The Numerical Simulation of Thermal Fatigue Crack Propagation on Mold Steel

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Abstract: H13 steel suffered periodic heating and cooling when used as die casting mold materials, and this will leading to emerge thermal fatigue easily. To solve this problem, this paper studied the thermal fatigue process of die casting mold steel by comparing the results of thermal fatigue test and ANSYS simulation method, and try to predict the initiation and propagation of thermal fatigue cracks. In this paper, HMTH1 thermal fatigue testing machine was employed to heat and cool the specimen in periodicity, and recorded the cycle times and crack lengths when thermal fatigue cracks were observed. The ANSYS software was used to complete finite element simulation of the experiment and obtain the result of temperature fields, heating stress fields and cycle crack paths of different thermal fatigue cycles. The result indicated that as the thermal fatigue cycles up to 500 and 1000, the main crack propagated 567.29μm and 225.29μm, and compared the simulation result under the same conditions to solve the problem of initiation and propagation of thermal fatigue cracks better.

1 INTRODUCTION

Die casting mold is a kind of hot work mold, which working environment is very bad. Under the service conditions of hot and cold shock, it will appear a lot of micro-cracks on the cavity surface of the mold, which mostly presenting the form of radially, parallel, and reticular, and is called the thermal fatigue crack. Therefore, it is a kind of die failure forms and its proportion has reached 60%~70%[1, 2]. Die casting mold requires low roughness of the surface, it can not continue to service after the hot-cold fatigue cracks have appeared, hence the key point of the service life of die casting mold is the time of thermal fatigue cracksappears.Moreover, the factors that affect the thermal fatigue of the mold include the cycle of different temperature, thermal conductivity and the coefficient of thermal expansion. The methods of thermal fatigue performance test includes rating crack method namely Uddeholm method, the plate specimen method[3], etc, and one of the earliest which is proposed by COLFIN in 1953.Compared with the plate specimen method, the cost of Uddeholm method is lower, resulting in its widely applied.

The Uddeholm is a method of thermal fatigue test, which heating and cooling the rod specimens repeatedly in high frequency induction, then compared with the standard fingerprint to evaluate the degree of surface cracks[4-5]. The advantages of this method is considering the local width and the overall breadth of the crack, andit is visual but with the drawback that it is difficult to be quantified, and it needs a lot of experienced engineers to evaluate the thermal fatigue crack, which was great influenced by subjective factors. And the test rod heating in the induction conditions have great difference with the actual casting conditions.The current study for the life of die casting mold is focused on improving the mold thermal fatigue life from the casting mold design[6-8],mold structure[9-12], mold material, mold processing, heat treatment process and die casting process parameters. In the paper, the HMTH1 thermocouple heating self constraint thermal fatigue testing machine was adoptedto conduct the thermal fatigue experiment and the ANSYS software was used to simulate the experiment. Finally, By comparing the results of the experiment and the finite element simulation, to explore how to improve the thermal fatigue life of die casting mold[13].

2 THE METHOD OF THERMAL FATIGUE TEST

In the experiment, the high frequency power was used to heat and cool the sample for the Uddeholm method[14], which can initiate thermal fatigue crack in the surface of the specimen. But it can only obtain the expansion trend of thermal fatigue crack, and can not accurately and intuitively observe the dynamic changes over time of the specimen's interior temperature field, thermal stress field. According to the situation of the numerical simulation of thermal fatigue crack, currently in the domestic and foreign research, the majority of the two-dimension plane model has been used[15, 16], yet the actual extend of crack, mostly occurs in the 3D model. Based on this situation, this paper used the ANSYS software to complete finite element analysis of the H13 die steel and gain the results of the temperature field and thermal stress of the three-dimensional crack, and compared with the result of the experiment to explore the thermal fatigue crack location, crack length and crack growth path better.

2.1 The Basic Theory of Thermal Transmission Ways

2.1.1 Thermal Radiation

This experiment adopts the way of the electromagnetic induction coil heating, which is a kind of heating transference of thermal radiation. The heat radiation refers to objects emit electromagnetic energy, which can be absorbed and transferred into the heat by other objects, as a kind of the heat exchange process. Its transfer mode does not require any medium, and the net heat radiation between the two objects can be calculated in the Stephen Boltzmann equation.

$$\mathrm{q} = \varepsilon\sigma A_1 F_{12}(T_1^4 - T_2^4) \quad (1)$$

Where q is the rate of heat flow, ε is the radiating rate of actual object and the numerical value is between 0 to 1, σ is the Stephen Boltzmann constant, which is about $5.67\times10^{-8} W/\mathrm{m}^2.K^4$, A_1 as the area of the radiating surface 1, F_{12} is the shape coefficient from the radiation surface 1 to the radiation surface 2, T_1 is the absolute temperature of radiation surface 1, T_2 is the absolute temperature of the radiation surface 2.

2.1.2 The Heat Convection

Thermal convection refers to the heat exchange caused by temperature difference between the solid surface and the contacting fluid surface. In this experiment, adopted the way of water cooling is a kind of transferring way of heat convection. Thermal convection can be described by Newton cooling equation.

$$\mathrm{q}'' = h(T_S - T_B) \quad (2)$$

Where h is the transferring coefficient of convection, T_S is the solid of surface temperature; T_B is the temperature of the around fluid .

2.2 The Basic Theory of The Thermal Fatigue Crack

The fatigue process is generally divided into the following stages, one is the formation of micro crack; then is the extension of small crack, next is the extension of large crack, the last one is the final failure. The first two stages are called "period of crack initiation", the growth of large crack are called as "period of crack extending". But one point should be clear, it is almost impossible to accurately determine the transition point of crack from crack initiation to crack extending. The total fatigue life N in the crack initiation period is determined by the stress cycle numbers N_i when fatigue crack initiation and the stress cycle numbers N_P when crack propagation.

$$N = N_i + N_p \quad (1)$$

One of the most important stage of the fatigue process is fatigue crack initiation, its form mainly depends on the material's geometric structure, the micro structure of the material and the type of applied stress. In the analysis, it is customary to assume that cracks usually occur at the maximum point of the material, and the fatigue crack initiation life in low cycle as follows.

$$\Delta\varepsilon = 3.5\frac{\sigma_b - \sigma_m}{E}N^{-0.12} + \left[\ln\frac{1}{1-\phi}\right]^{0.6}N^{-0.6} \quad (2)$$

Where $\Delta\varepsilon$ is the total cyclic strain amplitude, N is the number of load cycles, ψ is shrinkage rate of the materials section, R_m is average stress, when in the analysis of fatigue crack propagation, it's usually assuming that the fatigue crack propagation rate d_a/d_N is function of the range of stress intensity factor ΔK ,then determining the relationship between the crack growth rate and the propagation life as follows:

$$d_a/d_N = C_1(\Delta\sigma)^m a^{m/2} \quad (3)$$

the integrals:

$$N_P = \int_0^{N_P} d_N = \frac{1}{\left(1-\frac{m}{2}\right)C_1(\Delta\sigma)^m}\cdot\left(a_c^{1-\frac{m}{2}} - a_{th}^{1-\frac{m}{2}}\right) \quad (4)$$

$$C_1 = C\left[\frac{\Delta K}{\Delta\sigma\sqrt{a}}\right]^m \quad (5)$$

Where a is the crack length, a_c is the critical length of crack extension, N_p is the number of load cycles, C, m are parameters related to the materials, ΔK is the range of stress intensity factor ,a_{th} is the critical length of the crack initiation.

2.3 The Sample

H13 is most commonly used in die-casting mold, its composition is shown in Table 1, and the size of specimen is 32mm × 18mm × 3.5mm, as shown in Fig.1, in the middle of each sample processes a V notch by the way of line cutting, in order to the concentration of the thermal stress, and shorten the time of experiment. In the bottom of the groove, presets a width of about 1mmasthe crack source of the experiment. Before the experiment, polishing the surface of the specimen with sandpaper, then the specimen is tied up with copper wire to the test bench of thermal fatigue testing machine, set up the experimental parameters, and conducts the thermal fatigue test. Finally, the propagation mode of crack is observed and the experiment record is done.

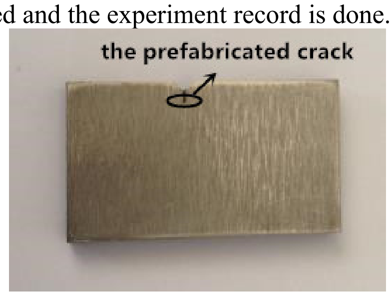


Fig.1 H13 steel sample.

Tab.1 Chemical compositions of H13 steel.

C	Cr	Mo	V	Mn	Si	P	S
0.38	4.80	1.50	0.90	0.30	1.00	0.03	0.03

2.4 Thermal Fatigue Testing

Thermal fatigue test can be completed on the HMTH1thermal fatigue test machine as shown in Fig.2, which can automatically control the heating temperature, cooling time and record the numbers of cycle. The high-frequency coil heating method is used in the experiment, and the heating time is 3 seconds and the heating temperature is 680 ℃.Then adopt the cooling way of spray water and the cooling time is 6 seconds, the temperature is 95 ℃ after cooling. The first experiment was conducted with 500 cycles of thermal fatigue, and then took out of the specimen from the machine and removed the surface oxide of the specimen with dilute hydrochloric acid, then polished the surface and analyzed the total length of crack expansion and the path of crack propagation with Nikon MA100inverted microscope and UPO image software. After that, every 500 times is a hot and coldcycle, and record the length of the fatigue crack and direction of crack propagation after each cycle, until the end of 10000 cycles.

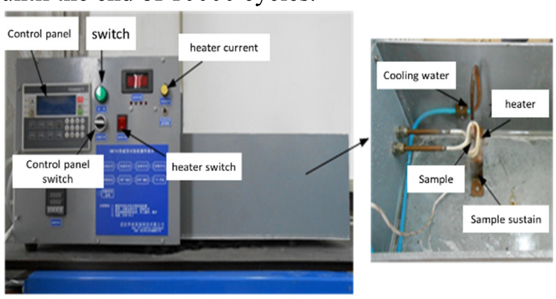


Fig.2 Thermal fatigue testing machine.

3 ANALYSIS AND OBSERVATION OF THERMAL FATIGUE CRACK

3.1 The Analysis of Surface Crack of the Die Mold

Thermal fatigue crack is one of the main failure forms of hot work die/mold, which is commonly known as thermal cracks. It is caused by the thermal stress of the material. Under the function of the thermal stress[14], due to the repeated and systolic strain, making the materials produce a continuous, local and permanent organizational changes. And the heat cracks usually occur in the surface of mold cavity, leading to the changes of the stress distribution state, and when the thermal crack grows to a certain length,as the plastic strain, resulting in the stress relaxation and the crack stop expanding. But along with the gradual increase of the alternating hot and cold cycles, some small holes appear around the tip of the crack and gradually developing into micro cracks, and then will merge with the cracks at the beginning of the formation continue to expand. Eventually, those cracks connected with each other to form a kind of serious network cracks, leading to failure and seriously affecting the surface quality of products as shown in Fig.3.

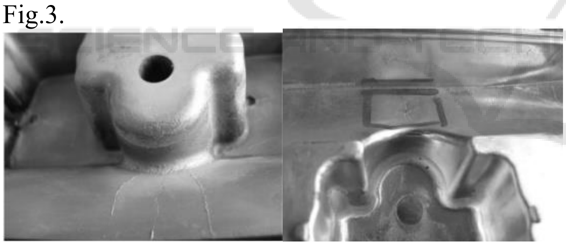
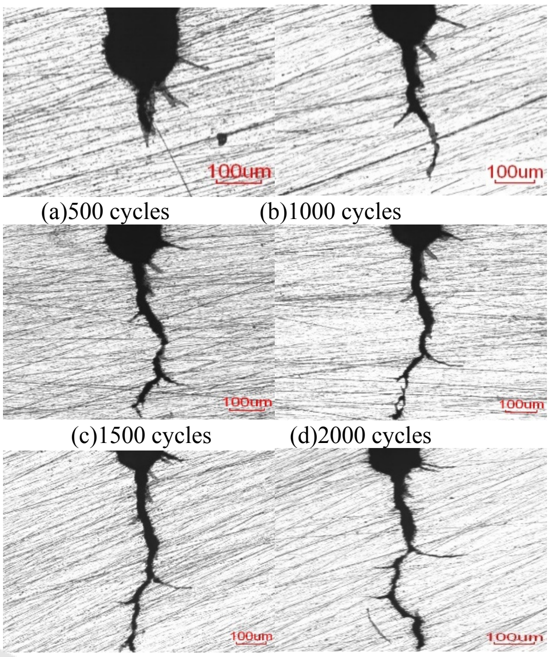


Fig.3 Thermal fatigue crack of the hot work mold surface.

3.2 The Observation of Thermal Fatigue Cracks

In this paper, due to the limited experimental conditions and the practical application condition for H13 die casting mold, and the crack initiation length of thermal fatigue is defined as 0.3 mm, and only take the first 3000 cycles to be accurately analyzed as shown in Fig.4 and Fig.5.



(a)500 cycles (b)1000 cycles

(c)1500 cycles (d)2000 cycles

(e)2500 cycles (f)3000 cycles

Fig.4 Crack growth after different cycles of thermal fatigue test.

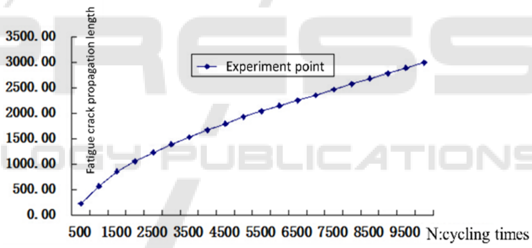


Fig. 7 A diagram on the connection between Ncycling times and crack propagation length.

The crack initiated at the local of the V type notch, as the hot and cold alternating thermal stress in the material. When the thermal fatigue cycles are 500 times, three cracks occurred at the gap, and the main crack at the notch has expanded 225.29 μmas shown in Fig.4(a).When the thermal fatigue cycles are 1000 times, as shown in Fig.4(b), a crack in the notch continues to expand, which has extended to 567.29 μ m, but the other two cracks don’t continue to expand clearly. As the concentrate stress in the V type notch, it’s easier to produce cracks, and a second crack occurs based on the main crack; when the thermal fatigue cycles up to 1500 times, as shown in Fig.4(c)the thermal fatiguecrack has reached to 860.82 μm, and a second thermal fatigue crack has appeared again. As can be seen in Fig.4(d), when the cycles are 2000 times, the length of the crack up to 1057.54 μm. Finally, when the thermal fatigue cycles reach to 2500 times and 3000 times, the thermal fatigue cracks have extended to 1229.06 μm and 1391.86 μm, and appears two second cracks as shown in Fig.4(e) and Fig.4(f).Combined with Fig.4 and Fig.5, it can be concluded that with the increase of the thermal fatigue cycles, after the thermal fatigue crack has initiated, the rate of the primitively crack propagation is very high, and then the speed decreases gradually and tends to be stable at last.

4 THE NUMERICAL SIMULATION OF THERMAL FATIGUE

4.1 Numerical Simulation of Thermal Stress

The parameters of H13 such as the coefficient of linear expansion, the coefficient of thermal conductivity, elastic modulus, ultimate strength, and yield stress are shown in Tab.2

Table 2 The physical parameters of the H13.

$T/^0C$	λ $(W/m\cdot K)$	$\alpha/(^0C)^{-1}$	E/Mpa	$\sigma_b(Mpa)$	$\sigma_s(Mpa)$
20	25.0	10.0×10^{-6}	227000	1790	1100
100	25.9	10.9×10^{-6}	221000	1748	900
200	27.6	11.4×10^{-6}	216000	1710	810
300	28.4	12.2×10^{-6}	208000	1650	708
400	28.0	12.8×10^{-6}	200000	1580	600
500	27.6	13.3×10^{-6}	192000	1400	398
600	26.7	13.6×10^{-6}	190000	1100	208

The temperature of the simulated sample will change in the process of heating and cooling, and the parameters of simulation are set to heat 3 seconds at the temperature of 680 ℃, and cold 6 seconds at the temperature of 95 ℃.

The analysis of thermal stress, actually that is the coupling analysis between two physical fields of the thermal and stress, and due to the change of load temperature over time, it belongs to the transient thermal analysis. ANSYS provides two analysis methods of thermal stress, the direct method and the indirect method [16].The direct method adopts the coupling unit with temperature and displacement degrees of freedom, then gets the results of the analysis of thermal stress and structure-stress at the same time; while the indirect method is carrying on the thermal analysis at the first, and then obtaining the node temperature, which is applied to the analysis of structure stress as body load.

In this paper, using the direct method for the thermal stress analysis, in the pretreatment, the unit of Coupled Field, Scalar Tet 98 was used to define the material parameters of H13 steel as shown in Table 2. Then the three dimensional model is built and meshed, adopting the way of free type mesh, and refine the meshing of the V notch part of the specimen as shown in the Fig.6,and then applying cyclic load of the thermal fatigue. At last, obtaining the temperature fields and the mises equivalent stress fields respectively, as shown in Fig.7 and Fig.8.

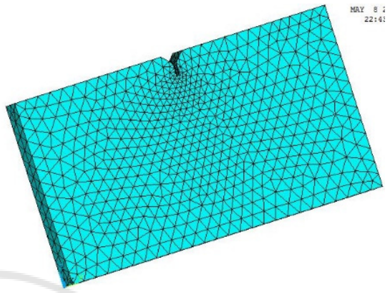


Fig.6 The meshed model.

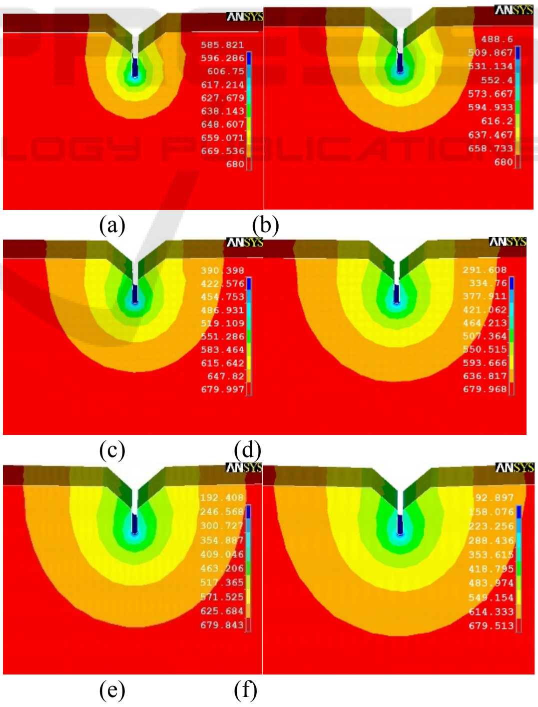


Fig.7 The different cooling time of the temperature fields: (a) 0.1s, (b) 0.2s, (c) 0.3s, (d) 0.4s, (e) 0.5s, (f) 0.6s.

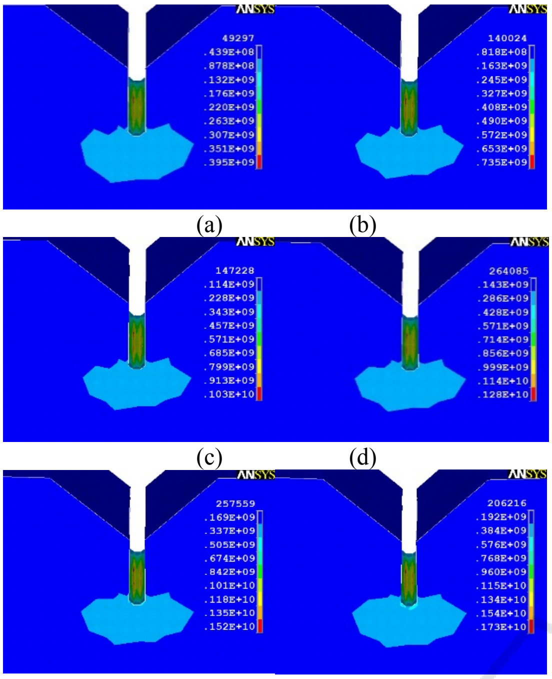


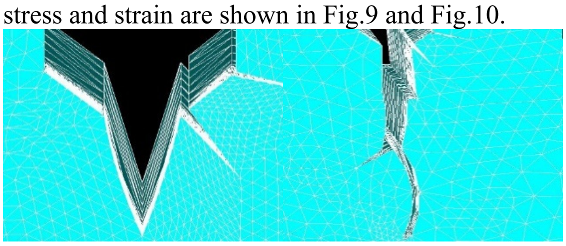
Fig.8 The different cooling time of the mises equivalent stress fields: (a) 0.1s, (b) 0.2s, (c) 0.3s, (d) 0.4s, (e) 0.5s, (f) 0.6s.

As given inFig.7 and Fig.8, in each process of the heat cycle, getting the temperature field and stress field changing with time. It can be seen in the process of cooling with water, the temperature in V groove of the specimen reduces by the time changes gradually. At the cooling time of 6 seconds, the temperature in the position of crack tip reaches a minimum value at 92.897 ℃,and the distribution of temperature field basically makes the crack tip as the center of a circle, presenting as a semicircle shape. The more closer to the center position, the more lower the temperature is, as the center of a circle cooling in water, and it transfers heat in the way of heat convection, leading to the lower temperature.

As presents in Fig.8, the maximum equivalent stress is in the red region, and it is the position to be easiest occurred crack initiation and propagation at the different points of the time. But the maximum equivalent stress of the v groove position (the red zone) does not change with the time, and through the verification of the experiment, which is basic consistent with the position of the crack initiation, therefore the position of thermal fatigue crack can be predicted by the simulation effectively.

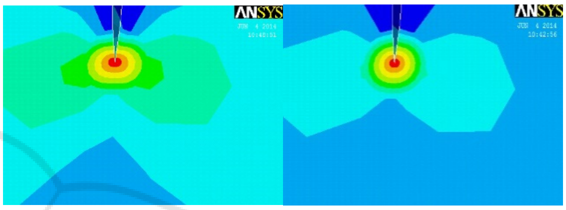
4.2 Numerical Simulation of Thermal Fatigue Crack Propagation Path

The finite element simulation results of the thermal fatigue crack propagation path and the Von mises stress and strain are shown in Fig.9 and Fig.10.



(a)500 times (b)1000 times

Fig.9 Crack growth paths after different cycles of thermal fatigue test. a 500 cycles. b 1000 cycles



(a)500 times(b)1000 times

Fig.10 The Von mises stress and strain in 500 cycles. a The Von mises stress. b The Von mises strain.

Fig.9(a) shows the thermal fatigue propagation path of the specimen under cycles of 500 times, and the main crack has extended to 231.58 μm. During the cycle of heating, the thermal strain produced due to the heat expansion of the specimen, and the two sides of specimen are bonded by copper wire, causing the compressive stress. When the stress exceeds the yield limit of the material, the compressive plastic deformation will be induced. While in the process of cooling, the specimen will appear shrink deformation, but due to the unrecoverable plastic deformation, resulting in the tension stress, which is perpendicular to the crack surface, causing the open of the crack. It can be seen in Fig.10(a) and Fig.10(b),the Mises equivalent stress and strain in the position of crack tip is the largest, and it's also the most easily extensible place for cracks. With the thermal cycle times increased gradually, the opening displacement of the crack will increase gradually. The length of the main crack increased to 580.62 μm, when the thermal fatigue cycles up to 1000 times. Compared the Fig.10(a) with Fig.4(a), and Fig.10(b) with Fig.4(b) respectively, it can be found that the results of the experiment is in accord with the ones of numerical simulation analysis in the path of thermal fatigue crack propagation and the position of crack occurring. It indicated that the fatigue cracks can be more accurately predicted in the path of thermal fatigue crack propagation and the position of crack occurring.Therefore, it will provide guidance for the prevention of die casting mold’s failure in the actual production.

5 CONCLUSION

The thermal fatigue experiment indicated that with the increase of the thermal fatigue cycles, after the thermal fatigue crack has initiated, the rate of the primitively crack propagation is very high, and then the speed decreases gradually and tends to be stable at last.

The finite element simulation results indicated that the thermal fatigue crack easily appears at the area of maximum concentration of thermal stress and also easily to be produced at the position with larger difference of temperature. Besides, at the tip of the thermal fatigue crack, it is easier to expand at the position of the largest mises equivalent stress and strain.

Compared with the results of the experiment and the simulation, it can be found that the results of the experiment is in accord with the ones of numerical simulation analysis in the path of thermal fatigue crack propagation and the position of crack occurring. Therefore, it will provide guidance for the prevention of die casting mold’s failure in the actual production.

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