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Energy-based approach to thermal fatigue life of tool steels for die casting dies

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ABSTRACT

Thermal fatigue cracking is one of the mostly encountered failure mechanisms for die halves in the die casting industry. This is due to rapid alternating heating and cooling of die surfaces during the casting process. In this paper, an experimental thermal fatigue test method based on cyclic induction heating and water cooling is proposed for the evaluation of thermal cracking of the tool steel used in the industry. An energy-based fatigue life model is formulated by accounting the test period. Finite element models are developed for better understanding of thermal loadings experienced by samples under the fatigue testing. The results demonstrate that thermal cracking is closely related to inelastic energies dissipated at the material levels. The outcome of this study enables accurate evaluation of crack growth and, thus, evaluation of thermal fatigue life of die casting dies by using the proposed energy-based model.

1. Introduction

Die casting is a cost-efficient method for forming geometrically complex, near net-shaped products with close tolerances and excellent surface finishes [1,2]. As a high volume production process, it commonly reaches a production rate of 200 parts per hour and a production batch of 300,000 parts [3]. Therefore, low cycle times require high flow velocities and rapid solidification of molten metal (large thermal gradients). For instance, during aluminium die casting, molten aluminium (670–710 °C) is injected into the mould at velocities of 30–100 m/s [3,2]. These severe conditions limit the service life of die halves. Die casting dies mostly fail in the modes, such as heat checking, soldering and corrosion. Heat checking (also known as thermal cracking) is the principal mode in hot working. It specifically accounts for 70% of failures in die casting dies [4]. Die failures cause significant loss to the die casting industry due to high cost of die halves and production suspension as a result of die downtime [5]. Therefore, this has become a major research topic for die workers to increase thermal fatigue resistance of hot-work die steels.

Christopher [6] and Srivastava et al. [5] developed computational models to understand thermal and structural behaviour of test samples and to predict fatigue cracking in die steel samples studied experimentally by the Wallace test [7]. Li et al. [8] defined thermal fatigue crack initiation (TFCI) life from engineering point of view and proposed an expression for the TFCI life of H13 and H21 steels based on a modified Coffin–Manson expression. Velay et al. [9], Persson [10] and Persson et al. [11] studied thermal fatigue cracking behaviour of die steels using an experimental thermal fatigue test method based on induction heating and internal water cooling. They developed a strain-based approach for thermal fatigue resistance. Klobčar et al. [12,13] and Klobčarand Tušsek [14] established finite element models for understanding thermal stresses experienced by die steel samples during immersion tests. The thermal loadings were then used to compare resistances of different tool steels, AISI H11, AISI H13 and maraging steel. Thermal fatigue resistance of surface engineered die steels was also popularly investigated. Yatsushiro et al. [15] applied laser peening for hot work die steel, AISI H13, for the improvement of the resistance to crack growth. Moreover, Borrego et al. [16] studied the effect of laser deposit welding on the fatigue resistance of two die materials in mould production (AISI H13 and P20).

In most of the literature, Coffin–Manson expression and its modifications are frequently applied for analysing thermal fatigue resistance. This approach correlates thermal fatigue life with cyclic strains. Christopher [6] and Sakhuja and Brevick [17] used the method of universal slopes to relate cyclic strain ranges to the number of cycles necessary for fatigue crack initiation. Persson [10] extended the strain-based approach to account for the crack

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propagation stage by defining corresponding strain intensity. Similarly, Li et al. [8] proposed a temperature-based approach for the TFCI life based on a modified Coffin–Manson model. The main problem for this method is that either crack initiation and propagation are not distinguished or the length for crack initiation is usually subjectively defined. Based on the measurements made on sections from failed die casting dies, according to Parishram [18], cracks that cause noticeable heat checks for the die casting application had an average of 0.5 mm in length. Therefore, for the die casting industry, a life approach capable of accounting for cracking procedure would be more appropriate.

In this paper, an energy-based approach is proposed to investigate thermal cracking of die material. Firstly, discrete thermal cracking data were obtained through thermal fatigue tests of die steel samples using a dedicated test machine. Then, numerical modelling was conducted to understand work loadings experienced by the material points. And lastly, crack data were correlated with the thermal/structural loadings and thermal fatigue life model for the die material was established.

2. Experimental work

Experimental work is investigated in this section to understand thermal cracking process. In this experimental work, the commonly used die material 8407S (produced by ASSAB company) is used. A thermal fatigue test machine is purposely designed for this research study. Temperature profiles of samples during testing are captured using an infrared camera for the calibration of thermal analysis in the forthcoming section for finite element modelling.

2.1. Specimen design and preparation

Test samples are made of the material 8407 supreme, which is a premium high quality AISI H13 die steel. It is characterized by high level of resistance to thermal shock and thermal fatigue. The elongation at break is 10% at 500 °C and 600 °C and 20% at 700 °C. The properties enable the material particularly suitable for tooling subjected to high mechanical and thermal fatigue stresses, e.g. die casting dies, forging tools and extrusion tooling [19]. The chemical composition and mechanical properties of the tool steel are depicted in Tables 1 and 2, respectively. The microstructure of the tool steel after heat treatment is illustrated in Fig. 1.

With heat treatment to be harder than 54HRC as die casting dies, the test materials were machined into specimens with dimensions of 20 × 20 × 5 mm. As shown in Fig. 2, the specimens have a notch of 0.1 mm in radius with a wire Electrical Discharge Machining (EDM) cut. The geometry of the specimen is defined to (i) obtain an effective thermal gradient in the cross section of the specimen; (ii) guarantee efficient cooling in the central part of the specimen; (iii) generate a state of stress concentration; (iv) limit manufacturing costs of the specimen; and (v) consider die geometry effects on thermal cycling. Surfaces under major thermal loads were also well finished to eliminate the effect of machining on thermal fatigue resistance.

2.2. Experimental set-up and arrangements

Until recently, numerous methodologies are proposed for thermal fatigue testing of hot-work mould steel materials [9,13,20]. The major difference amongst them is in the heating and cooling means obtaining rapid heating and cooling effects that are experienced in die halves. Therefore, this study utilizes induction heating based thermal fatigue test equipment, as schematically represented in Fig. 3. Each specimen was heated by an induction coil and immediately cooled by flushing water to achieve thermal shock effects as die casting dies experience. The controllable parameters include frequency for heating current (F, Hz), heating time (t_h, s), and cooling time (t_c, s). Test samples were taken out for the observation of cracking information in the vicinity of the notch tip firstly at 800 cycles and then every 400 cycles. After elimination of the oxide layer by ultrasonic cleaning in dilute hydrochloric acid solution (10%) for 10–15 min, thermal cracks within test samples were evaluated by optical microscopic observation. During thermal fatigue testing, temperature profiles of test sample surface were measured using a FLIR T640 thermal imaging camera. The data will then be applied in calibration of finite element modelling of thermal fatigue test as well.

Table 1
Chemical composition of the analysed mould steels (wt%).

Mould steel	C	Si	Mn	Cr	Mo	V
8407S (Premium AISI H13)	0.39	1.0	0.4	5.2	1.4	0.9

Table 2
Typical mechanical properties of the mould steel (Room temperature).

Hardness (HRC)	Tensile strength, R_m (MPa)	Yield strength, R_p (MPa)
52	1820	1520
45	1420	1280

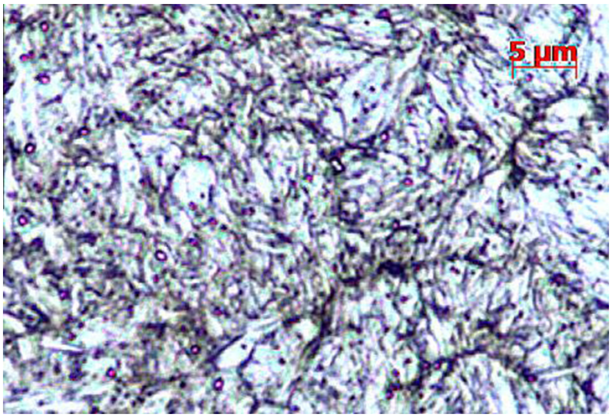

Fig. 1. Microstructure of 8407 supreme after heat treatment.

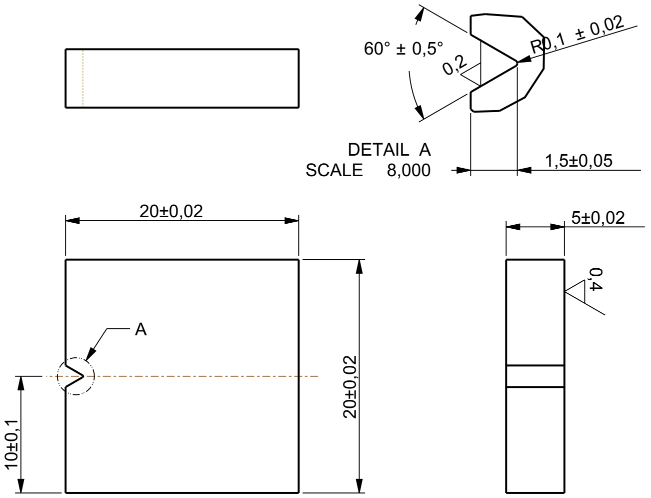

Fig. 2. Drawing of thermal fatigue testing sample.