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Life estimation and design optimization of High Pressure Die Casting Die, based on Thermal Fatigue Crack Analysis

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***Abstract:* --- Thermal fatigue stress cracking is one of the major modes of failure in high pressure die casting dies. The aim of this work was to predict the life of the die using fracture mechanics concept and optimize the design to improve its life. In this work, first the crack length was measured at the critical location. Then a transient thermal analysis and thermo- mechanical coupled analysis was performed in ANSYS Workbench on the actual die to obtain maximum stress occurring in the die. The stress value and the crack length measured were substituted in Paris law to obtain theoretical life. The theoretical life was compared with the actual life and an error of less than 5% was obtained. With the successful life estimation, two new designs using an optimized cooling circuit was proposed and same was analyzed using ANSYS. The die providing less thermal stress was chosen as an optimized design.**

***Index Terms*—ANSYS, Fracture Mechanics, Stress cracks, Thermal Fatigue**

I. INTRODUCTION

Die Casting is a manufacturing process in which molten metal under high pressure and high temperature is forced into a closely contained cavity known as die cavity. This cavity is made of out of hardened tool steel, which has an excellent fracture toughness and resistance to thermal fatigue cracking. Die casting is known for its high volume production, with its inherent capability of producing complex and close tolerance parts. Die casting is mostly favorable for casting non- ferrous metals like aluminum, zinc, magnesium and even copper, tin and lead based alloys. In die casting, a die can produce nearly 100,000 – 300,000 castings before failure, but there are cases where the die fails after a minimum of 5000 – 25,000 cycles [1].

In aluminum die casting, the surface of the die are subjected to a high temperature of 640°C -680 °C along with a high velocity of 30 – 100 m/s in addition to an injection pressure of 200 – 400 kgf /cm2. This combination of thermal mechanical loadings result in shorter in service of the tool life [2].

The service life of a die is greatly reduced due to following factors: (a.) thermal fatigue; (b.) erosion of the die surface; (c.) corrosion and soldering of alloy; and (d.) catastrophic failure [3]. Thermal fatigue cracking (heat checking) is one of the most important and frequent failure modes in a die. These cracks are distinguished by a network of fine cracks. In addition to it, there is another variant of cracks known as 'Stress Cracking'. Theses cracks are observed as standalone and clearly pronounced cracks [4]. The die surface are subjected to alternate heating and cooling phase, during the casting operation cycle. This setups a temperature gradient in the die and consequently thermal stresses high enough to cause plastic strain are induced on the die surface. This strain is high enough to initiate crack propagation on the die surface which may develop within a few thousands cycles or even earlier [5].

J.F.Wallace (1970) [6], developed a simple experimental technique to simulate the temperature cycles encountered in H13 dies. The experimental setup consists of an aluminum bath and water emulsion bath, in which the samples were alternately dunked to simulate a casting cycle. After a certain number of cycles, the test samples were examined under high power microscope; a plot of crack length versus number of cycles was constructed. Christopher Rosbrook [7] developed a computational model for this experiment and validated the test results obtained by Wallace. FEA results were in total agreement with experimental results. To prolong the in- service life of tool steel, the surface properties of the specimen was modified by cladding it with maraging steel, physical vapor deposition, chemical vapor deposition (CVD) coatings [8]. All surface treated test samples except for maraging steel showed a

decrease towards thermal fatigue resistance. When a die is subjected to thermal fatigue, it is assumed that, all the thermal strain is converted into mechanical strain [9]. But in actual practice only a part of thermal strain is converted into mechanical strain, hence due the accumulation of local plastic strain, crack initiation occurs [10]. Cyclic induction based experiments were developed to measure the strain directly with the help of non-contact laser speckle technique, hence the thermal stresses could be obtained directly [11].
With the increasing demand in concurrent engineering (CE), a CAD/CAM/CAE integrated system has been developed and used [12]. After successful designing in CAD software, the CAE package are used to calculate the stresses, strains, and displacements acting in the die [13]. A Niknejad [14] using the above technique, investigated the causes of crack initiation in cast bullion molds. He proposed two new designs, and with the help of Ansys software, the strain and thermal stresses at the critical region in each mold was determined and Universal slope method was applied to estimate the life of the die [15]. D. Concer [16] performed similar analysis using ABAQUS software and then used Basquin equation to determine the life of the extrusion die. Taking forward Dconcer work, S.Z. Qamar et. Al. [17] determined the factors responsible for thermal fatigue cracks in extrusion die using fracture mechanics concept.

Most of the researchers in their published work, have investigated the life of the die based on thermal fatigue cracks. In this work, the life of the die affected by stress cracks (another variant of thermal fatigue cracks) will be studied and with the help of fracture mechanics concept its life will be estimated.

II. OPERATING CONDITIONS OF THE DIE

The aluminium cast components are manufactured in a cold chamber die casting machine. The die under study, has been used for the production of a spring brake housing component used in heavy vehicle air brake system. The die used for the casting of spring brake components is shown in the figure 1. During aluminium die casting process, molten aluminium at 660°C is ladled into the machine and forced into the die cavity, under a high pressure of 300 kg/cm2. The aluminium casting is then allowed to solidify in the machine for 12 seconds, after which it is ejected out of the machine and cooled in ambient air. The total cycle time for each casting cycle was 46 seconds. Each die casting cycle can be split into a number of steps, table 1 shows the time split between various operations performed during each casting cycle.

Table 1: Time split of each step in a casting cycle

Operations	Time
Ladling time	4
Plunger forward stroke	3
Solidification time	12
Die Open	3
Ejection time	3
Lubrication time	18
Die close time	3
Total Cycle time	**46**

Fig. 1: Die used for Casting Spring housing components

With the ongoing die casting, the die is simultaneously internally water cooled with help of cooling channels drilled into the die. Water circulated at a temperature of 20°C at the inlet. The service life of the die is normally estimated to be 100, 000 cycles.

The stress cracks only occurred on side cores of the die, thus only side core 1 die will be studied and analysed to estimate the die life. The stress crack occurring in side core 1 is shown in figure 2.

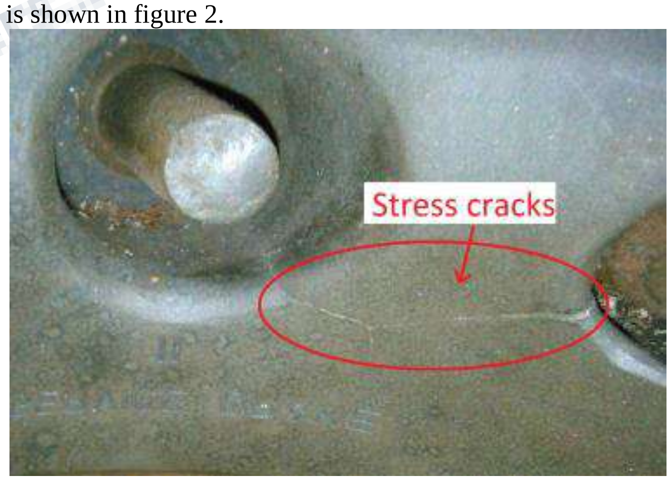

Fig. 2: Stress cracks

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III. IN SITU METALLOGRAPHY

Surface replication is a non-destructive metallography evaluation technique, in which the topography of a metallographic specimen is created in the form of a negative film. These replicas are then observed under Scanning Electron Microscope and Light Microscope, to study their microstructural characteristics. This test was performed at two separate locations on side core 1 as shown in figure 3. This test was performed to study the changes in microstructural properties of the material due to thermal fatigue criteria near the exposed face and away from the exposed face.

Fig. 3: In situ metallography test location.

The specimens were studied under light microscope 400x magnification. The microstructure at location 1 reveal fine tempered martensitic structure as shown in figure 4. These microstructures are formed as result of rapid quenching of H13 tool steel. This occurs during the spraying action of cold water after the ejection of the cast. But microstructure at location 2 reveal coarse martensite structure as shown in figure 5. It can be concluded that because of the formation of fine tempered martensite microstructure, there are high chances that crack will initiate in this region. It can also be concluded that die faces away from the exposed surface are little affected by the temperature exposed at surface.

Fig. 4: Fine tempered martensitic structure location 1

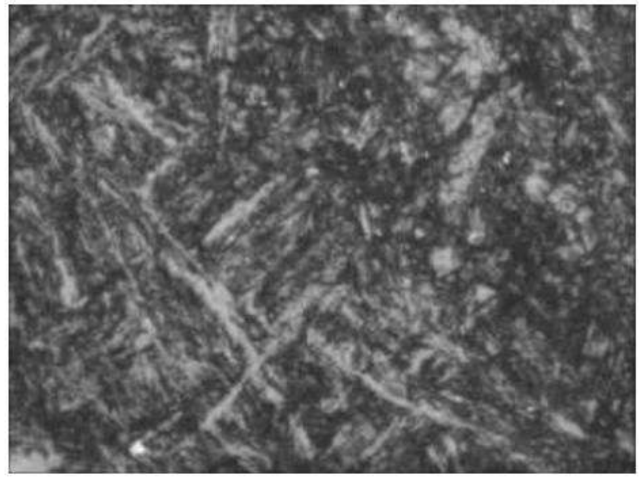

Fig. 5: Coarse martensitic structure location 2

IV. CRACK LENGTH MEASUREMENT

Crack length measurement strongly depends on the number of cycles [5]. Crack length is an important parameter in fracture mechanics concept, which can be used to determine the life of the die. Stress cracks being a standalone crack, can be easily measured and can be used with fracture mechanics concept to determine the life of the die. Crack length at location 1 was measured using a conventional measurement technique. The measured length of the crack was 23 mm.

V. CAD DESIGN

A CAD model of the actual die was designed in SolidWorks V2014 as shown in the figure 6. It was exported in .iges for Finite Element Analysis

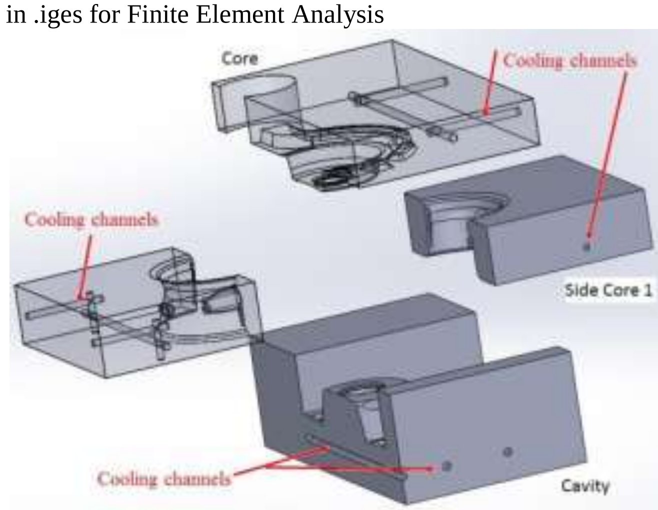

Fig. 6: CAD model of the die

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VI. FINITE ELEMENT ANALYSIS

A die is subjected to a wide variation of temperature during entire casting operation. To take into account this variation, first a transient thermal analysis will be performed on the die. The temperature distribution from thermal analysis will be then coupled with Static structural analysis, so as to take into account the clamping forces and injection pressures that the die is subjected to during the die casting operation. Static structural analysis will provide the maximum stress acting at the critical location of the die.

A. Transient Thermal analysis

In die casting process, the temperature varies with time, hence a transient thermal analysis was performed on the side core 1 of the die in ANSYS Workbench V14.5. The temperature variation wrt the time for each cycle is shown in the figure 7.

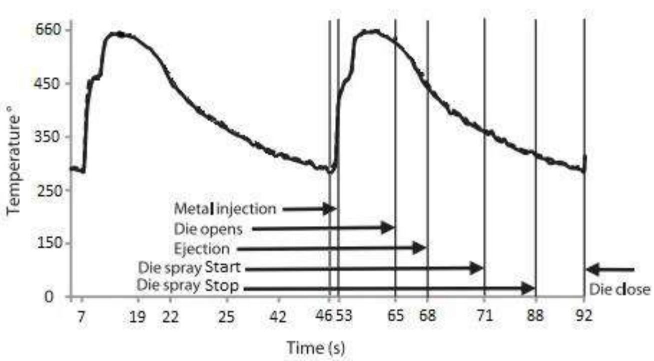

Fig. 7: Temperature variation during the die casting process.

During casting process, heat is continuously radiated and convected to outside environment, hence a heat transfer coefficient of 5e-6 W/mm2°C was applied to the entire die. In addition a die also functions as a heat excahnger, which transfers heat to cooling water passing in through the die. A heat transfer coefficient of 2e-3W/mm2°C was applied to free surface of the cooling line in the die. After ejection process the die suface is sprayed with water to clean the surface for next cycle. To closely simulate this, a heat flux of 0.5W/mm2 was applied to the surface of the side core exposed to molten aluminium. Thermal analysis was performed on actual design and temperature distribution was saved in a separate file. Figure 8 shows the temperature distribution of side core 1

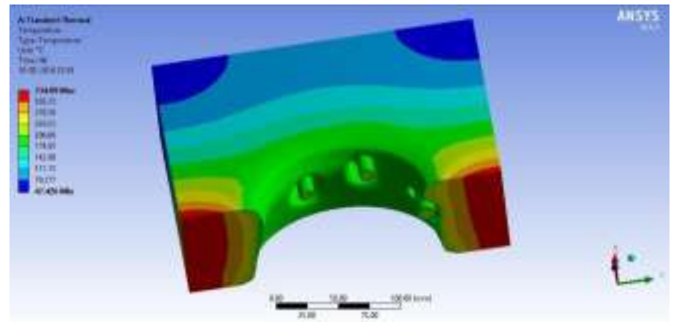

Fig. 8: Temperature distribution of the actual die

B. Thermal mechanical coupled analysis

To consider the clamping forces and injection pressure acting on the die surface, a static structural analysis has to be performed on to the die. A clamping force of 250T was applied on to one of the faces of the die with rest of the other faces fixed as supports. Injection pressure of 30 MPa was applied to the surface of the die exposed to molten aluminum. The temperature distribution result from thermal analysis was applied as an input and a static structural analysis was performed. Figure 9 shows the Von Mises stress of side core 1.

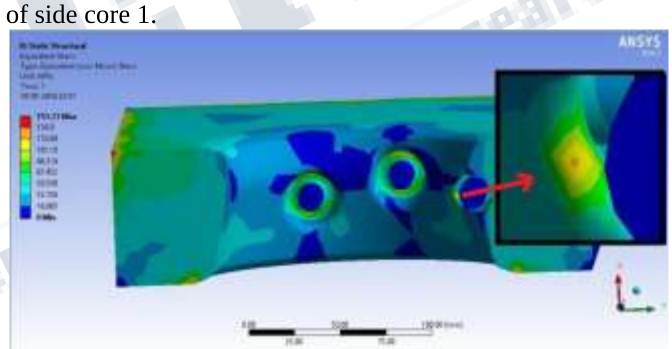

Fig. 9: Von Mises Stress of side core 1

The maximum stress occurring in the die was 134.9 MPa. The maximum stress occurred in the same region where crack initiated in actual die. The maximum stress obtained from FEA, will be used along with crack length to determine the life of the die.

VII. LIFE DETERMINATION

There are different models that can be used to determine the life of a component. For this case study, fatigue crack growth model (da/dN – ΔK) also known as Paris Law, was used to determine the die life. It states that,
da/ dN = C (ΔK)m (1)

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Where

- C and m are material constants that are obtained experimentally.
- dK = dKmax - dKmin is the stress-intensity parameter range.

ΔK can be expressed in terms of Δσ and crack length a.
ΔK = dK max – dK min
ΔK = (Y × σ max ×√πa) - (Y × σ min ×√πa)
ΔK = Y × Δσ ×√πa ……………………………(2)

Where Y is dependent on the specimen geometrical feature. Substituting equation 2 in 1 and rearranging the terms,

dN= da/(C (Y × Δσ ×√πa)m)…………….. (3)

Integrating the above equation, from initial crack length to final crack length, the equation in terms of number cycles is given as,

Nf = [a0 (1-m/2) - ac (1-m/2)]/[C (m/2-1) Ym π (m/2) Δσm] ………………………..(4)

The above equation, thus can be used to determine the life of the die.

For H13 tool steel the values for C and m are 1.6 × 10-12 and 2.85 respectively. Since the cracks originate from the edge, assuming it as an edge crack, Y is 1.12. The initial size of the crack is taken as (a0) 1 mm since it can be easily detected by any inspection method in a die casting die. Substituting the values in equation 4.

The life of the die is:

Nf = 130390

The actual service life of the die is 136766. The obtained result was compared with the actual service of the die. On comparing both the result, a percentage error of less than 5% was obtained.

To obtain a clear picture of the crack growth history, a graph of crack length vs the number of cycles to failure was extrapolated by varying the value of crack length (ac). Figure 10 shows a graph of crack length vs the number of cycles to failure.

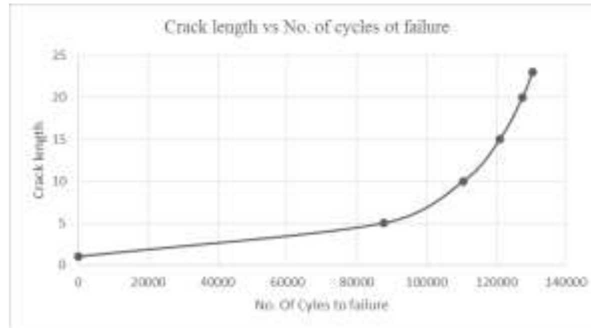

Fig. 10: Crack length vs Number of cycles to failure.

VIII. DESIGN OPTIMIZATION

A. New designs

To improve the life of the die, the thermal stresses acting on the die should be reduced. To reduce these stresses, the temperature gradient of the die should lowered. This can be achieved by optimizing the cooling circuit layout of the die. In addition, geometrical features also are responsible for stress concentration in the die. Thus based on this, two new designs were proposed. Figure 11 shows new designs for side core 1

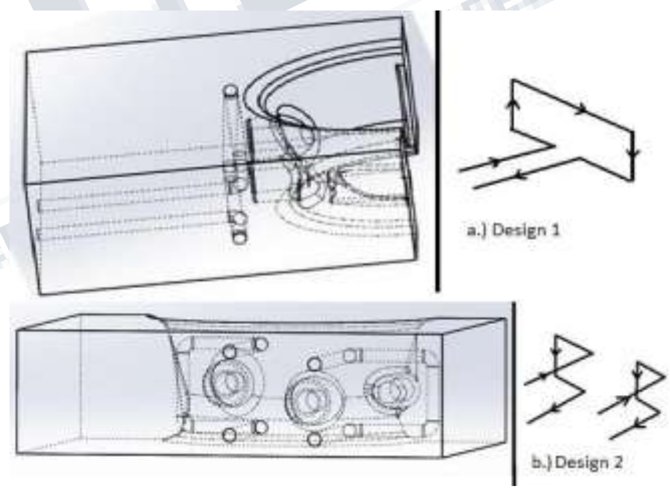

Fig. 11: New designs for side core 1

Design 1 contains a rectangular cooling circuit and design 2 has a twin U cooling circuit designed into the die. In both the designs, the relative location of the cooling line from the surface was taken as 2 times the cooling line diameter.

B. Finite element analysis

FEA analysis was performed on new designs by applying the same sets of boundary conditions as applied to the actual design. First thermal analysis was performed on

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the designs. Figure 12 shows the temperature distribution of new designs.

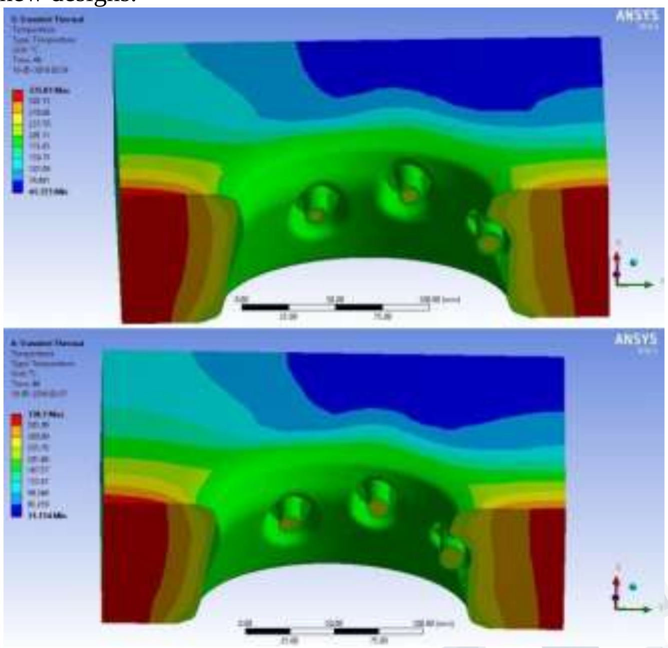

Fig. 12: Temperature distribution of new designs.

Then a thermal mechanical coupled analysis was performed on new designs and the maximum stress acting on each design is shown in figure 13.

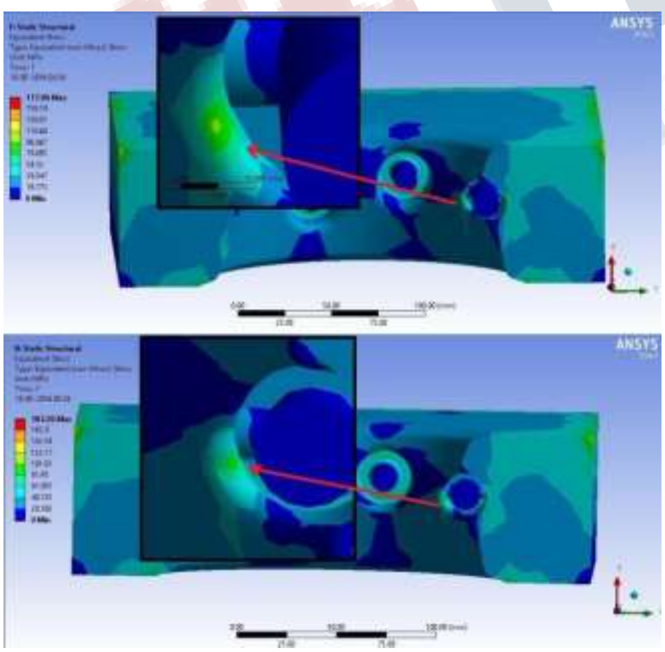

Fig. 13: Von Mises stress contours

C. Result

The Surface temperature and the Von Mises stress for the actual design and optimized design is tabulated in table 2.

Table 2: Surface temperature and the Von Mises stress

	Surface Temperature	Von Mises stress
Actual design	206.68°C	138.04 MPa
Design 1	205.11°C	138.41 MPa
Design 2	201.68°C	122.17 MPa

Comparing design 1 with the actual design, the stress has remained fairly the same. This means the rectangular cooling circuit proposed in design 1 is not cooling the die surface sufficiently. On comparing design 2 with the actual model, the maximum stress of the die has reduced. Also the surface temperature of the die is close to the initial temperature of the die casting process. Hence the design 2 with twin U cooling circuit is the best design, and will give an improved life of the die.

IX CONCLUSION

1. The study of microstructure under Light Microscope reveal that, the stress cracks are generated due to the presence of fine tempered martensitic structure and are formed only on the surface of the die.
2. The total life of the die estimated using fracture mechanics concept gave an error of less than 5% when compared with actual life. Hence this concept can be used to predict life in die casting dies.
3. Thermal stresses of 134.9 MPa was obtained in the actual die, whereas in the selected improved design a stress of 122.17MPa. Thus it can be concluded that thermal stresses generated in the die, depends on the relative location and the configuration of the cooling line from the die surface.
4. It is observed twin U cooling channel has two inlet ports and hence it provides uniform cooling as compared to single inlet port rectangular cooling circuit. Thus better cooling results in less stresses generated in the die.
5. The use of FEA tools eliminates the need of trial and error method, to obtain the best cooling circuit design. The modification to the design and analysis can be done at much shorter time.

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