International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 4, Number 2, Year 2024
DOI: https://doi.org/10.62051/ijmee.v4n2.09
Journal homepage: https://wepub.org/index.php/IJMEE/index

Influence of Cooling Rate on Crack Growth and Stress Distribution in Die Steel under Thermal Cycles

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ABSTRACT

Die casting molds are prone to thermal fatigue under high-temperature and high-pressure cycles, which significantly affects their service life. In this study, a three-dimensional numerical simulation method is employed to analyze the temperature field, stress field, and crack development process of the mold under different cooling cycles. The results show that shorter cooling cycles (15s, 30s) lead to larger temperature gradients and stress concentrations within the mold, thereby accelerating crack initiation and propagation. In contrast, longer cooling cycles (70s) help to reduce the temperature gradient and stress fluctuations, which in turn slows down crack propagation and effectively extends the mold's service life.

KEYWORDS

Die Steel; Thermal Fatigue; Cooling Cycle; Numerical Simulation.

1. INTRODUCTION

Die casting technology, as an efficient near-net-shape forming process, is widely applied in the production of complex automotive components. However, molds undergo frequent thermal cycling under high-temperature and high-pressure conditions, leading to significant thermal fatigue issues. Studies have shown that the thermal stresses accumulated in the mold during the die-casting cycle, combined with high-pressure and tensile stresses, particularly in areas with localized plastic deformation at the material surface, are prone to initiating cracks. These stresses accumulate over time, eventually leading to the propagation of fatigue cracks, which reduces the mold's strength and service life. According to Ding [8], the failure of H13 steel molds is primarily caused by corrosion and cracking, with cracks concentrated in regions of high localized stress, such as around corner radii and holes/inserts. Mold damage caused by thermal fatigue accounts for more than 70% of all discarded molds, severely impacting production stability and market competitiveness [9]. Therefore, mitigating thermal fatigue and extending mold life have become critical challenges in die-casting technology.

Various methods have been proposed to alleviate thermal fatigue issues in molds. For instance, Chen [10] proposed an energy-based fatigue life model to assess the thermal fatigue life of die-casting molds; Lu [11] developed a thermal fatigue crack life prediction model based on temperature and validated its effectiveness through finite element simulations; Wei [12] introduced a new approach to simulate the thermal stress distribution and interface heat transfer resistance evolution between the mold and the casting during the die-casting process. However, these methods still have limitations when dealing with complex variations in cooling cycles, especially regarding the mechanism of how cooling cycles influence the thermal fatigue life of molds. Systematic research and in-depth numerical simulations on this topic have yet to be fully explored.

This study uses three-dimensional numerical simulations to investigate the impact of cooling cycles on the thermal fatigue life of die-casting molds. A numerical model matching the actual cooling cycles was established to comprehensively simulate the thermal fatigue crack propagation behavior of the mold under different cooling cycles. The model accurately reproduces the thermal stress distribution and crack propagation characteristics under varying cooling conditions. Through a systematic analysis of the effect of cooling cycles on the thermal fatigue performance of die-casting molds, detailed data on crack propagation patterns and thermal fatigue life were obtained. The simulation results not only reveal the key role of cooling cycles in thermal fatigue of die-casting molds but also provide a scientific basis for optimizing cooling strategies.

2. EXPERIMENTATION

To study the effects of temperature cycles on thermal fatigue life and thermal crack formation, Liu [13] designed a thermal fatigue testing device based on induction heating. The specimen is heated to 650°C using a high-frequency induction coil and then cooled by an air-cooling system to simulate the thermal fatigue cycling effects of die-casting mold steel. Samples are taken after every 500 cycles to observe crack development. The upper and lower temperature limits of the cycle are 650°C and 150°C, respectively, while the heating rate and cooling time are controlled by adjusting the heating frequency and the air flow of the cooling system. Based on actual die-casting process tests, cooling cycles of 15 seconds, 30 seconds, and 70 seconds were ultimately determined.

The specimen design is shown in Figure 1, and consists of a rectangular plate region and a clamping cylinder region. The dimensions of the rectangular plate are 50×20×6 mm, with a V-shaped notch featuring a 60° angle and a radius of 0.1 mm on the main cooling surface. This notch is designed to concentrate thermal stress and control the crack location, thereby inducing and facilitating the propagation of thermal fatigue cracks.

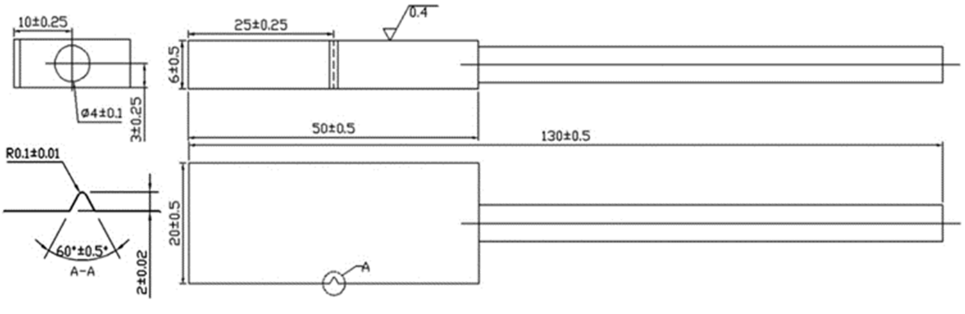


Figure 1. Thermal fatigue sample

3. NUMERICAL SIMULATION

In Liu's experiment, AISI H-13 hot work tool steel was used, and its chemical composition is shown in Table 1. The material has a density of 7800 kg/m³ and a Poisson's ratio of 0.3. The temperature-dependent properties used in the simulation are shown in Figure 2.

Table 1. Chemical composition of AISI H13 die steel

Elements	C	Cr	Mo	V	Si	Mn
Weight%	0.35	5.06	1.31	0.90	0.97	0.32

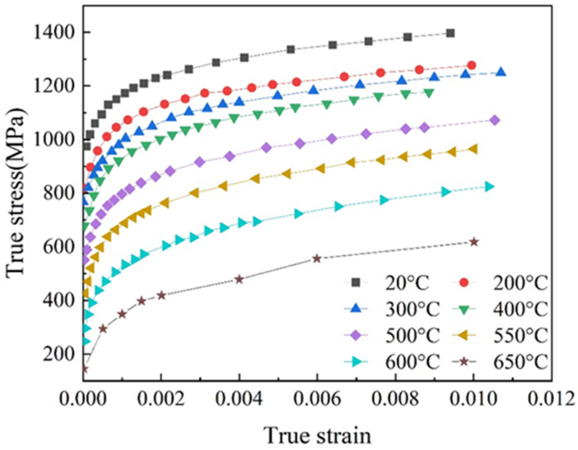


Figure 2. Stress-strain curve of H13 die steel [14]

The component modeling is similar to the experiment, using 3D deformable solid modeling (Figure 3). In the thermal cycle simulation, the heat transfer coefficients of the heating and cooling surfaces were adjusted to better match the experimental thermal cycling results. During the induction heating phase, the heat transfer coefficient was set to 1000 W/(m²·K). In the cooling phase, the heat transfer coefficient at the notch's main cooling surface was set to 36 W/(m²·K), while other cooling surfaces were set to 25 W/(m²·K). These parameters were adjusted to obtain temperature curves that match the thermal distribution observed in the experiment, as shown in Figure 4.

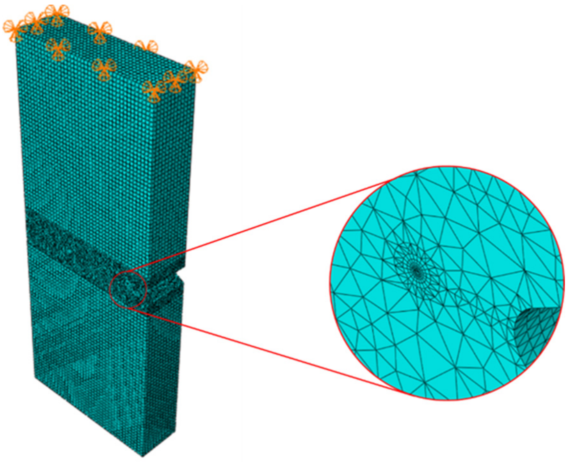


Figure 3. 0.768mm crack length simulation model

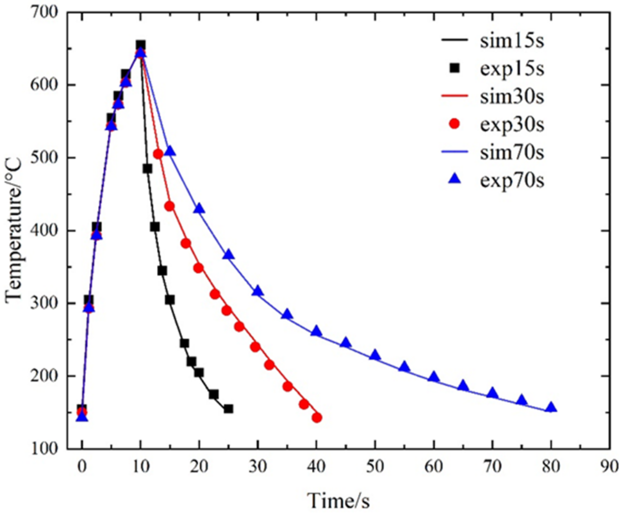


Figure 4. Comparison of experimental and numerical heat distribution

The numerical simulation was defined as transient heat transfer models for 250s, 400s, and 800s, with the goal of successfully completing 10 thermal cycles. The model used C3D8R and C3D6 type elements for structural meshing, with the total number of elements ranging from approximately 200,000 to 300,000.

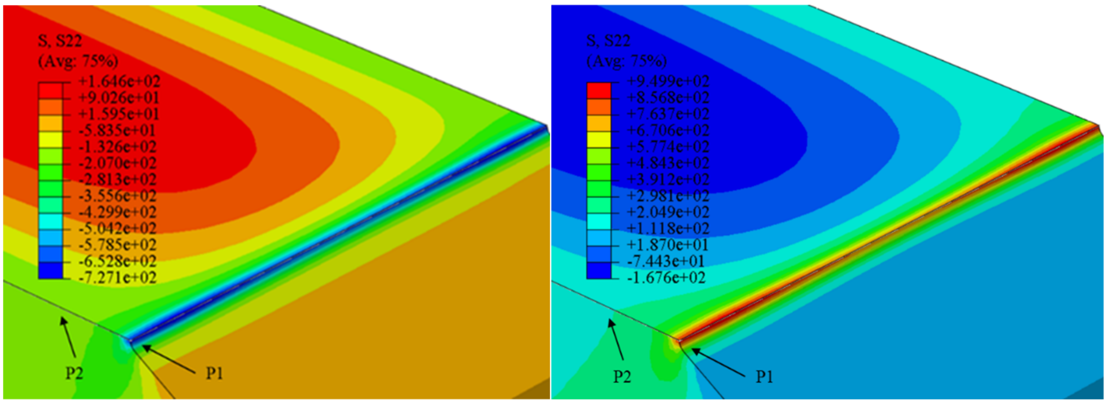
A coupled thermomechanical simulation model was established to simulate the thermal fatigue crack propagation behavior of a rectangular notched specimen made of H13 tool steel. The same material properties as those shown in Figure 2 were used, and a predefined temperature field was applied to simulate the thermal distribution, with one end fixed to replicate the experimental boundary conditions. Crack propagation was analyzed for different cooling cycles (15s, 30s, and 70s) and crack lengths (500, 1000, and 1500 cycles), with the results presented in Table 2.

Crack analysis was performed using a contour integral model, with five contour rings defined around the crack tip to ensure the accuracy of the results. Figure 3 shows the simulation model with a crack length of 0.768mm, highlighting the boundary conditions and mesh elements.

Table 2. Crack length under different cooling periods

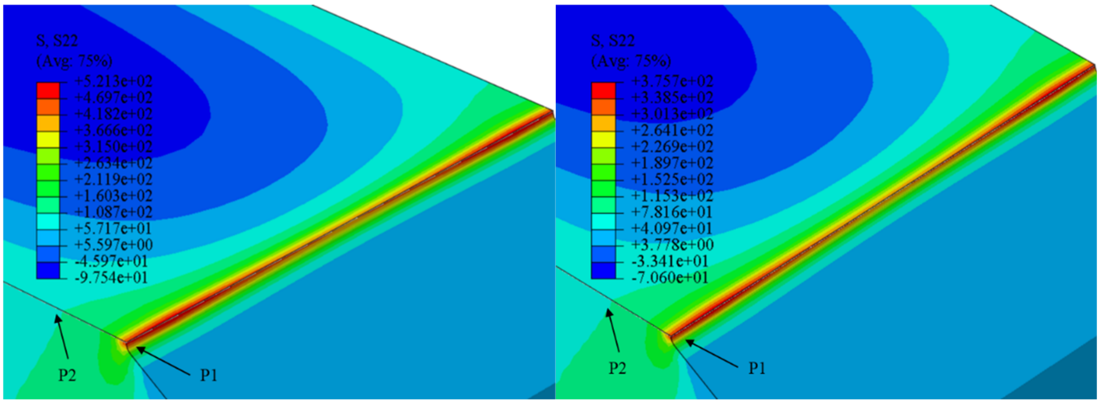
Cooling period /s	500 cycles	1000 cycles	1500 cycles
15	0.278 mm	0.462 mm	0.768 mm
30	0.137 mm	0.217 mm	0.369 mm
70	0.059 mm	0.102 mm	0.175 mm

4. SIMULATION RESULT ANALYSIS



(a) 10s heating cycle

(b) 15s cooling cycle



(c) 40s cooling cycle

(d) 70s cooling cycle

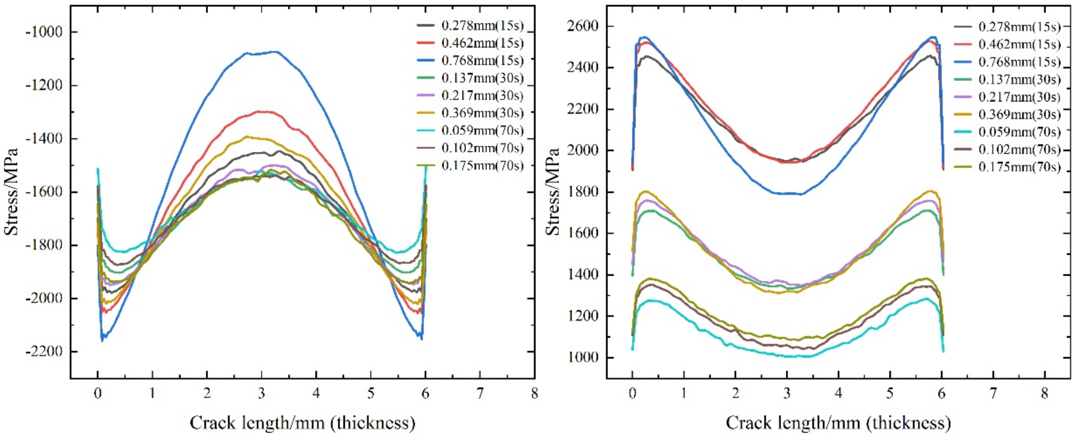
Figure 5. No crack specimen peak stress

The cooling cycle has a significant impact on the stress distribution under thermal fatigue loading, particularly the peak stress, which plays a crucial role in crack initiation and propagation. Figure 5 shows the peak stress of the specimen without cracks.During the initial heating phase, thermal expansion is restricted, resulting in the rapid formation of compressive stresses within the specimen, especially at the notch where stress concentration occurs. As heating continues, the stress gradually decreases and approaches a state of equilibrium. During cooling, the compressive stress transitions into tensile stress. Shorter cooling cycles (15 seconds) lead to a more pronounced stress concentration effect, causing the stress at the notch to rapidly change from compressive to tensile, reaching a higher peak value. As the cooling cycle duration increases (40 seconds, 70 seconds), the stress concentration effect diminishes, and the peak stress decreases.

Specific data show that under a 15-second cooling cycle, the peak stress at the notch and at 0.5 mm from the notch are 856 MPa and 224 MPa, respectively, with a difference of 632 MPa. Under a 40-second cooling cycle, the values are 476 MPa and 126 MPa, with a difference of 350 MPa. Under a 70-second cooling cycle, they are 328 MPa and 86 MPa, with a difference of 242 MPa. As the cooling cycle increases, the peak stress at the notch decreases by 528 MPa from 15 seconds to 70 seconds, and at 0.5 mm, it decreases by 138 MPa.

Based on the contour integral model, the crack propagation behavior and stress distribution of the specimen under different cooling cycles were investigated. The crack length after 500, 1000, and 1500 temperature cycles was used as the basis to observe the evolution of the maximum compressive and tensile stresses at the crack tip (Figure 6).

Shorter cooling cycles (15 seconds) lead to significant stress concentration and localized stress peaks, which accelerate crack propagation. In contrast, longer cooling cycles (70 seconds) help to reduce the thermal gradient and achieve a more uniform stress distribution, which in turn reduces crack growth. Therefore, longer cooling cycles exhibit better performance in mitigating crack propagation, contributing to improved durability and crack resistance of die-casting molds.



(a) Compressive Stress (b) Tensile Stress

Figure 6. Peak stress at crack tip

5. SUMMARY

This study developed a three-dimensional numerical simulation model using real-time material data and realistic boundary conditions to analyze crack initiation, propagation, and stress distribution in notched specimens. The following main conclusions were drawn:

(1)During thermal fatigue, the material undergoes plastic deformation during heating and cooling cycles, leading to the generation of stresses. Peak compressive and tensile stresses typically occur only at the beginning of heating or cooling.

(2)Shorter cooling cycles (15s and 30s) result in significant stress concentration and localized stress peaks, which promote rapid crack propagation. In contrast, longer cooling cycles (70s) reduce crack growth by mitigating the thermal gradient and promoting more uniform stress distribution.

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