**B. KOSEC**

ISSN 0543-5846
METABK 47(1) 51-55 (2008)
UDC – UDK 621.74.043:669.71=111

# FAILURES OF DIES FOR DIE-CASTING OF ALUMINIUM ALLOYS

Received – Prispjelo: 2006-12-23
Accepted – Prihvaćeno: 2007-04-20
Preliminary Note – Prethodno priopćenje

Die-casting dies for casting of aluminum alloys fail because of a great number of different and simultaneously operating factors. Material selection, die design, and thermal stress fatigue generated by the cyclic working process (heat checking), as well as to low and inhomogeneous initial die temperature contribute to the failures and cracks formation on/in dies for die-casting of aluminium alloys. In the frame of the presented investigation work the intensity and homogeneity of the temperature fields on the working surface of the testing die were checked through thermographic measurements, and failures and cracks on the working surface of the die were analysed with non-destructive metallographic examination methods.

*Key words:* die-casting, working surface, aluminium alloy, temperature field, failure analysis

**Oštećenje kalupa za lijevanje aluminijskih legura.** Do oštećenja kalupa za lijevanje aluminijskih legura dolazi zbog istodobnog utjecaja brojnih različitih radnih čimbenika. Kod kalupa za lijevanje aluminijskih legura izbor materijala, konstrukcija kalupa, zamorno termalno naprezanje zbog cikličkog radnog procesa te niska i nehomogena polazna temperature kalupa doprinose oštećenju i nastajanju pukotina. U okviru ovog istraživanja kontroliran je intezitet i homogenost temperaturna polja na radnoj površini ispitanog kalupa pomoću termografskih mjerenja, a oštećenja i pukotine na radnoj površini analizirani su nedestruktivnim metalografskim metodama.

*Ključne riječi:* lijevanje u kalup, radna površina, aluminijska legura, temperaturno polje, analiza oštećenja

## INTRODUCTION

Die-casting is the most cost efficient and technical easy method of casting sophisticated and accurate aluminium alloys parts in great-scale series [1]. Aluminium alloys die-castings require little machining prior the final installation.

Approximately half of all castings worldwide made of aluminium alloys are manufactured in this way are used for a wide range of automotive parts and other consumer goods [2]. The comparison of nine parameters of the die-casting versus stamping, forging, sand casting, permanent mold casting and plastic molding [3] is presented in Table 1.

Aluminium alloys die-casting dies fail because of a number of different and simultaneously operating stresses. The stresses are of two basic kinds [4]: stresses created by the manufacturing of the die and stresses formed by the exploitation process.

A long die working life is of essential importance for the economical production of aluminium alloys die-castings [4,5]. 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 divided into four basic groups [1]: heat checking, corner cracking, sharp radii or sharp edges cracking, 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 induced by the thermal stress fatiguing of a die surface [6-8].

Some of the factors that affect die failures may be controlled to some extent by the die-casting experts (designers, manufacturers and operators) [9]. These factors include [10]:

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

## TESTING OF DIE-CASTING DIES

In the frame of our investigation work a complex analysis of a typical dies for die-casting of aluminium alloys has been carried out [11]. The whole die-casting machine is shown in Figure 1, and the fixed half of the testing die-casting die is in Figure 2.

---

B. Kosec, Faculty of Natural Sciences and Engineering, University of Ljubljana, Ljubljana, Slovenia

Table 1. **Comparison of nine parameters of the die-casting and other processes** [3]

| | Compared with | | | | |
|---|---|---|---|---|---|
| Nine points of comparison | 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 |

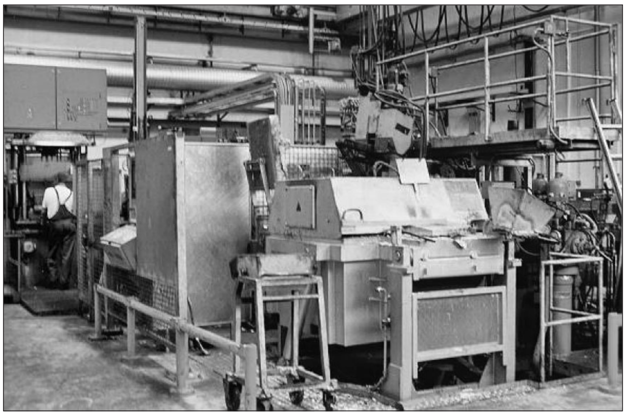

**Figure 1.** Die-casting machine

The hot work die steel must have excellent properties [12]. Requested properties and damage mechanisms of the die material are shown in Table 2 [13].

The testing die was manufactured from the BOEHLER W300 ISODISC [14] hot work tool steel, which is widely used for all kinds of hot working tools and dies.

The thermal and mechanical properties of BOEHLER W300 ISODISC steel are given by the producer. The liquidus temperature of casted aluminium alloy AlSi9Cu3 is approximately of 593 °C, and casting temperature is approximately 50 °C higher, therefore the properties in the temperature interval from the ambient temperature up to approximately 700 °C are important for the analysis of the discussed case.

The density of BOEHLER W300 ISODISC steel at ambient temperature (20 °C) is approximately 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$^3$. This steel has a relatively low and nearly linear increasing temperature dependent heat conductivity (from 19,2 to 26,3 W/mK), and proportionally constant thermal diffusivity (the whole time it is approximately of $5 \cdot 10^{-6}$ m$^2$/s). Specific heat is increased with higher temperature and it is from 456 to 587 J/kgK, respectively, for the boundary values of the chosen temperature range. The 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 the modulus of elasticity, with boundary values of 211 and 168 GPa, decreases with the increase of temperature.

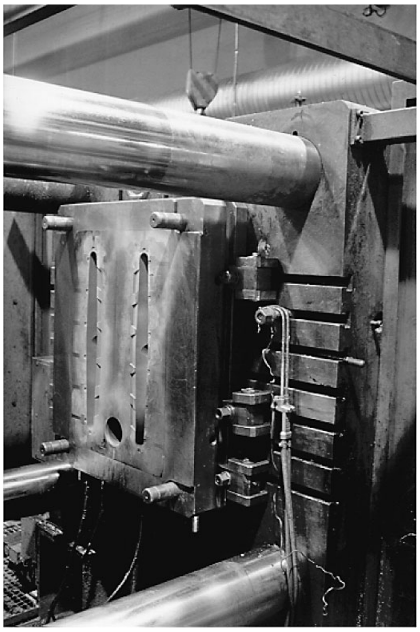

**Figure 2.** Fixed half of the testing die-casting die

## TEMPERATURE MEASUREMENTS AND ANALYSIS

When the melts wets the die active working surface the die expands and then contracts as the surface temperature is lowered by the diffusion of heat into the steel be-

Table 2. **Damage mechanisms and requested properties of die material**

| Damage mechanism | | Requested property |
|---|---|---|
| High mechanical loading | | High hardness<br>Suitable fracture toughness |
| High mechanical loading at elevated temperatures | | High hot hardness<br>High thermal stability of the microstructure |
| Repeated mechanical loading (fatigue) | | High hardness<br>High fatigue resistance<br>Fine microstructure<br>Low content and small size of internal defects |
| Wear | Abrasion | High hardness<br>High volume fraction, optimum size and distribution of hard wear resistant particles |
| | Adhesion | High hardness<br>Oxide layer at the surface<br>Low chemical reactivity between tool and work material |
| | Surface fatigue | High hardness<br>High fatigue resistance |
| High temperature | | High thermal stability of the microstructure<br>High oxidation resistance |
| Thermal cycling | | High thermal stability of the microstructure<br>High hardness at elevated temperatures<br>High creep resistance<br>High resistance against plastic cycling<br>Low thermal expansion<br>High oxidation resistance |

low the surface of the die [15]. 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 show the effect of heat checking [16].

Since the stresses produced on the die surface are inversely proportional to the die temperature, it is good practice to keep the dies as hot as it is economical. Aluminium alloys die-casting dies should be preheated to approximately 240 to 300 °C. Experience has shown that by increasing the die operating temperature from 205 to 315 °C, die production may be doubled [17].

The required intensity and homogeneity of the initial temperature field on the working surface of the fixed die half was examined with thermographic measurements [18,19]. The testing thermographic measurements were carried out on a die of relatively simple geometry and simple thermographs (heat images) were obtained.

In comparison with optical pyrometers, which application is limited to the very small surface, investigated object is enabled by thermographic camera (Figure 3). Camera field vision is of about 30 ° horizontally and of 20 ° vertically. Within that field of vision the temperature image of about 30.000 information points on temperature were obtained with the camera. The geometric resolving power of single details depends on the distance of camera to object.

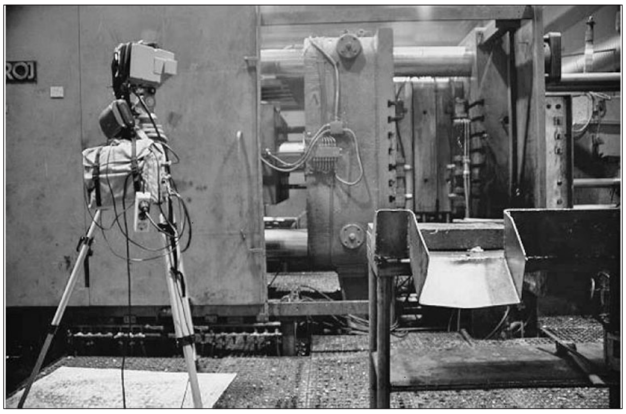

**Figure 3.** Position of the thermographic camera

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

Checking temperature measurements on the die surface and calibration of the thermographic camera have been carried out using a contact Ni-NiCr thermocouple and the temperature of 61,2 °C was measured at time of 42 min (Table 3) in the marked point on the surface of the fixed die half. A few seconds later not calibrated thermographic camera (with the virtual value of emissivity equal 1,0) was centered to the same point with the virtual temperature of 67,1 °C. The ratio between both measured temperatures represents the value of emissivity of $\varepsilon = 0,91$. The emissivity has to be determined experimentally before each measurement.

Thermographs, shown in Figure 4, are just parts of longer continuous prints. The temperature distribution on working surface of the die-casting die is shown by the colour on the thermographs. Black and white thermographs have been coloured with sixteen distinct colours. Distinct transitions between colours show the difference in temperature, while the geometric details are less clear.

For each thermograph, the time of formation of image print is very important (Table 3). The first thermograph on the left is presented with extended colour scale to be directly comparable to the second which was done later, when the surface temperatures of the preheated die was significantly higher. Only the same temperature range coloured thermographs can be directly compared.

Thermographs (left) in Figure 4 are presented for the temperature range of 90 to 161 °C, with black (uncoloured) regions below 90 °C. Right thermograph is the same as the left thermograph (1), but it is presented in the lower temperature range between 90 and 124 °C.

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

| **Operation** | **Time / min** | **Maximal surface temperature / °C** |
|---|---|---|
| Start of preheating | 0 | – |
| Start of measurements | 40 | 91 |
| Calibration of thermographic camera | 42 | – |
| Opening of the die (1) | 60 | 125 |
| Increasing of heating oil flow | 90 | – |
| Opening of the die | 190 | 150 |
| Opening of the die (2)<br>End of measurements | 250 | 161 |

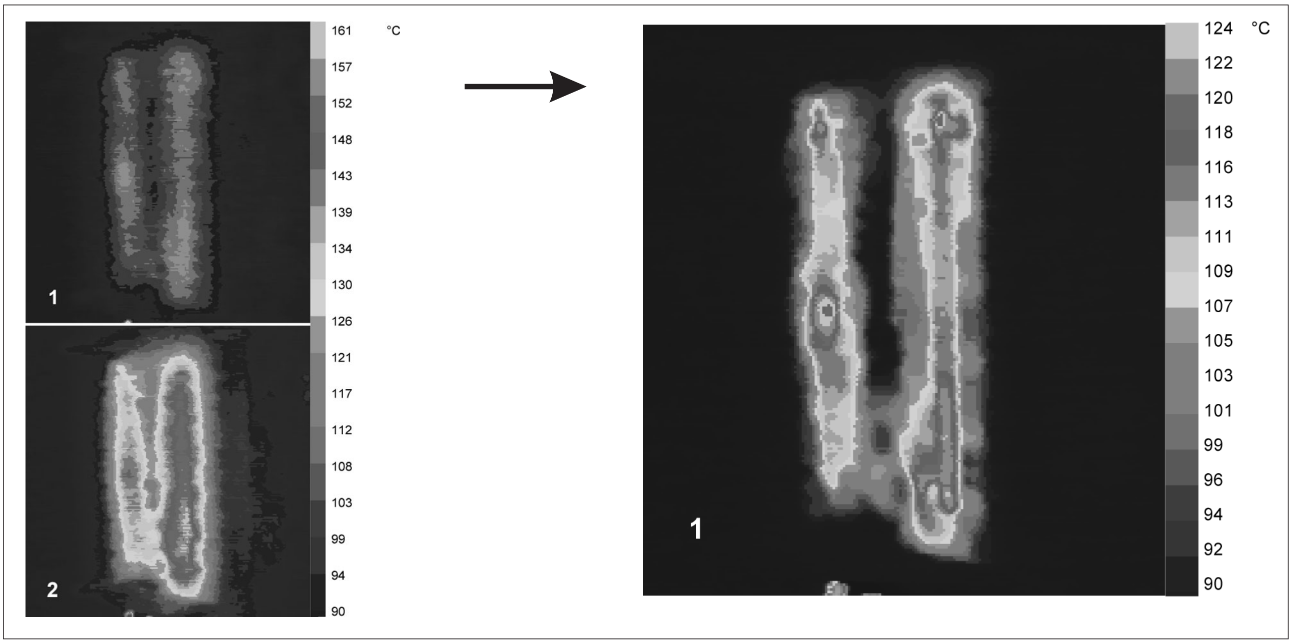

**Figure 4.** Working surface of the fixed part of testing die-casting die (Figure 1 and Table 3). Preheating process. Thermographs. At the beginning (1), and at the end (2 – initial temperature field) of the die preheating process

In the foundry praxis the preheating time is for similar dies much shorter than it was by our tests (maximally up to two hours). Furthermore, the flow of heating oil (with the temperature approximately 250 °C) was increased during our test measurement after approximately 1 hour from 30 l/min (in the foundry praxis usually applied) to 60 l/min (for 100 %).

## FAILURE ANALYSIS

The cracks appeared on the working surface of the fixed die half after less than thousand shots were revealed and identified with penetrants. Some of them were also clearly seen by the use of magnifying glass or even by visual observation. In the frame of our experimental work also non-destructive metallographic examination by optical microscopy (OM) and by scanning electron microscopy (SEM) of polymer replicas was applied [20].

Readily accessible convex parts of the fixed half of the testing die were polished with fine grade (higher than 500) emery paper and diamond paste and examined in optical microscope. Polymeric foils were used to take imprints from the surface of the prepared spots [21]. The replicas obtained were so sharp that even small details of the surface e.g. microstructure constituents 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 [22]. Naturally, concave parts of the die surface, where the first long cracks initiated, were not accessible for machine polishing and microscope observation.

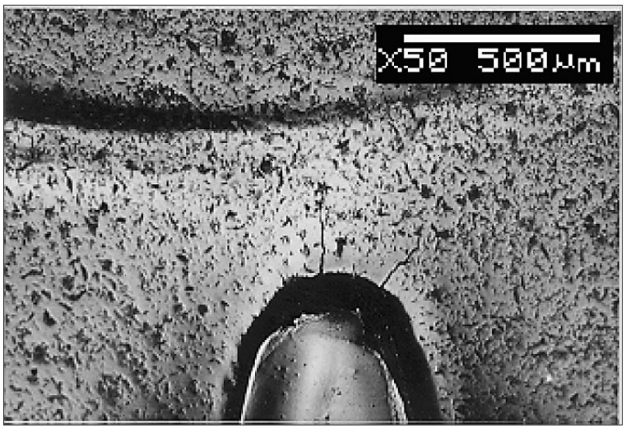

**Figure 5.** Working surface of the testing die-casting die. Surface pits and cracks at identification marks. OM

The contour lines of letters and numbers of an identification marks are well rounded. However, many cracks started from these signs and their lengths are within 20

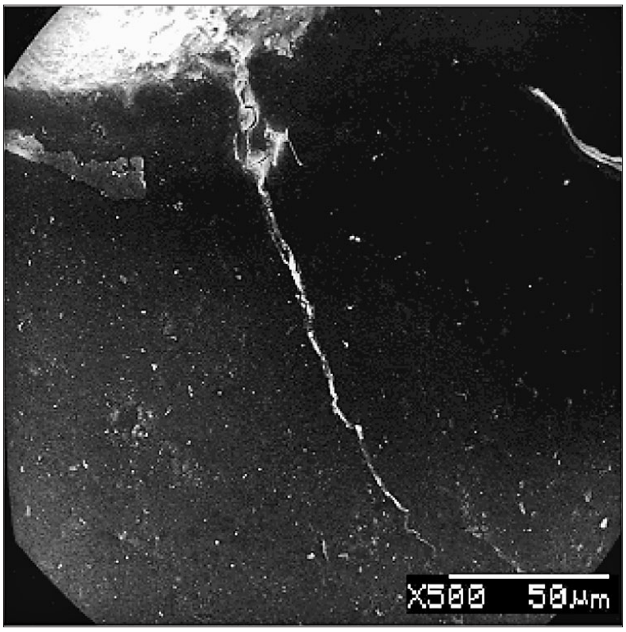

**Figure 6.** Working surface of the testing die-casting die. Surface crack and pits. SEM

to 200 $\mu$m range [23]. Based on the shape and type of propagation they can be attributed to heat checking (Figures 5 and 6).

## CONCLUSIONS

Cracking on/in die-casting dies of 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.

The 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 changing of 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.

## REFERENCES

[1] S. Kalpakjian, Tool and Die Failures - Source Book, ASM International, Metals Park, Ohio, 1982.

[2] R.M. Lumley, R.G. O'Donnel, D.R. Gunasegaram, M. Girord, Heat Treating Progress, 6 (2006) 5, 31 – 37.

[3] S.S. Manson, Thermal Stress and Low-Cycle Fatigue, McGraw – Hill, New York, 1996.

[4] L.A. Dobrzanski, Technical and Economical Issues of Materials Selection, Silesian Technical University, Gliwice, 1997.

[5] K. Strauss, Applied Science in the Casting of Metals, Pergamon Press, Oxford, 1970.

[6] J.V. Tuma, J. Kranjc, Forschung in Ingenieurwessen – Engineering Research, 66 (2001) 4, 153 – 156.

[7] L. Kosec, F. Kosel, Mechanical Engineering Journal, 29 (1983) 7-9, 151 – 158.

[8] B. Smoljan, Journal of Materials Processing Technology, 155 (2004) 11, 1704 – 1707.

[9] P.F. Timmins, Fracture Mechanisms and Failure Control for Inspectors and Engineers, ASM International, Materials Park, Ohio, 1995.

[10] Handbook of Case Histories in Failure Analysis, Volume 1, ASM International, Materials Park, Ohio, 1992.

[11] B. Kosec, Metalurgija, 45 (2006) 3, 217.

[12] I. Vitez, Ispitivanje mehaničkih svojstava metalnih materijala, Sveučilište J.J. Strossmayera u Osijeku, Strojarski fakultet u Slavonskom Brodu, Slavonski Brod, 2006.

[13] R. Ebner, H. Leitner, F. Jeglitsch, D. Caliskanoglu, Proceedings of 5th International Conference on Tooling, Leoben, (1999) 3 – 12.

[14] Böhler Edelstahlhandbuch auf PC V2.0, Kapfenberg, 1996.

[15] B. Kosec, G. Kosec, Metall, 57 (2003) 3, 134-136.

[16] L. A. Dobrzanski, M. Krupinski, J.H. Sokolowski, Journal of Materials Processing Technology, 167 (2005) 2-3, 456 – 462.

[17] B. Kosec, G. Kosec, M. Sokovic, Journal of Achievements in Materials and Manufacturing Engineering, 20 (2007) 1-2, 471 – 475.

[18] L. Masalski, K. Eckersdorf, J. McGhee, Temperature Measurement, John Wiley & Sons, Chichester, 1991.

[19] H. Haferkamp, F.W. Bach, M. Niemeyer, R. Veits, Aluminium, 75 (1999) 11, 945 – 953.

[20] B. Kosec, M. Sokovic, G. Kosec, Journal of Achievements in Materials and Manufacturing Engineering, 13 (2005), 339 - 342.

[21] R. Celin, J. Tusek, D. Kmetic, J.V. Tuma, Materials Science and Technology, 35 (2001) 6, 405 – 408.

[22] I. Anzel, Metalurgija, 39 (2000) 3, 237 - 241.

[23] B. Kosec, J. Kopac, L. Kosec, Engineering Failure Analysis, 8 (2001) 4, 355 – 359.

**Note:** English language lecturer: Bernarda Kosel, Faculty of Mechanical Enginering, University of Ljubljana, Ljubljana, Slovenia