Thermal fatigue analysis of H13 steel die adopted in pressure-die-casting process

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MS received 9 October 2018; revised 6 March 2019; accepted 18 March 2019; published online 22 May 2019

Abstract. The thermal fatigue of die casting die steels causes reduction in tool life and seriously affects the surface conditions such as microstructure, hardness, surface finish and residual stresses. The improvement of die life by suitably modifying the die design assumes utmost importance for die designers. In this regard, a key issue is the size and location of cooling channels relative to the surface of the die, which affect the thermal stresses and fatigue life of dies. This paper focuses on thermal fatigue analysis of pressure-die-casting die steel H13 and analyses the effect of coolant channel location on temperature distribution and fatigue parameters such as life, damage, equivalent alternating stress and biaxiality using ANSYS Workbench 15.0 finite-element package. Increase in wall thickness (location of coolant channel from base) caused an increase in temperature and decrease in die life, which led to increase in volume porosity and hence crack initiation. The optimum coolant channel location from the base is obtained as 1 mm, which corresponds to minimum normal stress of 149.1 MPa, fatigue life of 4.1×10^5 cycles, fatigue damage of 2436.9 and equivalent alternating stress of 100.62 MPa.

Keywords. AISI-H13 steel; thermal fatigue; coupled field analysis; coolant channels.

1. Introduction

Cold-chamber pressure-die-casting materials such as H13 tool steel (chromium–molybdenum hot work steel) are widely used in hot- and cold-work tooling applications [1]. The hot hardness of H13 tool steel resists thermal cracking, which occurs as a result of cyclic heating and cooling in hot working applications. During the process, aluminium alloy melt is injected in a temperature range of 600–650°C into the cold chamber of die casting through a hydraulic operated plunger (figure 1). The die is naturally cooled with water and the surface is mostly sprayed with a die lubricant. The dies are always subjected to varying temperatures owing to the injection of molten metal, solidification of part by cooling the die, part ejection and the application of die lubricant for the next cycle.

These processes cause the die to undergo thermal fatigue and gradual failure thermal fatigue that the dies undergo causes reduction in tool life and seriously affects the surface conditions such as microstructure, hardness, surface finish and residual stresses [3]. Preliminary growth of crack is facilitated by oxidation of the crack surfaces. Continuing growth of crack is facilitated by this oxidation in mixture with crack filling of the cast material and by softening of the tool material [4]. Originally, liquefied metal contacts

the die, which causes the surface temperature to rise above that of the inner side of the die [5]. The face of the die starts to expand, even though the cooler primary layer resists this expansion, forming a temporary compressive stress layer [5, 6]. When the casting is removed, the surface of the die starts to cool and the surface contracts. The exterior cools more rapidly than the interior of the die [7]. Hence, the die surface is subjected to irregular compressive and tensile stresses causing plastic deformation [7]. Continuous cycling reduces the yield strength of the tool, which causes increased residual tensile stresses to develop and cracks to initiate.

In order to deeply understand this phenomenon, some of the researchers have focused on experimental and numerical simulation of thermal fatigue of various die-casting materials.

Persson *et al* [8] reported that low-cycle fatigue occurs at maximum temperatures 600 and 700°C, even though the computed tensile stress after cooling does not exceed the yield stress. The reason is the gradual softening of the tool steels during the thermal cycling and the presence of stress concentrators. Bounds [9] reported the thermal behaviour of the zinc pressure die-casting process by measuring the temperature of the die to obtain the operating conditions. J-type mineral-insulated thermocouples were placed through the die block and die surface so that they would be in contact with the casting, and additional thermocouples

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Figure 1. Cold-chamber die casting [2].

were positioned 2.5 mm behind the die surface. The temperature of zinc solidus was reported as 380°C, the liquidus as 386°C and the casting alloy temperature, prior to injection, as 410°C.

Srivastava *et al* [10] reported skin effect when aluminium was injected; on average the external surface temperature of the shot sleeve directly below the pouring hole reached 350°C while the internal temperature reached between 480 and 500°C. The shot sleeve removes a significant amount of heat from the molten aluminium prior to injection. Oberg *et al* [11] reported that although the die was hot, metal entering the die was quickly cooled, producing layers of rapidly chilled, dense and about 0.4 mm thick material. Klobcar *et al* [12] reported that H13 tool steel yielded good results demonstrating small cracks, small crack density and small hardness drop. The crack length was almost equal to the depth of decarburized layer. H11 steel experienced slightly longer cracks and higher hardness drop than H13. It was found that high yield strength materials show increased crack density, whereas low yield strength materials show increased crack length. At high pressure, die-casting tool life would be increased by using high-strength materials, with high thermal stability of mechanical properties at operating temperatures.

Fissolo *et al* [13] reported that in order to increase the number of life cycles of the die the temperature differences during the high-pressure-die-casting process must be kept as low as possible. Sakhuja [14] reported that an initial bulk die temperature of 650°C resulted in the best thermal fatigue life performance for both Haynes 230 and Inconel 617 alloys. The predicted thermal fatigue life of the tooling was increased by a factor of approximately three for the nodes evaluated when the bulk die temperature was increased from 200 to 650°C. Pawłowski *et al* [15] reported that the crack initiation occurred at the edge of the cooling hole and further crack propagation took place in stages, probably corresponding to the die-casting cycles. All observed surface cracks were parallel to the revealed microstructural bands, which promote crack propagation.

A review of literature [8–15] indicates that thermal fatigue is exorbitant for die casters as it causes downtime, loss of production and the need for die maintenance. Gaining an understanding of the material behaviour and its failure due to thermal fatigue assumes utmost importance for die casters and designers. Die design and the selection of material are also essential as they affect the performance and the life expectancy of dies. A small change in the radius of the die thickness can cause enhanced thermal fatigue as they act as stress crack initiators. This paper focuses on thermal fatigue analysis of pressure-die-casting H13 steel dies in order to analyse the effect of coolant channel location on temperature distribution and fatigue parameters such as life, damage, equivalent alternating stress and biaxiality using ANSYS Workbench 15.0 finite-element (FE) package. The model was developed by varying the coolant location from the base when the die got exposed to molten metal.

2. Transient thermal and structural analysis of H13 tool steel die

2.1 Geometric modelling of die-casting die

The geometric modelling of the specimen was carried out using Solidworks 2016 CAD package. A rectangular block of H13 tool steel was created, in order to simulate the virtual condition of the die behaviour during its application in pressure-die-casting process (figure 2). By varying the coolant channel location from the base, six geometric models were developed in the range of 0.5–5 mm wall thickness (H).

2.2 Material properties

AISI H13 hot work tool steel is the most extensively used steel for aluminium dies. It possesses good red hardness and abrasion resistance with an ability to resist heat cracking. It is also adopted for extrusion press tooling because of its ability to withstand drastic cooling from high operating temperatures. The chemical composition and the mechanical properties of the material are listed in tables 1 and 2. Temperature-dependent material properties such as density, specific heat, thermal conductivity and coefficient of thermal expansion were considered.

2.3 FE modelling of pressure die-casting die

The discretization of the geometric model was carried out using ANSYS Workbench 15.0. SOLID 186 element was used to discretize the CAD model with higher order 20-noded 3-D solid element. Quadratic displacement behaviour is exhibited by the elements. The element supports plasticity, large deflection, creep, hyper-elasticity, stress stiffening and large strain capabilities. It also has

Table 1. Chemical composition of (AISI) H13 tool steel [13].

Element	C	Si	Mn	Cr	Mo	V	Ni	P	S
Composition (%)	0.32–0.45	0.80–1.20	0.20–0.50	4.75–5.50	1.10–1.75	0.80–1.20	0.3	0.03	0.03

mixed formulation capability for simulating deformations of fully incompressible hyper-elastic materials and nearly incompressible elastoplastic materials. Figure 3 shows the sectioned FE model of the H13 tool steel die in which 42,688 elements and 149,384 nodes were generated.

Boundary conditions for the thermal and structural analyses were applied during their corresponding stages (figure 4). The following boundary conditions were adopted during thermal fatigue: the ambient temperature was 22°C and the temperature at the base of the specimen was about 600°C; the heat transfer coefficient between the specimen and the molten aluminium alloy was found to be 0.009 W/m² K at 600°C, and between the specimen and air was 0.000005 W/m² K at 22°C. The heat transfer

Table 2. Mechanical properties of (AISI) H13 tool steel [13].

Property	Value
Modules of elasticity E (GPa)	210
Poisson's ratio ν	0.3
Yield strength (MPa)	1230
Tensile strength (MPa)	1430

coefficient between the internal cooling channel and the cooling water varied linearly, from 0.016 W/m² K at 22°C to 0.0157 W/m² K at 640°C [12].

Figure 2. Orthographic view of H13 tool steel die-casting die.

3. Results and discussion

3.1 Effect of coolant channel position on temperature distribution

Figure 5(a) depicts the temperature distribution for the coolant channel location situated at 1 mm from the base and (b) depicts temperature distribution for varying coolant channel locations. The coolant channel location situated at 0.5 mm from the base experienced a temperature of 158.38°C, whereas other positions at 1, 2, 3, 4 and 5 mm from the base experienced 158.51, 159.32, 160.37, 161.01 and 161.81°C, respectively. The minimum temperature of the die that has to be maintained to reduce the thermal crack is 170°C, and the average tool temperature is usually kept at determined levels through internal cooling. Cooling channel close to the bottom surface increases the heat transfer rate through forced convection, resulting in less thermal expansion. From this, it is expected that the thermal

Figure 3. Sectioned FE model of the H13 tool steel die.

Figure 4. Boundary conditions of H13 tool steel die.

fatigue cracks will appear at the specimen surface due to higher temperature and due to the decreased strength at elevated temperature [12]. As the coolant channel location distance from the base increases, the surface temperature also increases. Hence, it leads to expectation of crack initiation at higher distance from the coolant channel location.

3.2 Effect of coolant channel location on die fatigue life

Geometry plays an important role in the stresses produced during thermal fatigue loading. Table 3 shows the results of coolant channel location on die fatigue life. For the analysis, the Goodman theory was adopted as mean stress correction theory and it proposes a failure line that extends the endurance limit on the vertical axis to the ultimate tensile strength on the horizontal axis as shown in figure 6 [16]. The coolant channel location situated at 1 mm from the base experiences increase in fatigue life due to cooling channel nearer to the base; it experiences a minimum normal stress 149.1 MPa due to thermal expansion. As the wall thickness of the die increases, the normal stresses start increasing as shown in figure 7(a). Also the die life drastically decreases as shown in figure 7(b). This may be explained by the fact that die casting of thin-walled specimen encounters high turbulent flow of molten material, which will induce volume porosity; this in turn decreases the die life. Also the normal stress component decreases with increase in wall thickness. These results are in accordance with those given by Aghion *et al* [17], according to which a non-proportional correlation between the specimen wall thickness and the mechanical properties such as yield strength and ultimate strength was established. The normal stress distribution plot for 1 mm from base is as shown in figure 8(a) and fatigue life plot for 1 mm from base is as shown in figure 8(b).

Figure 5. (a) Temperature distribution for the coolant channel location situated at 1 mm from base. (b) Temperature distribution for varying coolant channel locations.

Table 3. Results of thermal fatigue simulation test.

Sl. no.	Coolant channel location	Normal stress (MPa)	Fatigue life (cycles)	Fatigue damage	Equivalent alternating stress (MPa)	Biaxiality indication
1	0.5 mm from base	228.55	70072	14271	152.05	0.99942
2	1 mm from base	149.1	4.1×10^5	2436.9	100.62	0.99727
3	2 mm from base	173.09	2.94×10^5	3398.2	106.6	0.99589
4	3 mm from base	181.8	2.07×10^5	4821.8	113.28	0.99639
5	4 mm from base	184.22	1.93×10^5	5188.8	115.17	0.99645
6	5 mm from base	180.77	91056	10643	140.36	0.99883

Figure 6. Mean stress correction theory.

3.3 Effect of coolant channel position on fatigue damage

Fatigue damage is a contour plot of the fatigue damage at a given design life. Fatigue damage is defined as the design life divided by the available life [16]. The coolant channel location 1 mm from the base, as shown in figure 9, experiences less fatigue damage of about 2436.9 when

compared with the farther coolant channel locations. The fatigue damage decreased from 14271 to 2436.9 when the coolant channel position increased from 0.5 to 1 mm. The thermal fatigue damage is a function of thermal gradient and thermal expansion coefficient of the material. According to Abdulhadi *et al* [18], compression stresses developed exceed the elastic limit of the die material only if the integration of the temperature gradient and the widespread thermal expansion is high enough. In the present case, when the coolant channel position is increased from 0.5 to 1 mm, there is no considerable change in temperature distribution (figure 5b) and hence thermal gradient does not contribute for increase in fatigue damage. Also the stresses developed (149.1 MPa) are far lower than elastic limit (1430 MPa). Hence the fatigue damage decreased from 14271 to 2436.9. Further increase in coolant position from 1 to 5 mm in steps of 1 mm increased the fatigue damage up to 10643.

3.4 Effect of coolant channel position on equivalent alternating stress

In a stress–fatigue life analysis, one always needs to query for an *S–N* curve to relate the fatigue life to the

Figure 7. (a) Normal stress for varying coolant channel location. (b) Fatigue life for varying coolant channel locations.

Figure 8. (a) Normal stress for the coolant channel location situated at 1 mm from base. (b) Fatigue life for the coolant channel location situated at 1 mm from base.

Figure 9. Fatigue damage for the coolant channel location situated at 1 mm from base.

stress state. Thus the “equivalent alternating stress” is the stress used to query for the fatigue $S-N$ curve after accounting for loading type, mean stress effects, multiaxial effects and any other factors in the fatigue analysis. Thus, in a fatigue analysis, the equivalent alternating stress can be thought of as the last calculated quantity before determining the fatigue life [16]. The usefulness of this result is that in general it contains all of the fatigue related calculations independent of any fatigue material properties. The coolant channel location 1 mm from the base has less equivalent alternating stress of about 100.62 MPa (figure 10) when compared with the other results. Equivalent alternating stress decreased from 152.05 to 100.62 MPa when the coolant channel location increased from 0.5 mm (figure 11) to 1 mm. Further increase in coolant channel location from 1 to 5 mm (figure 12) in steps of 1 mm increases the stresses up to 140.36 MPa.

Figure 10. Equivalent alternating stress for the coolant channel location situated at 1 mm from base.

Figure 12. Equivalent alternating stress for the coolant channel location situated at 5 mm from base.

Figure 11. Equivalent alternating stress for the coolant channel location situated at 0.5 mm from base.

Figure 13. Biaxial indication for the coolant channel location situated at 1 mm from base.

3.5 Effect of coolant channel position on biaxiality indication

Biaxiality indication is defined as the principal stress smaller in magnitude divided by the larger principal stress with the principal stress nearest zero ignored. A biaxiality of zero corresponds to uniaxial stress, a value of -1 corresponds to pure shear and a value of 1 corresponds to a pure biaxial state [16]. Variation of coolant channel locations for the biaxiality plot indicates that the model approaches towards biaxiality stress state. Some of the locations also exhibit pure shear and pure uniaxiality as indicated by negative values and the values nearing 0 as shown in figure 13. A summary of thermal fatigue simulation results obtained is presented in table 3.

4. Conclusion

The life of high-pressure die-casting dies could be increased by using an effective cooling channel near the base and with greater thermal stability of mechanical properties at operational temperatures. Thermal fatigue analysis was carried out using ANSYS Workbench 15.0 package in order to characterize the thermal fatigue resistance of H13 tool steel. The characteristics mainly included temperature distribution, fatigue parameters such as fatigue life, damage, alternating stress and biaxiality. The results indicated that the coolant channel location at 0.5 mm from the base induces maximum normal stress of 228.55 MPa, minimum fatigue life of $70,072$, maximum thermal fatigue damage of $14,271$ and equivalent alternating stress of 152.05 MPa. However, the coolant location at 1 mm from

the base experiences the temperature of 158.51°C, which corresponds to minimum normal stress of 149.1 MPa, fatigue life of 4.1×10^5 cycles, fatigue damage of 2436.9 and equivalent alternating stress of 100.62 MPa, which is considered to be the best among the coolant channel locations.

Nomenclature

E	modulus of elasticity (GPa)
ν	Poisson's ratio
H	wall thickness
T	temperature
h	heat transfer coefficient

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