil and cylinder type coil.

![Figure 12. Original displacement distribution of the main journal](image)
Figure 13. Improved displacement distribution of the main journal

Figure 14. Original displacement evaluation of the upper center

Figure 15. Improved displacement evaluation of the upper center

6. CONTACT ANALYSIS UNDER DIFFERENT INTERFERENCES

6.1. Contact stresses under different interferences
The maximum shrink fitting interference of this kind of crankshaft is defined as 1.37mm by the manufacturer. To get the lower limit value, we select 5 discrete points with 0.1mm intervals to calculate the contact stresses and deformations of the shrinkage. Fig.16 shows half section nephogram of the contact stress in the shrinkage under different interferences 1.27mm, 1.17mm, 1.07mm, 0.97mm and 0.87mm. As illustrated in Fig.16, the axial contact stress in the middle position is small, while the contact stress at the edge of both sides is relatively large. This is due to the fact that the chamfer at the edge is simplified during journal modeling, resulting in stress concentration at the outer edge. In addition, with the decrease of interference, the contact pressure also decreases.

(a) δ = 1.27mm  (b) δ = 1.17mm
The actual values of the contact stress in the shrinkage under different interferences are larger than the theoretical average values, which is shown in Table 2. When the interference is 0.87mm, the contact stress is in the range of 173.96MPa to 111.09MPa and some local contact stress of the shrinkage does not meet the requirements of transmitted torque. When the interference is in the range of 0.97mm to 1.37mm, the coupling strength fulfill the requirements for normal operation.

| Interference δ/mm | 1.27  | 1.17  | 1.07  | 0.97  | 0.87  |
|-------------------|-------|-------|-------|-------|-------|
| Theoretical contact value /MPa | 180.09 | 165.91 | 151.723 | 137.55 | 123.37 |

6.2. Crankweb deformations under different interferences

In this section, we choose four measurement points shown in Fig.17 as the key nodes to discuss the influence of interference on the crankweb deformation. The details are listed in Table 3.
In general, points A and B on the edge of the crankweb hole have relatively large deformations and point A is larger than point B. The total deformation in the middle of the crankweb hole is small. With the decrease of the fit interference, the contact stress in the shrinkage decreases correspondingly. Consequently, the deformation of the crankweb hole is also decreasing. When the interference is reduced to 0.87mm, the deformation of node D is too small to provide adequate torque for the normal operation.

7. CONCLUSION
This study has enabled us to develop and study the induction heating approaches for semi built-up crankshaft manufacturing. Some of the conclusions are as follows:

1) The thermal-structure coupling analysis is carried out using ANSYS Workbench, and contact stress evaluations of the shrink fitting connection by the original and improved heating devices are obtained respectively. The simulation and comparative analysis results show that the optimized multiple induction heating method with an arc-shaped frame coil and a cylinder type coil would be helpful to improve the uniformity and sustainability of contact.

2) For requirements of optimizing characteristics, assembly method such as theoretical studies, computer generated calculations and experimental trials should be utilized to verify the improved induction heating innovation. Consequently, we will realize it and do a lot of experiments to further improve the method.

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