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Abstract: As a basic study for explanation of shaft misalignment after fully built-up of marine engine crankshaft and reducing its amount, following analyses are performed. First, heating process is simulated and variation in web bore diameter according to time and temperature distribution is investigated. Individual fitting process is simulated by two methods. Static analysis and coupled temperature-displacement analysis are performed. Global deformation after fitting of journal into web bore of crank throw is investigated through static analysis, and relative deformation of crank throw and journal according to time is observed through coupled temperature-displacement analysis. The former does not consider thermal effect but the latter consider thermal effect during shrink fitting process. Finally, deformation of fully built-up shaft due to self-weight is analyzed.

Figure 1 shows semi built-up type crankshaft of marine engine and its assembling process. Crankshaft is installed on engine bed plate, and it transforms reciprocation motion of piston to rotatory motion of propeller shaft through connecting rod. Crankshaft of small-scale engine is manufactured by closed-die forging and machining, but closed-die forging is not available for manufacturing large scale marine engine crankshaft. Full built-up and semi built-up type crankshaft are used for large-scale marine engines. Nowadays almost all large-scale marine engines adopt semi built-up type crankshaft. As shown in Figure 1 crank throw and journal manufactured by open die forging are assembled by shrink fitting. Journal is shrink fitted into one side of web bore of crank throw (individual shrink fit), and journal of individually shrink fitted body is assembled into the other side of web bore (built-up shrink fit). There are several methods to enlarge the web bore of crank throw for shrink fitting, but in this study heating of inside plane of the crank throw by the use of one burner is considered. After fully built-up, crankshaft goes through final machining on crank lathe.
Some amount of deviation (called big run-out) occurs in the shaft alignment after fully built-up and makes it difficult for the shaft to be machined on crank lathe for final machining. Even though there are several reasons of the big run-out, non-uniform deformation of crank throw and journal after shrink fitting process is thought to be the main reason. In addition, when pre-stressed shaft due to shrink fitting is simply supported at its ends and imposed on self-weight, there may occur some amount of plastic deformation.

As a basic study for explanation of big run-out mechanism and reducing its amount, following analyses are performed. First, heating process is simulated and variation in web bore diameter according to time and temperature distribution is investigated. Individual fitting process is simulated by two methods. Static analysis by using "CONTACT INTERFERENCE, SHRINK" command and coupled temperature-displacement analysis are performed. Global deformation after fitting of journal into web bore of crank throw is investigated through static analysis, and relative deformation of crank throw and journal according to time is observed through coupled temperature-displacement analysis. The former does not consider thermal effect but the latter consider thermal effect during shrink fitting process. Finally, deformation of fully built-up shaft due to self-weight is analyzed.

Stress by shrink fitting goes beyond the yield point locally, therefore elasto-plastic material properties are introduced (Table 1), and Table 2 shows thermal constants for the analysis.

Figure 2 shows model of crank throw for heating analysis. Only upper surface of two inside planes of crank throw is heated by gas, and top and outer surfaces of upper web exposed to atmosphere are covered with thin plate to prevent heat loss. Film coefficient of heating surface is 0.2 kg/mm.sec.°C, and film coefficient of surfaces covered with plate and atmosphere is 0.051 kg/mm.sec.°C.

It takes 3 hours to enlarge the web bore diameter to average 4.4mm, but lower bore is larger than upper bore, because one side heating is adopted (Figure 3). This means crank throw web is bent due to thermal gradient in thickness direction. This makes it difficult for journal to be inserted into web bore and it also results in non-uniform deformation during shrink fitting process. Therefore we should wait for the crank throw to be straightened. During the waiting time lower bore diameter decreases, but the upper bore diameter increases for the first 30 minutes. This is the result from the fact that heat of lower part of crank throw is transferred to upper part of crank throw and bending moment is released. Figure 4 shows temperature distribution and deformation during heating and cooling processes.
Figure 5 shows model for individual shrink fitting process by static analysis. Web diameter is 861mm, and journal shaft diameter is 863.1mm, so fitting allowance is 2.1mm, “CONTACT INTERFERENCE, SHRINK” command is used for describing journal behavior to be shrink fitted into web bore.

Figure 6 shows deformed shape of the crank throw after shrink fit. Upper web of crank throw deflects downwardly, even though analysis does not contain self-weight effect. This is very meaningful result. It can be known from the deformed shape of journal that journal diameter near upper surface of web is larger than that near lower surface because part of journal outside fitted part constrains deformation (compression) of part of journal which is compressed by web bore. If configuration of crank throw web is symmetric about journal, section of journal which is compressed by web bore will form symmetric trapezoidal shape, but left side (pin side) of web is much thicker (stiffer) than right side. Therefore right side web elongates more than left side and the section of journal is not symmetric trapezoidal. That is the reason why web deflects downwardly after shrink fitting.

Contact pressure from elastic theory can be expressed as following equation (1) and it yields average contact pressure of 15 kgf/mm², and Figure 7 shows contact pressure results by ABAQUS.

\[
P_a = \frac{E}{2} \cdot \frac{\delta}{2} \cdot \frac{(r_2^2 - r_1^2) \cdot (r_3^2 - r_2^2)}{r_2^2 \cdot (r_3^2 - r_1^2)}
\]

Where \( P_a \) is pressure at the fitted area
- \( r_1 \) is inside diameter of cylinder
- \( r_2 \) is outer diameter of inner cylinder
- \( r_3 \) is outer diameter of external cylinder
- \( \delta \) is fitting allowance
- \( E \) is elasticity of material

Using static analysis, global deformation of crank throw and journal is investigated. This approach has several merits comparing to coupled temperature-displacement analysis. Overall deformation behavior of crank throw and journal can be obtained in relatively short computation time. It is not confined to be applied to analyze individual shrink fitting process, but it can be extended to analyze built-up process. However thermal effect during shrink fitting process should not be omitted. It is impossible in shrink fitting shop to heat all crank throw to have same temperature distribution. Although a crank throw is heated to such an extent that journal can be fitted into web bore, every crank throw has different temperature distribution. This causes differences in deformation after shrink fitting process, and then overall shaft misalignment occurs. Especially non-symmetric geometry of crankshaft makes the problem more complicated.
As mentioned above, there are several key parameters to govern shrink fitting process analyzed by coupled temperature-displacement analysis. Temperature distribution at the moment of journal inserting is the first one. Gap conductance of the interface of journal and crank throw through which heat of crank throw is transferred to journal is also very important. Different cooling condition may result in different deformed shape after fitting is completed. Another important factor is initial location of journal when it is inserted into enlarged web bore by heat.

Figure 8 (A), (B) shows FE model of coupled temperature-displacement analysis of crank throw and journal for shrink fitting. To reduce computation time only upper half of crank throw and half of journal is modeled. For the analysis, the first step is heating. In the heating process, journal and contact pair of journal outside surface and crank throw inside surface is not necessary. So "MODEL CHANGE" command is used to remove journal and contact pair. The second step is cooling for the crank throw to be straightened. The third step is inserting journal into web bore and seating journal on liner by gravity. In the third step, we activate journal and contact pair again. Before seating journal, crank throw upper surface and journal stopper is set to be parallel. Otherwise there may occur problem in convergence. In shrink fitting shop several special jigs are used to level crank throw surface and journal stopper. The fourth step is cooling the crank throw with the journal being inserted into crank throw.

As an example analysis, we set journal and crank throw as shown in Figure 8 (C). Initially journal contacts with web bore at pin side. As time goes by, heat of crank throw goes away into atmosphere and is transferred to journal, and web bore size decreases.

Figure 9 shows temperature drop according to time of the spot of the crank throw marked with * in Figure 9. Both results from ABAQUS and measured data have same tendency that around 3,000 seconds after journal inserting temperature drops rapidly for following 5 minutes, then temperature decreases steadily. From this graph, it can be known that clearance between journal and crank throw in profile side (δ in Figure 9) approaches zero in 3,000 seconds after inserting. Difference of temperature between analysis and experiment maintains about 30 ~ 40 °C throughout time interval. This difference is regarded as the results of heating and cooling.

Figure 10 shows distance between journal stopper and upper surface of crank throw after inserting (f in Figure 8 (C)) at the profile side. During the shrink fitting process, deformation of journal and crank throw at profile side can be divided into 3 zones as shown in Figure 10. Zone 1 is the first 3,000 seconds during which clearance between journal stopper and crank throw upper surface decreases. In Zone 2 very rapid change in clearance occurs during short time interval. Finally in Zone 3 journal is fitted into crank throw tightly, floating slowly during long time. Because, at the moment when seating journal on crank throw, journal is set to contact with web bore surface at pin side, floating amount of journal around this area is less than that of profile side. In Figure 10, for the first 3,000 seconds (5 minutes), distance decreases for about 0.16mm (Zone 1 in Figure 10). No other force except gravity is acting on journal. However cooling rate is different at profile side and pin side. Crank throw of profile side is heated easily and also cools rapidly. Therefore thickness of crank throw of profile side decreases more rapidly than pin side. This is the reason why distance between stopper and crank throw at profile side decreases at Zone 1.

At around 3,000 seconds after journal inserting, journal floats rapidly for about 5 minutes. The end of Zone 1 and the beginning of Zone 2 is the time when clearance between journal and crank
throw approaches zero. This instant has already been shown in Figure 9. At this moment temperature of crank throw drops rapidly. Journal floats by 0.16 mm without any resistance. In addition journal floats by 0.3 mm within 5 minutes. After 5 minutes from the beginning of Zone 2, Zone 3 starts and floating velocity decreases gradually.

Floating at Zone 3 is due to the shrink fitting action of journal into web bore. During fitting process, journal is compressed in radial direction, therefore it extends in axial direction.

As shown in Figure 9 temperature of crank throw drops about 80 °C in 5 minutes, and at that moment journal temperature may increase by same level. This means that, after contact of journal and crank throw, journal will extend in axial direction and crank throw will contact in thickness direction. It can explain journal floating by 0.3 mm in 5 minutes during the period crank throw temperature drops by about 80 °C.

ABAQUS results and experimental data are in good agreement with each other.

Figure 11 (A) shows equivalent plastic strain distribution due to shrink fitting with material temperature of 100 °C. Shrink fitting already has some amount of plastic deformation on shaft. After fully built-up, crankshaft, which is simply supported at its both ends, waits for the next process (final machining). Shaft deforms like a bow by gravity as shown in Figure 11 (B). This deformation adds plastic deformation as shown in Figure 11 (C). Added maximum plastic strain value is about 5 % of shrink fitted state. However plastic deformation because of horizontal waiting contributes about 15 ~ 20 % to total big run-out.

From the study, following conclusions are obtained.

- When crank throw is heated at one side, temperature distributes non-uniformly and this thermal gradient causes the crank throw bent. During cooling process, diameter of upper bore hole increases because of released bending moment, for the first few minutes.
- Through static analysis to investigate individual shrink fitting process, it is known that upper web of crank throw deforms downwardly because of deformation of journal.
- Through coupled temperature-displacement analysis, temperature variation and floating phenomenon is investigated with respect to time.
- When fully built-up crankshaft which is simply supported at its both ends is subjected to self-weight at its both ends simply supported before final machining, around 5 % of plastic strain is added to initially shrink fitted state.


Figure 1. Semi built-up marine engine crankshaft.
### Table 1. Mechanical properties of crank throw and journal.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Elasticity (kg/mm²)</th>
<th>Yield Stress (kg/mm²)</th>
<th>Tensile Stress (kg/mm²)</th>
<th>Elongation (%)</th>
<th>Reduction in Area (%)</th>
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### Table 2. Thermal constants of crank throw and journal.

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<tr>
<th>Temperature (°C)</th>
<th>Thermal Conductivity (kcal/m.hr.°C)</th>
<th>Specific Gravity (kg/m³)</th>
<th>Specific Heat (kcal/kg.°C)</th>
<th>Linear Expansion Coefficient (3×10⁻⁶ mm/mm°C)</th>
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Figure 2. Model for heating and cooling analysis.

Figure 3. Extension of bore diameter versus time.
(A) Heating 3 hours.  
(B) Cooling 1 hour after heating 3 hours.

Figure 4. Temperature distribution and deformation during heating and cooling process.
Figure 8. Model for individual shrink fitting (coupled temperature-displacement analysis).
Figure 9. Crank throw temperature versus time after inserting.

Figure 10. Relative deformation (floating) between journal and crank throw according to time.
(A) Result of plastic strain after shrink fitting.

(B) Deformation of fully built-up crankshaft simply supported at its ends.

(C) Result of plastic strain due to shrink fitting and horizontal waiting.

Figure 11. Plastic strain and deformation of fully built-up crankshaft.