Research Article

Guodong Li, Xiaosheng Zhou*, Li Zhang, YunFei Du, and Dong Zhang

Dynamic evolution of residual stress upon manufacturing Al-based diesel engine diaphragm

https://doi.org/10.1515/htmp-2024-0032
received April 10, 2024; accepted May 21, 2024

Abstract: As a thin-walled complex structure, the manufacturing of Al-based diesel engine diaphragms involves casting and heat treatment. Residual stress is introduced during the uneven temperature field in casting and heat treatment, as well as the plastic deformation and cutting heat during mechanical processing. This research investigates the evolution and accumulation models of residual stress in casting and heat treatment for Al-based diesel engine diaphragms using ProCAST and ABAQUS software, combining with the experimental tests. To mitigate residual stress, the optimal parameter combination for casting temperature, knockout temperature, and mold preheating temperature in casting process is explored. The results indicate that the knockout temperature has the most significant influence on casting residual stress, and mold preheating is beneficial for reducing residual stress. Despite improvements, some internal stress concentration areas persist on the knockout casting surface. Furthermore, T6 heat treatment proves to be effective in eliminating more than 50% of the residual stress.

Keywords: diesel engine diaphragm, residual stress, cast, hot treatment

1 Introduction

In the high-precision machining production of diesel engine, stress redistribution can result in deviation between the tool envelope surface and the final shape upon clamp release, leading to the machining deformation [1]. Engine blocks containing residual stresses are susceptible to cracking or expanding during usage, significantly impacting their service life [2–4]. The cylinder block spacer, with its complex structure and non-uniform thickness in contact with the main shaft, plays a crucial role in retaining and propagating residual stresses during casting and heat treatment across various segments [5,6]. He et al., in his research on residual stress, used the finite element method to analyze residual stress in diesel engine pistons during manufacturing, demonstrating reduction through sand falling and elimination via heat treatment [7]. Zhang et al. optimized low-pressure casting parameters for ZL205A alloys, employing simulations and experiments to investigate the microstructure-stress interaction, thereby reducing residual stress [8].

In diesel engines, the evolution of residual stress often leads to damage in various parts, negatively impacting the overall service life. The pouring temperature affects the liquid fluidity. High pouring temperature can result in defects, such as porosity and cold segregation, while low pouring temperatures may lead to issues like shrinkage holes [9,10]. Additionally, the sand temperature, which refers to the temperature of the sand box, imposes stress on the casting. Maintaining suitable sand temperature and time is essential, and preheating the sandbox proves beneficial in reducing casting stress.

This study utilizes ProCAST software for casting and ABAQUS software for knockout joint simulation. The modeling of the casting process for physical production is combined with experimental studies on residual stresses. The objective is to study the effects of casting process of the spacer plate and the heat treatment on the evolution and accumulation model of residual stresses. The aim is to clarify the distribution of residual stresses and identify potential methods for their elimination. Quantitative analysis is conducted on stress concentration areas in diesel
engines. Figure 1 shows the process flow diagram of the diesel engine diaphragm [11–15].

2 Spacer model and sprue design

To meet the specific requirements of a single partition size measuring of 504 mm (length) × 346 mm (width) × 200 mm (height), a modeling ratio of 1:2 was employed in three-dimensional modeling software. The thinnest position was set to a thickness of 7.5 mm. An open casting model was utilized to validate data for the large Al-based casting model. The size of each gate in the gating system was determined using the minimum cross-section method. In this study, the minimum cross-section of components served as the basis, and the areas of other components were determined proportionally. Subsequently, the size of each component was determined based on the structure of casting system. The casting time between each component was set at 7 s. The primary function of the riser is to compensate for shrinkage and prevent shrinkage and porosity during casting. Vertical parting was chosen in the selection of the parting face to maximize compensation for the riser system.

Equation (1) is used to calculate the minimum blocking area.

\[
\sum R = \frac{G_p}{\gamma \sqrt{g \cdot t_A \cdot \delta \cdot W}},
\]

where \( \sum R \) represents the minimum cross-sectional area of the casting system, cm²; \( G_p \) represents the mass of the casting (excluding the pouring riser), kg; \( \gamma \) represents the density of the metal, kg/cm³; \( g \) represents the acceleration of gravity, 980 cm/s²; \( \delta \) represents the thickness of main wall, cm; \( W \) represents the material index, and the aluminum-copper system alloy is generally taken as 0.29; and \( t_A \) represents the effective pouring time of the casting, s.

3 Experimental materials and finite element analysis

The accumulation behavior of casting residual stresses is influenced by various factors, including uneven cooling rates, plastic deformation, and phase transformations. These self-equilibrating internal stresses significantly impact the mechanical properties and service life of castings. Modern casting
processes often use finite element analysis to predict stress distribution and employ physical testing methods and non-destructive testing techniques to effectively control and enhance product quality by optimizing process parameters.

The studied material in this work is ZAlCu5MnCdVA. The thermophysical properties and mechanical parameters of the material required in model casting are shown in Table 1.

In Table 1, \( \rho \) is the density, \( E \) is the Young’s modulus, \( \mu \) is denoted as is Poisson’s ratio, \( K \) is the conductivity, \( c_p \) is the specific heat, and \( \alpha \) is the thermal expansion coefficient. The model is meshed in the ProCAST Mesh module.

The number of nodes in the model is 266,269, and the number of cells is 782,299. The mesh type is tetrahedral cell C3D4. The sand model is rigid in order to reduce computation of the stress type, while the casting and sprue are elastic-plastic models.

Orthogonal experiments were designed for spacer casting to simulate the casting process, incorporating variables such as casting temperature, knockout temperature, mold preheating temperature, and residual stress. The stress value represents the averaged stress value derived from the stress cloud diagram. Figure 2 shows the stress cloud diagram of the sand falling state. Large stress concentrations are

![Figure 2: Residual stress profile calculated from the parameters listed in Table 2. (a) A1B1C1, (b) A1B2C2, (c) A1B3C3, (d) A2B1C2, (e) A2B2C3, (f) A2B3C1, (g) A3B1C3, (h) A3B2C1, and (i) A3B3C2.](https://example.com/figure2.png)
evident in the thin-walled position of the single spacer or the arc part. Stress concentration is also observed at the step corner position with significant thickness, and some stress values approach the yield strength of the material.

The effects of factors listed in Table 2 on the residual stress were evaluated, where $k$ represents a factor calculated in the range analysis. It is found that $k_d(89.67) > k_c(78.25) > k_a(77.25)$, larger $k$ values indicate high level of significance. Among the factors examined, knockout temperature exhibited the greatest effect on casting residual stress, while the casting temperature had the least effect. It can be concluded that the combination type of $A_3B_3C_3$ should result in less residual stress, making it a preferable choice for the Al-based diesel engines. The simulation results were analyzed by using ABAQUS software for air cooling to room temperature after the mold unloading. The findings indicate that the surface stress of the casting can be reduced to 80 MPa after removing the sand mold, exhibiting spotted patterns. However, stress concentration still exists at the thinnest position of the casting, with the stress value exceeding 100 MPa. The stress cloud at room temperature after the mold unloading is shown in Figure 3.

4 Experiment verification for the casting diaphragm

3D printing and disappearing mold casting were used to fabricate the Al-based diesel engine. Due to the challenge of

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Accumulation model (MPa)</th>
<th>Measured value in cast state (MPa)</th>
<th>Measured value in heat treatment state (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>147.74</td>
<td>131.28</td>
<td>65.68</td>
</tr>
<tr>
<td>Position 2</td>
<td>154.51</td>
<td>135.82</td>
<td>46.74</td>
</tr>
<tr>
<td>Position 3</td>
<td>134.15</td>
<td>152.91</td>
<td>50.35</td>
</tr>
</tbody>
</table>
mold removal associated with 3D printing, disappearing mold casting was adopted. The removal of the mold was facilitated by using a drying oven, resulting in the creation of the partition cavity. Figure 4 shows the photographs of the disappearing mold and the fabricated cast. Casting tests were performed with the optimal parameter combination specified in Table 2. The actual residual stress was measured using the blind hole method. The difference between the measured and fitted values falls within the range of 12.5–13.8%, confirming the reliability of the casting modeling in this study. The tensile strength of the cast, prior to the heat treatment, was determined as 217 MPa. After undergoing T6 heat treatment, the strength increased significantly to 423 MPa. Moreover, the residual stress of the cast subjected to T6 heat treatment was notably reduced, as indicated in Table 3.

5 Conclusion

1. The residual stress accumulation model demonstrated effective prediction of residual stress in Al-based diesel engine. The maximum difference between predicted and measured values was 13.8%.
2. Casting modeling revealed that a parameter combination of casting temperature at 740°C, knockout temperature of 450°C, and mold preheating temperature at 60°C, would result in reduced stress concentration.
3. The implementation of T6 heat treatment significantly alleviated residual stress within the cast and concurrently improved tensile strength.

Acknowledgments: The authors gratefully acknowledge the financial support provided by Graduate Student Innovation Program in Shanxi Province (Grant No. 2023KY576).

Funding information: This work was supported by Graduate Student Innovation Program in Shanxi Province (Grant No. 2023KY576).

Author contributions: Guodong Li: writing – original draft and formal analysis; Xiaosheng Zhou: writing – review and editing; Li Zhang: resources and supervision; YunFei Du: experimental preparation and project administration; and Dong Zhang: methodology and formal analysis.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The data presented in this study are available on request from the corresponding author.

References


