Engineering Failure Analysis 95 (2019) 171–180

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Experimental and numerical analysis of failures on a die insert for high pressure die casting

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ARTICLE INFO

Keywords:
Die failures
Nitriding
Finite element analysis
Microanalysis
X-ray analysis

ABSTRACT

A comprehensive study of failures on a used insert of a die for high pressure die casting of aluminium alloy AlSi9Cu3Fe was conducted. The analysed insert was made of hot work tool steel Dievar, heat treated and plasma nitrided according to specifications. Before the start of analysis, the insert was subjected to 170,000 die casting cycles. X-ray diffraction, light microscopy, scanning electron microscopy and hardness measurement methods were used for experimental analysis of soldering, corrosion, erosion and thermal fatigue failure modes on the insert. A special procedure, which combines use of commercial software MAGMA5.3 and open source software CalculiX, was developed for numerical calculations of temperature fields on the insert. Experimental and numerical results showed strong dependence between die surface temperatures and die failure modes. Hardness drop, nitride diffusion layer removal and microstructural changes were observed at more thermally affected areas. Surface crack with a thin oxide and thicker soldered layer was identified and analysed.

1. Introduction

High pressure die casting (HPDC), designated in this article as die casting, is a technology that enables fast and high quality production of geometrically complex parts with high mechanical and dimensional requirements. Due to high absolute values and rapid fluctuations of temperature, pressure and melt velocity, die casting dies are exposed to cyclic thermo-mechanical loading, which gradually leads to the occurrence of wear and damage. Typical maximum melt velocities during die filling are between 30 m/s and 100 m/s [1]. The additional pressure applied during the solidification phase is of magnitude from 50 MPa to 80 MPa [1,2].

One of the most important parameters in a die casting process is the temperature of the die. A lot of studies have been conducted to monitor the temperature at the die surface during a real die casting cycle [2–4]. Norwood et al. [2] performed temperature measurements during casting of aluminium alloy Al8Si3Cu with use of thermocouples and temperature-sensitive paints. The maximum and minimum measured temperatures were in the range from 400 °C to 450 °C and from 150 °C to 200 °C, respectively. Dargusch et al. [3] and Long et al. [4] measured temperatures in the die surface layer during the casting process of aluminium alloy AlSi9Cu3Fe. From the temperature measurements the heat transfer coefficient was determined and then used in a numerical simulation for surface temperature calculation. The minimum and maximum calculated temperatures were 240 °C and 500 °C, respectively.

Die wear and damage mechanisms are generally divided in four groups: (1) soldering, (2) corrosion, (3) erosion, (4) thermal fatigue and cracking.

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https://doi.org/10.1016/j.engfailanal.2018.09.010
Received 22 May 2018; Received in revised form 30 August 2018; Accepted 13 September 2018
Available online 15 September 2018
1350-6307/

Soldering (or die sticking) is seen as the adhesion of cast material to the die surface during the die filling and solidification phases. Soldering can be subdivided into two categories [5–8]: (1) metallurgical soldering, characterised by a high number of loading cycles and high temperature of the die surfaces [5,9–14] (2) mechanical soldering, characterised by a low number of loading cycles and high melt pressures [5]. A soldered layer is usually the product of the simultaneous action of metallurgical and mechanical soldering.

Corrosion of dies in die casting is characterised by loss of die material from the die surface and it is a metallurgical process [14]. There is often a simultaneous occurrence of corrosion and soldering on a particular region of a die surface [14].

Erosion is also characterised by loss of die material from the die surface, but it is a mechanical process [15]. An increase in the occurrence of erosion with an increase of die surface temperature was identified in several studies, [16–18]. Baker et al. [19] observed the appearance of cracks on previously eroded die surfaces.

The main cause for thermal cracking of die casting dies are high temperature and pressure gradients [20–22,24]. The most influential parameters on thermal cracking are: (a) maximum heating temperature and heating/cooling rate, (b) oxidation, (c) hardness and microstructure of the die material. Research has shown, that crack initiation and propagation are increased by higher heating temperatures and higher heating/cooling rates [22,24–28]. In some studies it has been observed, that crack growth is increased by surface oxidation [29–31]. From thermal fatigue tests it has been found out, that crack density and crack depth decrease with increasing surface hardness [26–28,32,33]. Thermal fatigue also affects the microstructure of the die material. It causes thermal softening of the die surface, which is seen as surface hardness drop [26,29,30,34,35]. Thermal softening and hardness drop are accelerated by higher heating temperatures [25,27,28,31].

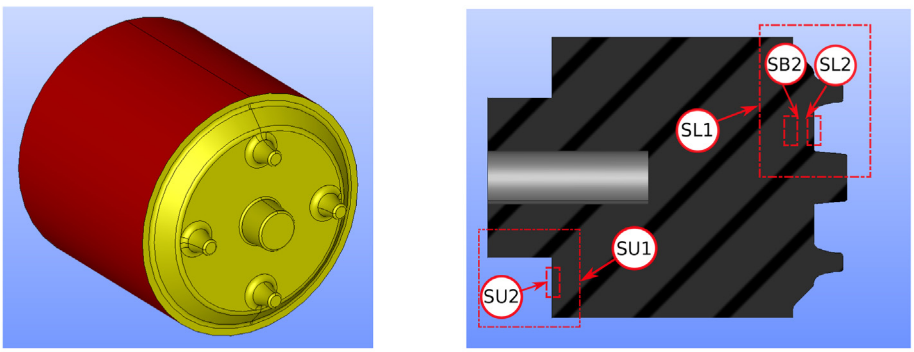
To reduce the occurrence of damage and wear mechanisms on die casting dies, it is important to choose an appropriate material, heat treatment and optionally surface treatment of the die [29]. One of the most often used surface treatments on die casting dies is nitridation. Joshi et al. [12] found out, that nitridation decreases the rate of metallurgical soldering on die surfaces. However, soldering on nitrided surfaces is present due to mechanical soldering after the formation of thermal cracks and erosion of the nitrided layer [6]. Persson [27] discovered that nitrided surfaces have better resistance to thermo-mechanical fatigue than untreated surfaces do. An increase in the thermal stability of the microstructure of nitrided surfaces has also been observed. The final crack depth on a nitrided surface is dependent on the nitridation depth, because crack growth stops at the interface between diffusion zone and substrate material [36].

In this paper, a comprehensive analysis of a used insert of a die casting tool, made of hot work tool steel Dievar [37], is presented. The die casting tool was used for casting of aluminium alloy AlSi9Cu3Fe. The focus is on determining the influence of temperature on the occurrence of individual wear and damage mechanisms.

2. Experimental analysis

2.1. Materials and samples preparation

A three-dimensional model of the analysed insert is presented in Fig. 1a. The chemical composition of hot work tool steel Dievar, used for production of the analysed insert, is presented in Table 1. Before use, the insert was heat treated and surface treated according to specifications. Heat treatment was composed of heating the insert to the austenitising temperature of 1020 °C for 30 min, followed by quenching in warm oil and final double tempering for 2 h at 550 °C. After heat treatment, the insert was additionally surface plasma nitrided for 10 h at 480 °C to reach the final nitridation depth of 150 μm and final surface hardness of 1100 HV. The die casting tool with the analysed insert was used for die casting of aluminium alloy AlSi9Cu3Fe. The die casting cycle consisted of spraying the insert for 2 s, blowing the insert for 5 s, dosing the melt at a temperature of 670 °C, filling of the die, and solidification of the casting for 10 s. The duration of the entire die casting cycle was 62 s. The insert was exposed to 170,000 die casting cycles and then removed from the die casting tool for analysis. During die casting process the yellow coloured surface was in contact with melt and hence thermo-mechanically loaded. This surface will be in this paper designated as the active surface. During die casting process



(a) (b)

Fig. 1. Insert presentation and samples preparation: (a) three-dimensional model of the analysed insert of dimensions Ø35x44.73 mm, (b) samples cutting scheme.