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Thermal fatigue of materials for die-casting tooling

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Abstract

This research is conducted to study the thermal fatigue resistance of different hot-work tool steels; AISI H11 and H13, special tool steel and 18% Ni maraging steel. The maraging steel is surface cladded by GTA welding to study the thermal fatigue resistance of surface layer. An influence of mechanical and microstructural properties on thermal fatigue resistance is evaluated. An innovative apparatus for thermal fatigue testing is developed to study the thermal fatigue resistance. The test specimens are subjected to cyclic heating in bath of molten Aluminum Alloy 226 and cooling in bath of water-based lubricant. They are continuously internally cooled with cold water. The specimens are periodically analyzed after completion of particular number of cycles. The microstructure, hardness profile and the surface cracks developed are analyzed. Temperature transients at different locations of test specimen are measured and used in computation of transient stresses performed by finite elements. The specimens of special geometry are developed using finite element modeling to improve testing efficiency. An optimal set of thermal fatigue testing parameters are developed to establish efficient testing. The influence of thermal loading on tempering of hot work tool steel and on aging of maraging steel claddings during testing is determined. The results showed significant differences in thermal fatigue resistance of tested materials and their heat treatments. The best thermal fatigue resistance achieved special tool steel due to its high thermal stability. The resistance of AISI H11 tool steel is slightly superior to that of maraging steel weld.

Keywords: High-pressure die-casting; Hot-work tool steel; Heat treatment; Thermal fatigue; Immersion test; Finite element modeling

1. Introduction

Die-casting is a high volume production process, which produces geometrically complex parts of nonferrous materials. A production of 300,000 castings is a common series for die-casting industry. The production cost of die-castings is highly depended on the tool life, which is influenced by the tool design, material selection, its heat treatment, and casting process parameters. During aluminium die-casting, molten aluminium at temperatures of about 700 °C is injected into the mold at velocities of 30–100 m/s. The injection pressures are of the order 50–80 MPa [1]. The in-service tool life is affected by (a) thermal fatigue, which causes heat checks on the surface of the die, (b) corrosion and soldering of aluminium to the die surface, (c) erosion due to melt flow, and (d) catastrophic failures [2–5]. In order to minimize these effects different approaches are applied to extend tool life. Application of surface coatings minimizes corrosion, soldering and erosion. Surface coatings have good resistance to erosion and soldering, and a poor resistance to thermal fatigue [6], whereas, newly developed surface coatings achieve improved thermal fatigue resistance [7,8]. The second approach is to study thermal fatigue mechanisms and resistance of different materials and heat treatments [4,6,9,10] in order to extend the in-service tool life. This is established by development of a test apparatus for simulation of thermal fatigue during die-casting. The main difference between the testing methods and the casting process is in the specimen heating, which is achieved by immersion in molten alloy, induction heating or laser heating [2,4,6,11]. An innovative apparatus for thermal fatigue testing based on molten aluminium heating is developed for this study.

In-service die life used for aluminium die-casting could be improved by proper material selection, its heat treatment or by development of repair welding technology. As part of this investigation four different hot-work tool steels are tested: (1) a generic AISI H11, (2) a premium H13, (3) a special tool steel (STS), and (4) a particular 18% Ni maraging steel

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Table 1
Chemical composition of tested materials (%) [15–17]

EN 10027-2/AISI	Specimen indication	C	Cr	Si	Mn	Mo	Ni	Co	Al	Ti	V
1.2343/H11	R3	0.38	5.10	1.0	0.40	1.25	–	–	–	–	0.40
1.2344/H13	T2, O[a]	0.40	5.15	1.05	0.40	1.35	–	–	–	–	1.00
STS	Q72	0.38	2.6	0.3	0.75	2.25	–	–	–	–	0.9
1.6356/MS	V[a]	0.02	–	–	–	4.0	18.0	12.0	0.1	1.6	–

[a] Specimen number indication.

(MS) deposited to the specimen surface by GTA welding. These materials are tested on developed thermal fatigue testing apparatus. This test enables good reproduction of thermal fatigue cracking similar to that occurring in die-casting of aluminium alloys. The interior surface of the test specimen is continuously cooled. Specimens are subjected to cyclic heating in bath of molten aluminium alloy and in bath of cold water emulsion. The temperature in particular places of test specimen is measured during testing and used in computation of transient stresses by finite elements (FE).

Materials are characterized before the tests by measuring hardness, toughness, tensile strength, and by performing metallographic examination. Specimens are periodically analyzed after completion of particular number of test cycles to study the evolution of metallurgical and mechanical properties, and the evolution of thermal cracking.

A FE model for prediction of stresses and strains during immersion test is developed [12,13]. An extensive parametric FE analysis of specimen design factors, immersion test parameters and depth of maraging steel cladded layer is performed [14]. This analysis enables better understanding of transient stress development during thermal cycling. Optimal specimen geometry is developed to improve testing efficiency. Optimal thermal fatigue test parameters are established that enable severe testing conditions and improve efficient testing.

The results showed significant differences in thermal fatigue resistance of tested materials and their heat treatments. Among tested materials, STS achieved best thermal fatigue resistance due to its high thermal stability of mechanical properties during testing at operating temperature. The resistance of H11 tool steel is slightly superior to the maraging steel weld claddings due to aging of maraging steel during testing.

2. Experimental

Experimental tests are performed to establish correlation between mechanical and metallurgical properties of different hot-work tool steels on one, and thermal fatigue resistance on the other hand. The idea is that steels with higher thermal conductivity, lower coefficient of thermal expansion, and lower modulus of elasticity experience smaller thermal stresses and have better thermal fatigue resistance. Chemical composition of tested materials is shown in Table 1, whereas, mechanical and physical properties are shown in Table 2.

2.1. Thermal fatigue testing

Schematic thermal fatigue test apparatus is shown in Fig. 1a. It enables a controlled thermal fatigue cycling test of materials at conditions similar to aluminium die-casting. Heating of test specimens is achieved by their immersion in bath of molten Aluminium Alloy 226 at temperature around 700 °C for 10 s. The test specimens are internally continuously cooled with water at temperature 20 °C. Fatigue loading is achieved by cyclic movement of test specimens from bath of molten aluminium, through air at temperature 28 °C into the bath of water based lubricant at temperature 32 °C. Air cooling takes 4 s, while water emulsion cooling 3 s. Water emulsion also prevents sticking of aluminium to the surface of the specimen. Total cycle duration is 21 s. The thermal fatigue test specimens are not subjected to pressure or aluminum flow. All specimen movements during testing are achieved with two pneumatic cylinders, which are controlled by a personal computer. Test specimens V*1 made 4000 cycles, specimens V*2 and R3 8000 cycles at 4 s in a bath of molten aluminium, while all other specimens held 10 s in Al bath.

2.2. Test specimens preparation

Fig. 1b shows 150 mm long test specimen with 9.5 mm axial hole 140 mm deep. A tube connected to the cooling circuit is inserted into the hole. Cooling water at temperature 20 °C is brought to the bottom of the specimen. The water then flows upwards between the tube and the specimen inner wall to cool the

Table 2
Mechanical and physical properties of tested materials [15–17]

Property	H11	H13	STS	MS
Modulus of elasticity (GPa)	210	210	210	191*
Tensile strength (MPa)	1410	1430	1620	1763*
Yield strength (MPa)	1170	1230	1400	1688*
Coefficient of thermal expansion				
20–400 °C (10^{-6} mm/mm °C)	13.2	12.5	12.6	10**
20–600 °C (10^{-6} mm/mm °C)	13.7	13.1	13.2	5.6**
Thermal conductivity (W/m °C)				
20 °C	25	25	28	28**
500 °C	28.5	28.5	32	32**
600 °C	29.3	29.3	33	33**
Thermal stability of hardness [16,18]				
ΔHRc = −5 HRc at 600 °C (h)	–	18	65	–

*Data for 14% Ni maraging steel [17], **experimentally measured data for 18% Ni maraging steel weld.