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Temperature field and failure analysis of die-casting die

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ABSTRACT

Purpose: Dies for aluminium alloys die-casting fail because of a great number of a different and simultaneously operating factors. Some of them may be controlled to some extent by the die-casting experts.

Design/methodology/approach: In the experimental part of our work the failures on the working surface of the fixed half of the testing die for die-casting of aluminium alloys were observed with the use of non-destructive testing methods: such as thermographic analysis, penetrants, and metallographic examination of polymeric replicas.

Findings: In the process of the die-casting the primary source of loading is cyclic variation of the temperature; the influence of other loads is relatively insignificant.

Research limitations/implications: For economical production of aluminium and aluminium alloys die-castings it is important that the dies have a long working life. The replacement of a die is expensive in both: money and production time.

Practical implications: Beside, the die design, the material selection and the process thermal stress fatigue course, which is the consequence of the working conditions, the inhomogeneous and to low initial temperature of the die, contribute to the cracks formation.

Originality/value: It is clearly seen from the presented thermographs, that the required temperatures and homogeneity of the temperature field of the discussed case are not possible to reach without the changing both: the heating method and the die design. Therefore in the first stage a solution of the problem should be in changing of the position of heating and/or cooling channels, i.e. their closer shifting to the working surface of the die.

Keywords: Casting; Aluminium alloys; Die-casting die; Temperature field; Failure analysis

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Die-casting is technical easy and the most economical process of casting very sophisticated and precise aluminium products of big-scale series [1].

Aluminium alloys die-castings are made for final installation, and need very little machining. They are used in automotive industry, household appliences, electrical industry and instalations, fittings, etc. [2].

At the moment approximately half of all castings worldwide made of auminium alloys are manufactured by die-casting [3].

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Table 1.
Comparison of nine parameters of the die-casting vs other processes [2]

	Nine points of comparison	Compared with				
		Stampings	Forgings	Sand castings	Permanent mold castings	Plastic molding
1	Cost	Lower machining	Lower final	Lower production and machining	Lower labor, production and machining	Generally higher
2	Design flexibility	More complex shapes	More complex shapes	Thinner wall sections possible	Thinner wall sections possible, less draft required	Much greater
3	Functional versatility	Better designs possible	More versatile with less machining	More versatile with less machining	More versatile with less machining	Many more uses
4	Tolerances	Closer	Closer	Closer	Closer	Closer
5	Wall thickness	Greater variations	Thinner sections	Thinner sections	Thinner sections	Thinner sections for the same strength
6	Surface finish	Wider variety	Smoother	Smoother	Smoother	Wider variety
7	Material waste	Less	Less	Less	Less	Less
8	Strength	Depends on design	Lower tensile	Greater with same alloy	Greater with same alloy	Much greater
9	Weight	Depends on design	Lighter	Lighter	Less	Less

Comparison of nine parameters of the die-casting versus stamping, forging, sand casting, permanent mold casting and plastic molding is presented in Table 1.

Aluminium die-casting dies fail because of a number of different and simultaneously operating stresses. The stresses are of two basic kinds [4] the first which are created during the manufacturing of the die, and the second which are produced during exploitation process.

For economical production of aluminium alloys die-castings it is important that the dies have a long working life [5-7]. The replacement of a die is expensive in both: money and production time.

The most frequent failures of aluminium alloys die-casting dies can generally be devided into four basic groups [1]:

- heat checking,
- big cracks,
- cracking in corners, sharp radii, or sharp edges, and
- cracking due to wear or erosion.

It is generally agreed that one of the principal causes of termination of die life is heat checking, which occurs through a process of crack initiation and propagation from the thermal stress fatigue induced on a die surface [8-11].

Some of the factors that affect die failures may be controlled to some extent by the die-casting experts (designers, manufacturers and operators). These factors include [12]:

- design,
- materials selection,
- heat treatment,
- finishing operations, and
- handling and use.

2. Dies and materials properties

In the frame of our investigation work a complex analysis of a typical dies for die-casting of aluminium alloys has been carried out. The testing die-casting die is shown in Figure 1.

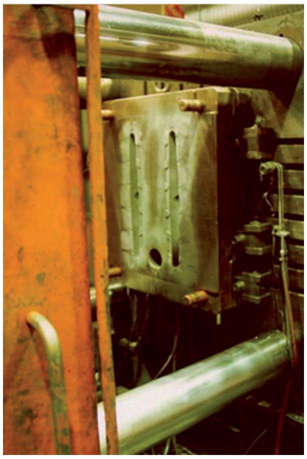

Fig. 1. Fixed half of the testing die-casting die

The die was made from the well known BOEHLER W300 ISODISC [13] hot work tool steel. This steel is mostly applied and considered material for all kinds of hot working tools and dies [14, 15]. The chemical composition of the steel is given in the Table 2.

Thermal and mechanical properties of BOEHLER W300 ISODISC steel are well known. Liquidus temperature of casted aluminium alloy AlSi9Cu3 is approximately 593 ^{o}C, therefore the properties in the temperature interval from the ambient temperature up to approximately 700 ^{o}C are important for the analysis of the discussed case.

Table 2.
Chemical composition of BOEHLER W300 ISODISC steel [12]

Element	C	Si	Mn	Cr	Mo	V
(mass. %)	0.38	1.10	0.40	5.00	1.30	0.40

The density of BOEHLER W300 ISODISC steel at 20 °C is approximately equal of 7800 kg/m^3, and it decreases with higher temperature. Up to the temperature of 700 °C it drops for about 200 kg/m^3. It is very interesting that this steel has temperature dependent relatively low and nearly linear increasing heat conductivity (19.2 to 26.3 W/m·K), and proportionally constant thermal diffusivity (the whole time aproximately $5 \cdot 10^{-6}$ m^2/s). Specific heat is increased with higher temperature to its values of 456 or 587 J/kg·K, respectively for the boundary values of the chosen temperature range. Linear coefficient of elongation slowly increases from $10.7 \cdot 10^{-6}$ /K (at 20 °C) to $13.2 \cdot 10^{-6}$ /K (at 700 °C), while modulus of elasticity, with boundary values of 211 and 168 GPa, decreases with the higher temperature [16].

3. Temperature field analysis

When hot aluminium or its alloy strikes the active working surface of the die, the die expands and then contracts during cooling, as the heat in the casting is conduced into the steel bellow the surface of the die.

The greater difference between the temperature of the die and that of the hot aluminium alloy shot into the die, the greater will be the expansion and contraction of the die surface, and sooner the die surface will be heat check [17, 18]. Since the stresses produced on the die surface are inversely proportional to the die temperature, it is good practice to run the dies as hot as is practical and/or economical [19].

Aluminium alloys die-casting dies should be preheated to approximately 240 to 300 °C. Experiences have shown that by increasing the die operating temperature from 205 to 315 °C, die production may be doubled (see Figure 2) [20].

By thermographic measurements [21, 22] the required intensity and homogeneity of the initial temperature field on the working surface of the fixed die half have been examined. Testing thermographic measurements on the chosen die have been carried out due to the relatively simple geometry of the discussed die, so the simple heat images (thermographs) analysis have been performed.

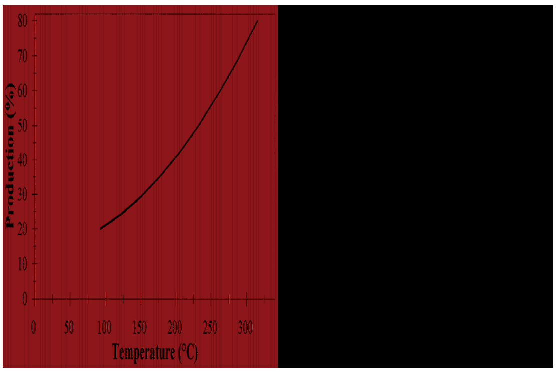

Fig. 2. Hot dies produce more

In comparison with optical pyrometers, which application is limited to the very small surface, investigated object is enabled by thermographic camera. Camera field vision is about 30 ° horizontally and 20 ° vertically. Within that field of vision the temperature image of about 30.000 information points or temperature patterns has been formed by the camera. The geometric resolving power of single details depends on the distance of camera to object.

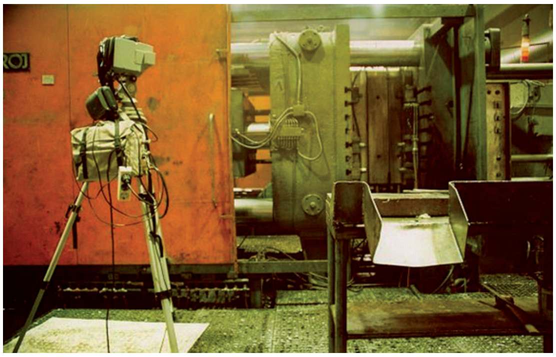

Fig. 3. Position of the thermographic camera and the die-casting machine

On the working surface of the fixed die half thermographic measurements have been carried out in the preheating period of the die heating to its initial operating temperature (240 °C and homogeneous through the whole working surface of the die).

Table 3.
Testing case - cronological flow of the preheating process

Time (hour : min)	Maximal surface temperature (°C)	Operation
00:00		Start of preheating
00:40	91	Start of measurements
00:42		Calibration of thermographic camera
01:00	125	Opening of the die (1)
01:30		Increasing of heating oil flow (for 100 %)
03:10	150	Opening of the die (2)
04:10	161	Opening of the die (3) End of measurements

Checking temperature measurements on the die surface and calibration of the thermographic camera have been carried out using contact Ni-NiCr thermometer. By the contact thermometer the temperature of 61.2 °C was measured at time of 00:42 (Table 3) in the given and marked point on the surface of the fixed half of the die, a few seconds later the thermographic camera (calibrated for the virtual value of emissivity equal 1.0) has been directed to the same point with the virtual temperature of 67.1 °C. The ratio between both measured temperatures was the value of emissivity of $\varepsilon = 0.91$, which was not automatically considered by non-directed thermographic camera. The emissivity has to be determined experimentally before each measurement [23].

Thermographs, shown in Figure 4, are just parts of longer continuous prints. The temperature distribution on working surface of the die-casting die is evidently presented on coloured thermographs. Black and white thermographs have been coloured with sixteen sober colours. Sober transitions between colours more evidently illustrate differences between all temperatures, while the geometric details are less clear.

In Figure 3 course of the die heating is presented with the thermographs – heat images. For each thermograph the time of formation of image print is very important (Table 3). The first thermograph is presented with extended colour scale to be directly comparable to the next two, which were done later, when the surface temperatures of the preheated die have been essentially higher. Only the same temperature range coloured thermographs should be directly compared. Thermographs in Figure 4 are presented in the temperature range between 90 and 161 °C, where black (uncoloured) regions are below 90 °C.

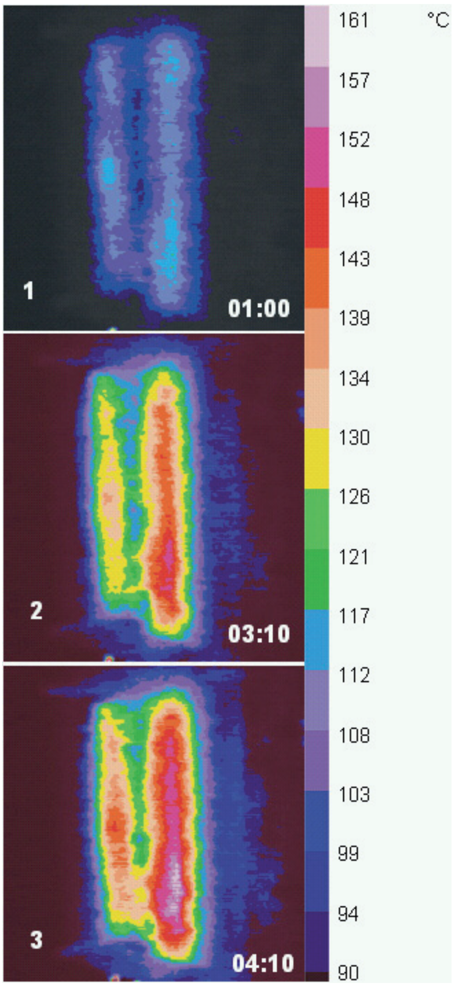

Fig. 4. Working surface of the fixed part of testing die-casting die (see Figure 1, Table 3). Preheating process. Thermographs. At the beginning (1), after approx. 2 hours (2) and at the end (3 – initial temperature field) of the die preheating process

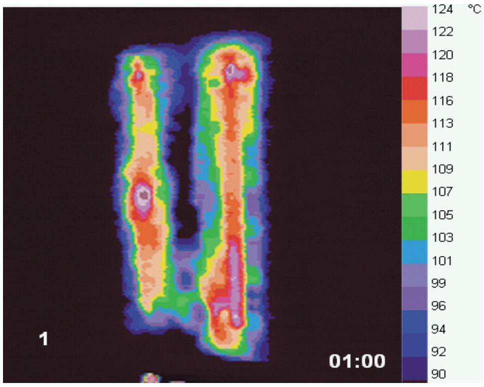

Fig. 5. Working surface of the fixed part of testing die-casting die. At the beginning of preheating process

Thermograph in Figure 5 is the same as the thermograph (1) in Figure 4, but it is presented in the lower temperature range between 90 and 124°C.

In the foundry praxis preheating times of similar dies are much shorter than they should be during our testing (maximally up to two hours). Furthermore the flow of heating oil (with the temperature approximately 250 °C) was increased during our testing measurements after approximately 1 hour from 30 l/min (usually applied in the foundry praxis) to 60 l/min. Regarding to the presented parameters the practical results of preheating of the discussed die can be mostly worse comparing to the results of the testing thermograph measurements.

4. Failure analysis

The cracks which appeared on the working surface of the fixed die half after less than thousand shots were revealed and identified by the use of penetrants. Some of them were also clearly seen by the use of magnifying glass or even by naked eye [24].

In the frame of our experimental work also non-destructive metallographic examination by optical microscopy (OM) and by scanning electron microscopy (SEM) of polymeric replicas was applied [25].

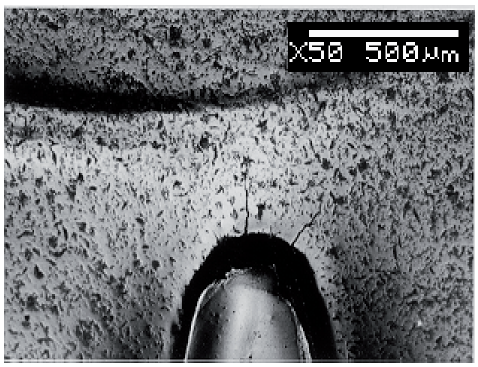

Fig. 6. Working surface of the testing die-casting die. Surface pits and cracks at identification mark. OM

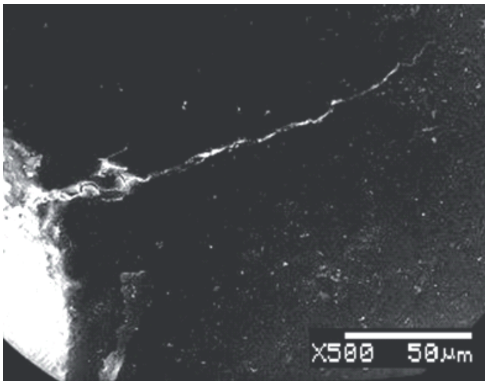

Fig. 7. Working surface of the testing die-casting die. Surface crack and pits. SEM

Readily accessible convex parts of the fixed half of the testing die were polished by fine grade (higher than 500) emery paper and diamond paste and examined by optical microscope. Polymeric foils were used to take imprints from the surface of the prepared spots. The replicas obtained were so sharp that even small details of the surface e.g. microstructure compounds could easily be observed with an optical microscope as well as a scanning electron microscope. High depth of field characteristics of scanning electron microscopy resulted in a sharp three-dimensional image of the observed object. Naturally, concave parts of the die surface, where the first long cracks initiated were not accessible for machine polishing and microscope observation.

The contour lines of letters and numbers of an identification marks are well rounded. However, many cracks started from these signs. Based on the shape and type of propagation they can be attributed to heat checking (see Figures 6 and 7). Crack lengths are within 20 to 200 μm range.

5. Conclusions

Cracking on/in die-casting dies for aluminium alloys is caused by a number of different and simultaneously operating factors. Some of them that affect die failures may be controlled to some extent by the die-casting experts.

Beside, the die design, the material selection and the process thermal stress fatigue course, which is the consequence of the working conditions, the inhomogeneous and to low initial temperature of the die, contribute to the cracks formation.

The die failures: cracks and pits observed on the working surface of the testing die-casting die belong to heat checking initiated at identification marks, and cracking in corners, sharp edges and transitions.

It is clearly seen from the presented thermographs, that the required temperatures and homogeneity of the temperature field of the discussed case are not possible to reach without the changing both: the heating method and the die design.

In the process of the die-casting the primary source of loading is cyclic variation of the temperature; the influence of other loads is relatively insignificant. Therefore in the first stage a solution of the problem should be in changing of the position of heating and/or cooling channels, i.e. their closer shifting to the working surface of the die, so the higher and more homogeneous heating should be reached.

Additional information

The presentation connected with the subject matter of the paper was presented by the authors during the 12th International Scientific Conference on Contemporary Achievements in Mechanics, Manufacturing and Materials Science CAM3S'2006 in Gliwice-Zakopane, Poland on 27th-30th November 2006.

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