Influence of the thermomechanical and thermophysical material properties on the thermal-fatigue behaviour of hot-work tool steels, employing a pulsed-laser testing system

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Summary

The damage of tool surfaces due to cyclic thermal loads results from a very complex loading situation which is described by many different parameters. These are, in particular, the die-casting process parameters, the significant die geometry influences and the thermomechanical and thermophysical properties of the hot-work tool steel used.

To quantify the thermal-fatigue stability of different hot-work tool steels, a substantial investigation program was carried out using a cyclic-laser testing facility. To prevent oxidation, the disk-shaped specimen was tested in a vacuum chamber using a pulsed 1.8 kW-diode laser as a heating source. The specimen was pre-heated to achieve temperature cycles similar to the thermal cycles experienced in manufacturing tools. Maximum surface temperatures of about 550 to 600°C were achieved in the experiments due to the different thermal conductivities of the tool steel materials used. A pulse duration of 5 sec was chosen. The experiments were carried out using different 5%-chromium hot-work tool steels, the standard steels used in many hot-work applications. The thermal fatigue behaviour of the materials was characterised by noting the number of cycles to form a crack network and the crack length at different numbers of cycles. It was found that thermal-fatigue stability is primarily influenced by the thermal conductivity, the thermal stability and the mechanical strength and ductility levels. Different optimised parameter combinations are required depending on the different cyclic thermal loads of the various hot-work processes.

Key words: Thermal Fatigue, Hot-Work Tool Steel, Vacuum-Arc Remelting, Thermal Conductivity, Toughness, Diode Laser

1. Introduction

The two main reasons for catastrophic failure of a die-casting die are gross cracking and thermal fatigue. While gross cracking is often caused by overloading, due to geometric stress concentrations or an inappropriate heat treatment, the initiation and propagation of thermal-fatigue cracks are complex processes which depend on the loading situation during die-casting and the material parameters of the die-casting die.

The most important materials properties required to resist thermal fatigue are [1]:

- a high hot yield strength to avoid or reduce the plastic deformation;
- a high temper-resistance, to keep the hardness;
- a high ductility to resist plastic deformation;
- a high thermal conductivity to reduce high peak temperatures and temperature gradients.

Fig. 1: Thermal-fatigue crack network on a die-casting die surface after approx. 110,000 cycles.

2. The die casting process

To obtain information about the thermal and thermo-mechanical load conditions in tools during the die casting process, an extensive finite element simulation of the filling and solidification processes is required. An example of the simulation results for an aluminium gearbox is given in Figure 2.

After filling, the temperature at the tool surface increases rapidly, which can lead to a maximum temperature at the surface of cores of between 500 and 600°C. After solidification, the die is opened and the component is removed. During the spraying and ejection process, the surface temperatures decrease significantly, and a temperature gradient of around 350°C can occur. At the end of the casting cycle the die is closed and a period of heat homogenisation follows. The maximum surface temperatures and temperature gradients that occur in the depth of the material, and which determine the thermal loads of the die, are affected by the casting parameters such as the melt temperature and casting velocity, and significantly affected by the thermo-physical material parameters such as the thermal conductivity and specific heat of the hot work tool steel used.

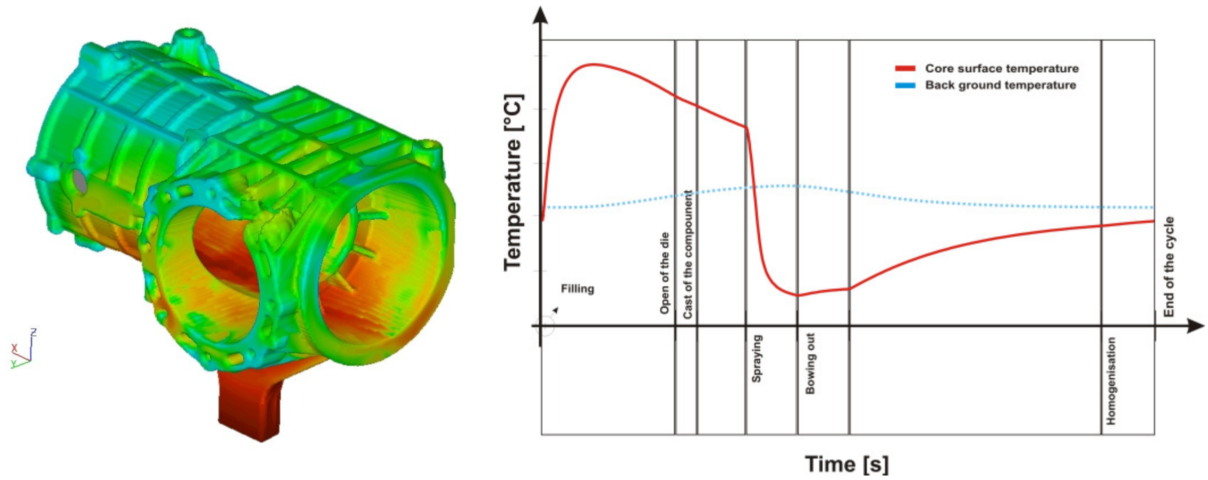


Fig. 2: Example of an FEM simulation of the die casting of a gearbox: solidification process and temperature distribution on the tool surface

3. Die-casting die materials

In addition to those mentioned above, the main material parameters which promote resistance to thermal fatigue damage are a high toughness and ductility level, a good thermal stability and a high thermal conductivity. Over the last few years, new hot work tool steel grades with a homogeneous microstructure, high cleanliness and consequently excellent mechanical properties have been realised using production routes such as electro-slag remelting (ESR) or vacuum-arc remelting (VAR). A list of different hot work steel tool steels with these improved material properties is given in Table 1.

Böhler name	DIN name	C [%]	Si [%]	Mn [%]	Cr [%]	Mo [%]	V [%]	Toughness, ductility	Thermal stability	Thermal conductivity
1.2343 ESR	1.2343	0.38	1.1	0.40	5.0	1.3	0.4	↑↑	↑↑	↑
W400 VMR	~1.2343	0.36	0.2	0.25	5.0	1.3	0.5	↑↑↑	↑↑	↑↑↑
W303 ISOBLOC	1.2367	0.38	0.4	0.40	5.0	2.8	0.5	↑↑	↑↑↑	↑↑
W403 VMR	~1.2367	0.38	0.2	0.25	5.0	2.8	0.7	↑↑↑	↑↑↑	↑↑↑

Tab. 1: Nominal chemical compositions of different hot work tool steels. ISOBLOC materials are electro-slag remelted (ESR), VMR materials are vacuum-arc remelted [2,3].

4. Thermal fatigue investigations

To quantify the heat-checking resistance of the 4 different hot work tool steels, a new thermal-fatigue testing rig with a diode laser was used, see Fig. 3.

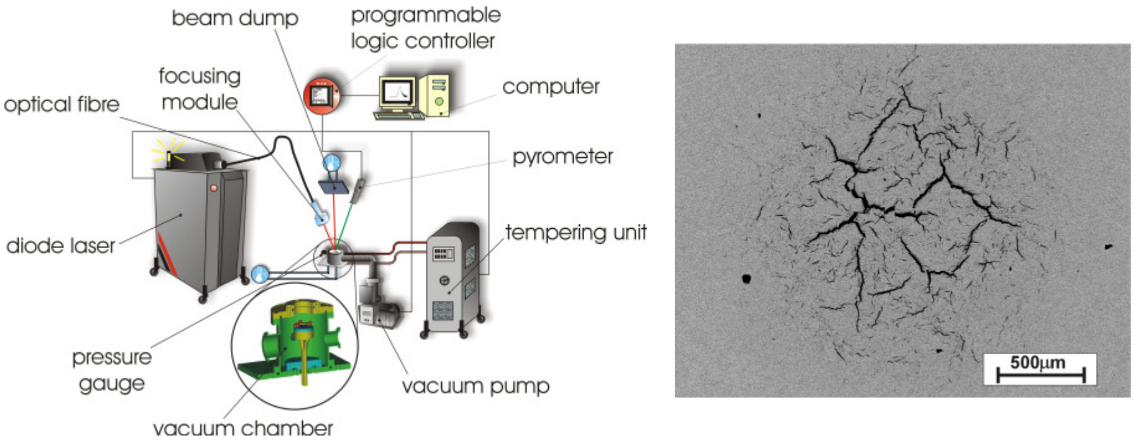
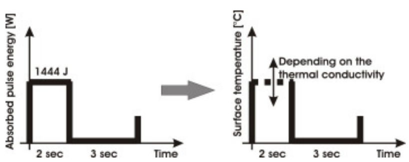


Fig. 3: Thermal-fatigue testing rig used to investigate the heat-checking resistance of different tool steel materials and an example of the thermal-fatigue crack network on a hot-work tool steel surface (DIN-Nr. 1.2343) after 10,000 cycles.

A disk-shaped specimen is tested in a vacuum chamber to prevent oxidation of the heated surface. All tests are carried out under vacuum at a pressure lower than $3*10^{-6}$ mbar. So no significant oxidation is observed even after the longest testing time of 24 hours. The sample is fixed mechanically onto a temperature-controlled copper mounting system, which is kept at a constant temperature of 180°C for all tests. The surface is heated cyclically using a pulsed diode laser beam with a maximum power of about 1.8 kW. All tests are performed at a pulse duration of 2 s and a cooling time of 3 s. The laser radiation is guided onto the specimen via an optical fibre, a focussing unit and a transparent window.

Böhler name	DIN name	Pulse shape	Pulse energy	Max. surface temperature	Background temperature	ΔT
1.2343 ESR	1.2343		1444 J	600 °C	180 °C	420°C
W400 VMR	~1.2343			555 °C		375°C
W303 ISOBLOC	1.2367			580 °C		400°C
W403 VMR	~1.2367			550 °C		370°C

Tab. 2: maximum surface temperature and temperature gradients arising during thermal cycling for the different hot-work tool steels investigated.

A circular area with a diameter of about 6 mm is irradiated. The laser radiation reflected is absorbed in a water-cooled beam dump. The temperature in the interaction zone is controlled by a pyrometer with an operating range of 250 to 1300 °C and a response time of 15 µs. A spectral filter in the optical system of the pyrometer prevents the unwanted effects of reflected and scattered laser radiation. An oscilloscope is used to display the thermal cycles and to provide an interface to a PC. A single pulse energy level was chosen for all thermal-fatigue damage simulations to achieve maximum surface temperatures of 600 °C in the DIN-Nr. 1.2343 ESR material. A comparison of the maximum surface temperatures arising due to the different thermal conductivities is shown in Tab.2. The specimens were tested in a quenched and tempered condition at two hardness levels, 44 to 46 HRc and 48 to 50 HRc.

5. Results

The results, after 11,000 cycles, of the thermal fatigue tests of the different hot work tool steel grades are given in Fig. 4.

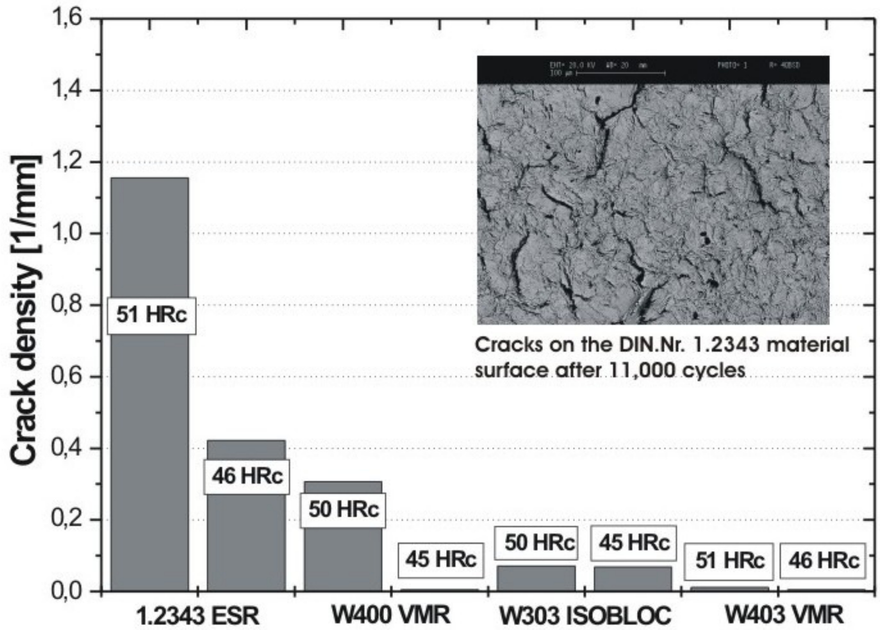


Fig. 4: crack density measured on the surface of different hot work tool steels after 11,000 cycles.

Two main results were found. Firstly, the crack density after 11,000 temperature cycles is minimized due to the higher thermal conductivity, which affects the maximum surface temperature significantly between 550 and 600°C (see Tab. 2), and the excellent toughness, ductility and thermal stability of W400 VMR and W403 VMR

Secondly, a lower hardness of 45 to 46 HRc, and consequently higher toughness, leads to a higher heat-checking resistance.

5. Conclusions

Heat checking is one of the main reasons for tool damage in die-casting processes. To prevent or reduce thermal-fatigue crack networks on the tool surface, an optimised combination of different thermo-mechanical and thermo-physical material parameters is required, e.g. a high, thermally stable hot yield strength, good toughness and ductility levels and a high thermal conductivity.

This can be achieved by an intelligent alloying concept in combination with modern production processes such as vacuum-arc remelting. Heat checking damage can be minimized, as demonstrated by investigations carried out on W400 and W403 VMR from Böhler Edelstahl using a new thermal-fatigue testing rig.

6. References

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