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THERMAL FATIGUE CRACKING OF DIE-CASTING DIES

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Die-casting dies are exposed to high thermal and mechanical loads. Thermal fatigue cracking of dies due to thermal cycling may importantly shorten the life-time of the die. Cracks degrade the surface quality of dies and consequently the surface of castings. In this study, thermal fatigue cracking of dies was analyzed during the process of die casting aluminium alloys. During the process cracks were observed and measured and their location and size were determined. Thermal and mechanical loads cause high local stresses and consequently surface cracks. First cracks occur as early as after 2000 cycles and propagate progressively with cycles.

Key words: Die casting, die defect, thermal fatigue, surface cracks

Pukotine na kalupima (alatima) za tlačno lijevanje uslijed toplinskog umora. Kalupi (alati) za lijevanje pod tlakom su izloženi velikim toplinskim i mehaničkim opterećenjima. Pukotine uslijed toplinskog umora su zbog izmjene toplinskih ciklusa važan ograničavajući mehanizam životnoga vijeka kalupa. Pukotine smanjuju (degradiraju) kvalitetu površine kalupa i posljedično površinu odljevka. U ovom radu su analizirane pukotine nastale na kalupu zbog toplinskog umora tokom tlačnog lijevanja aluminija. Tokom procesa su promatranjem i mjerenjem utvrđene lokacije i veličine nastalih pukotina na kalupu. Toplinska i mehanička opterećenja uzrokuju velika lokalna naprezanja i posljedično pukotine na površini kalupa. Prva pukotina pojavljuje se već nakon 2000 ciklusa i progresivno se širi povećanjem broja ciklusa.

Ključne riječi: Tlačno lijevanje, defekti na kalupu, toplinski umor, površinske pukotine

INTRODUCTION

Die casting is the process of forcing molten under high pressure into mold cavities (which are machined into dies). The process of die casting is a cost-efficient method of making castings from aluminium, zinc, magnesium and copper-based alloys [1–3]. Dies are exposed to high mechanical, thermal and chemical loads which cause surface defects. These defects are thermal fatigue cracks, erosion of the melt flow, corrosion and soldering of aluminium to the die surface, deformation of contact surfaces of dies and gross fracture (Figure 1) [1-7].

These defects are then reflected on castings. Figure 2 shows surface defects on aluminium castings. Figure 2a shows a worn-out surface, which is caused by the erosion of aluminium alloy melt flow. Figure 2b shows thermal fatigue cracks which occur due to thermal stresses during die casting. Figure 2c shows damage on an aluminium casting due to corrosion and soldering of aluminium to the die surface. The burr is caused by deformation of die parts (Figure 2d).

Die-casting dies usually fail due to thermal fatigue cracking [5–11]. Dies are exposed to high temperature gradients and high pressure peaks of melt. Temperature gradients between the surface and the die core are causing thermal stresses, which can exceed die material yield strength [8, 9]. This leads to the accumulation of local plastic strains on the die surface and consequently to surface cracks [10].

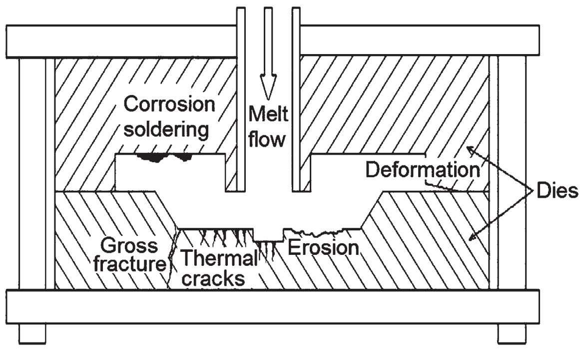

Figure 1. Schematic of defects occurrence on a die-casting die.

EXPERIMENTAL PROCEDURE

The material used in the investigation of thermal fatigue cracking was aluminium alloy AlSi9Cu3 (Table 1). (Figure 3). Experiments were made on an 8 MN cold chamber machine in actual production runs. The temperature of the aluminium melt was 680 °C and the total cycle time was 60 s during which the die was closed 25 s

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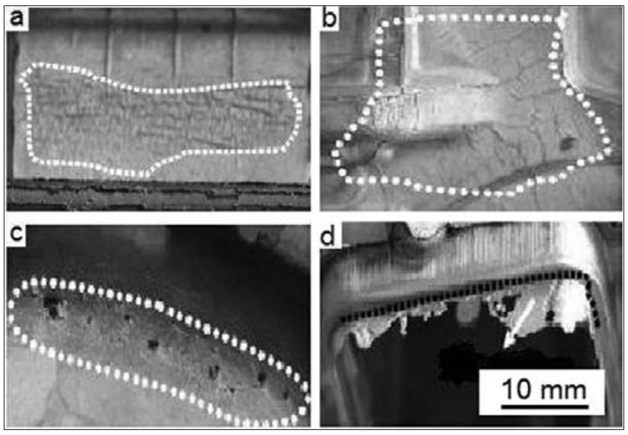

Figure 2. Surface defects of castings: a) erosion, b) thermal cracks, c) corrosion and soldering, d) deformation.

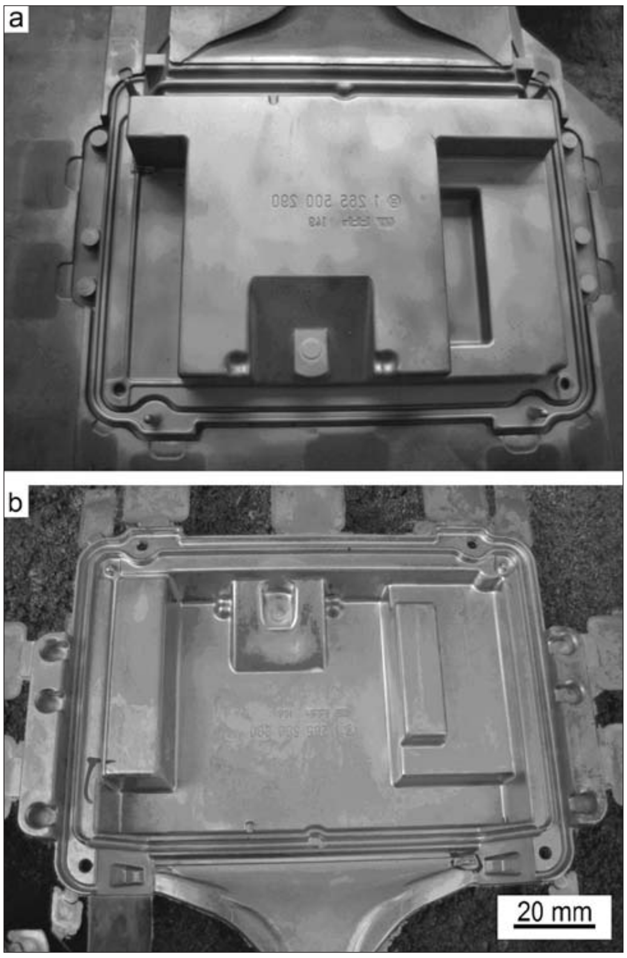

Figure 3. Die-casting die (a) and aluminium casting (b).

and open 35 s. Water at 200 °C was continuously circulating through cooling channels in the tool and the tool surfaces were lubricated. The weight of each casting was 332 g, the casting pressure 50 MPa, filling time 23 ms and the entrance velocity of the melt was about 52 m/s. The tool in this study was preheated to a temperature about 200 °C.

The die was made of Cr-Mo-V hot work tool steel AISI H11 (DIN X38CrMoV5.1, W. No.: 1.2343) (Table 1). The tool was hardened at 1000 °C and tempered at 600 °C to get the hardness of 45 HRc ~ 450 HV. The die surface was also nitrided to improve the wear resistance and prolong the in-service die life.

During the analysis thermal fatigue cracks were measured using thin wires of a diameter between 0,05 – 0,1 mm, by inserting them into cracks and measuring their approximate depth. The surface cracks length was determined with a string with a diameter of 0,2 mm by placing it into the cracks and measuring their length. The measurements were performed at every 1000 cycles up to 35000 cycles at four equal dies to get the relationship between crack size depth, length and number of cycles performed by the die.

RESULTS AND DISCUSION

Figure 4 presents the locations of the surface defects on the dies and detailed photos of these defects. The identified local surface defects did not appear at the same time, i. e. at the same number of cycles.

They are numbered according to the time of occurrence; the first was observed at the edge at location 1 and the last defect was observed at location 12. The majority of these surface defects generally occur on edges and corners. They tend to occur first at corners and edges with small radiuses. Locations closer to the gate were also subjected to higher temperature gradients and consequently higher stresses.

Figure 5 shows the locations and number of cycles at which the first thermal fatigue cracks occurred. At location 1 the first thermal crack occurred at around 2500 cycles, at location 2 at 3000 cycles and at locations 3 at 4000. Before 5000 cycles the cracks occurred at locations 1, 2, 3. The cracks at locations 4, 5, 6 were first detected after 6000, 7000 and 8000 cycles, respectively. The cracks at locations 7 and 8 were first observed at 16000 and 17000 cycles, at locations 9 and 10 at 21000 and 23000 cycles, and location 11 and 12 at 26000 and at 32000 cycles, respectively.

Thermal fatigue cracks occurred at all locations. At locations 3 and 4 the neighbouring cracks were united,

Table 1. **Chemical composition (mas.%) of the aluminum alloy AlSi9Cu3 and the Cr-Mo-V alloy hot work tool steel AISI H11 (DIN X38CrMoV5.1, W. No.: 1.2343) used in the experiment.**

Alloy	Chemical composition / mas. %											
	Si	Cu	Mn	Mg	Fe	Zn	Ni	Al	C	Cr	Mo	V
AlSi9Cu3	9,5	3,0	0,4	0,5	0,9	1,0	0,3	Rest	/	/	/	/
H11	1,00	/	0,40	/	/	/	/	/	0,38	5,00	1,30	0,40

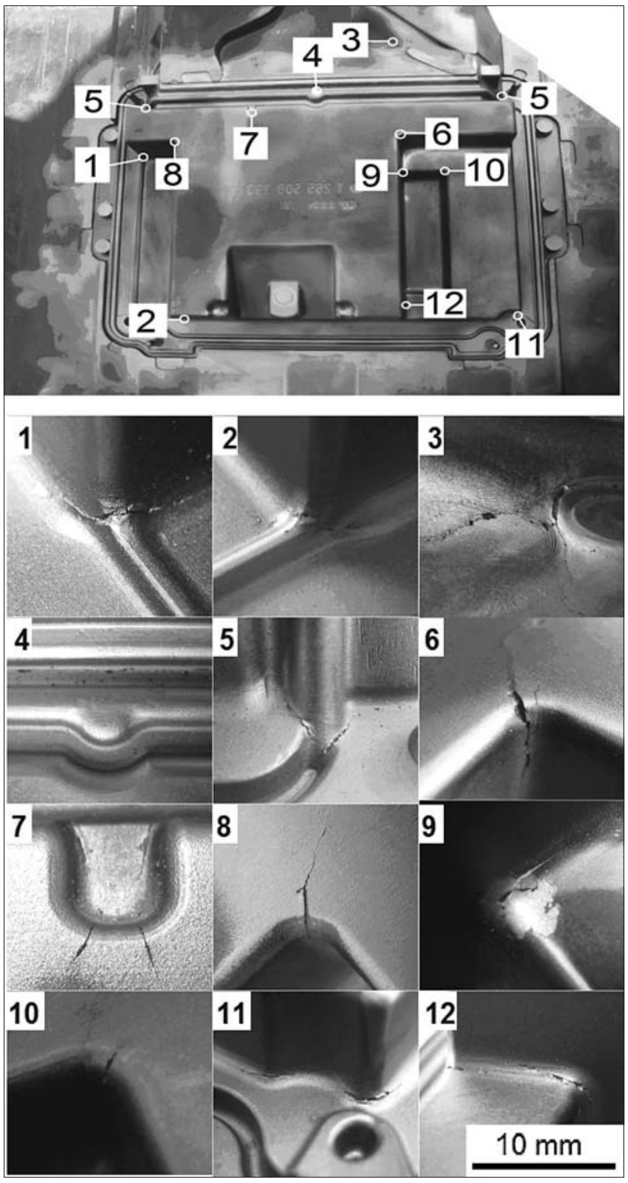

Figure 4. Locations of die surface defects and their detailed photos.

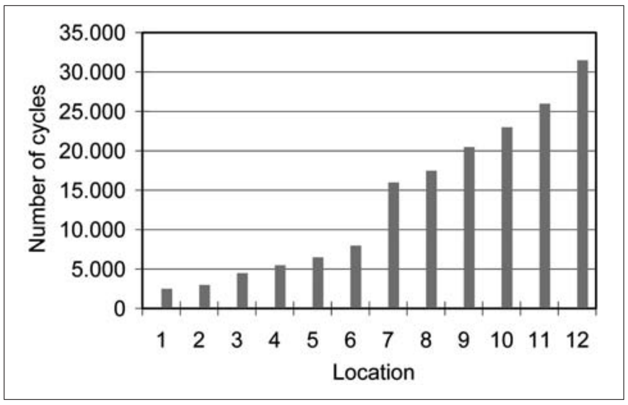

Figure 5. Die defect-crack occurrence (number of cycles).

so that the material between two cracks fell off and the crack widened.

Figure 6 shows mean and maximum crack depth at different locations. Mean values of depth vary from 0,4 mm to 1,9 mm, and the maximum depths from 0,7 mm

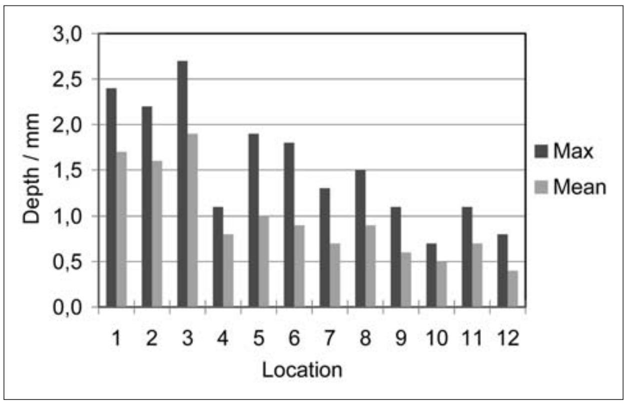

Figure 6. Mean and maximum crack depth and their locations.

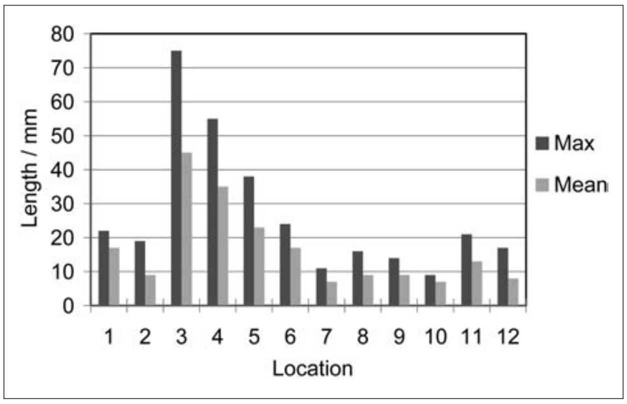

Figure 7. Mean and maximum surface crack length of and their locations.

to 2,7 mm. The deepest cracks occurred at locations 3, 1, 6 and 2 with the maximal depths measured at 2,7 mm, 2,4 mm, 2,3 and 2,2 mm, respectively. The deepest cracks showed a tendency to occur near the die gate, where higher temperature gradients caused higher thermal stresses. The local stress concentrators (corners with small radiuses) additionally raised these stresses, which caused the local accumulation of plastic strain.

Figure 7 shows mean and maximum length of cracks and their locations. Mean values vary from 7 mm to 45 mm and the maximum values from 9 mm to 75 mm. The longest cracks occurred at locations 3, 4, 5 and 6 with the maximal length measured at 75 mm, 55 mm, 38 and 23 mm, respectively.

The longest cracks also tend to occur near the die gate due to higher temperature gradients, which cause higher thermal stresses.

Figure 8 shows typical cross-sections of thermal fatigue cracks (found near the die gate at location 3). Depth of cracks amounts from a few tenths of a millimeter to a few millimeters. The deepest crack reaches the depth close to 3 mm. Width of cracks amounts approximately to 0,1 mm. The width is narrower at the tip of the crack (a few hundredths of a millimeter) and wider on the surface (a few tenths of a millimeter). The larger crack width on the surface is a consequence of melt erosion that causes constant loss of die material.

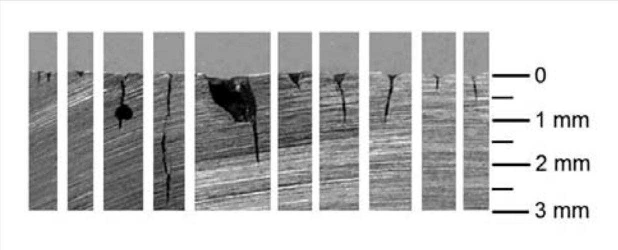

Figure 8. Cross-section of thermal fatigue cracks.

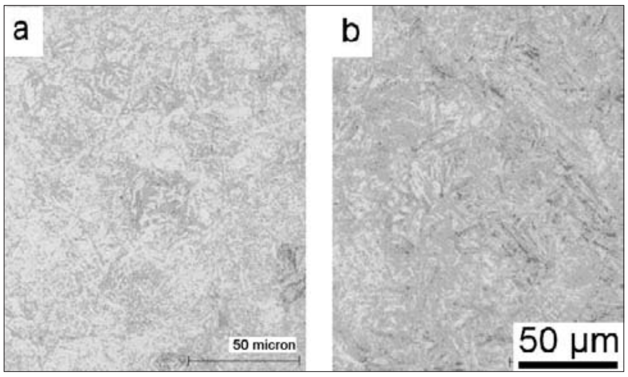

Figure 9. Microstructure of die material: a) near the surface and b) 3 mm below the surface.

The difference between the measured crack depth and its real depth varies from 30 % to 50 %. The reason for this deviation is in the diameter of measuring wires being too large, thus not enabling the crack tips to be reached.

Crack initiation is accelerated by gradual softening of die surface material during operation of the die [9, 11]. This is caused by tempering due to high temperature of aluminium alloy. Figure 9 shows micro-structures of die material near the die surface (Figure 9a) and three millimeters below the die surface (Figure 9b).

The microstructure near the die surface (Figure 9a) has been changed due to high temperature that leads to tempering of the martensite. The tempering of the martensite caused a decrease in hardness by about 130 HV (Figure 10) on the die surface compared to hardness of the die material deeper in the core. Decrease in die material hardness consequently led to decreasing material resistance against thermal fatigue cracking.

CONCLUSIONS

Thermal fatigue cracking is a dominating surface defect of die-casting dies made of aluminium alloy. First cracks occur before 2000 cycles and propagate progressively in subsequent cycles. They occur closer to the die gate, where the temperature gradients are higher due to higher melt temperature. Cracks also occur early on locations with higher stress concentration, i.e. edges and

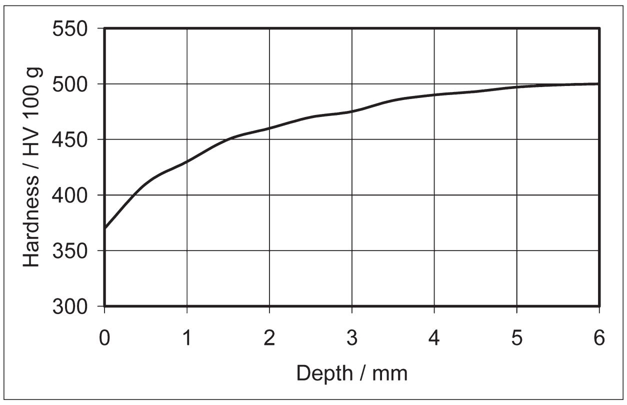

Figure 10. Die material hardness versus depth from surface.

corners with small radiuses. Cracks which occur sooner usually become deeper and longer during subsequent cycles. The observed crack depth ranged from a few tenths of a millimeter up to three millimeters and its length varied from a few millimeters to 75 millimeters.

The die material microstructure near the surface is gradually softening due to intense heating by the molten aluminium alloy. This causes tempering of the martensite and consequently a decrease in hardness. Surface softening increases the initiation of cracks and their further propagation.

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Note: The responsible for English language is Bernarda Kosel.