PREDICTION OF MECHANICAL, STRUCTURAL AND INTERNAL-STRESS PROPERTIES OF AUTOMOTIVE CASTINGS

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SUMMARY

This paper describes the experimental and simulation methods applied in the testing of a gravity-poured ductile-iron casting, called cylinder head cover for cars. Prediction of tensile strength, combined with measuring the speed of ultrasound waves, leads to very good results that are applicable in practice. Analyses of the microstructure of cylinder head covers show that the contents of pearlite and ferrite correspond with the values acquired by simulation. The values specifying the number of graphite particles per 1 mm² of material correspond with the values measured. By measuring internal stress with the aid of strain gauges and subsequently by simulation, the technician and design engineer can verify the effectiveness of heat treatment and test dangerous parts of a casting from the perspective of internal stress.

Key words: experimental measurement of temperature field, internal stresses, ductile iron, computer simulation

1. INTRODUCTION

Nowadays, as the demand for quality products continues to grow, while the period of product development and testing of new components in the foundries needs to be shortened, it is increasingly necessary to use sophisticated computer

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technology and special software which enable designers to perform computer simulations of the technological processes involved in casting.

The complexity of founding processes calls for work with a large number of data that vary with time, temperature, and chemical composition. The thermophysical data used in simulation must precisely copy the physical behaviour of casting alloys in both the liquid and the solid phase, thus ensuring accuracy in the calculation of the simulation process. Unfortunately, most of the required thermophysical data on casting alloys and casting moulds are not sufficiently exact. In order to define these thermophysical parameters more precisely, it is necessary to carry out numerous experimental measurements and perform corrective adjustments to these parameters. This is one of the steps to optimize casting results and predict structural and mechanical properties [1].

2. EXPERIMENTAL WORK

The following ductile iron castings were cast from a regular melt of the foundry of ŠKODA AUTO a.s. Mladá Boleslav: two cylinder head covers (Fig. 1) and a ridge block (Fig. 2). Their chemical composition and mechanical properties are specified in Table 1. The following measurements were taken on the first cylinder head cover: temperature field (points T4 and T5) and internal stress, points M1, M2, and M3 (Fig. 4). Stress-relief annealing thermally treated the second casting, whereupon the internal stress was measured at the said points. The pouring input parameters were: pouring temperature = 1 430°C, mould temperature = 20°C, mould filling time = 12 s.

A sand mould was used, specifically, a synthetic bentonite mixture at the following ratio – sand: bentonite : water = 100:7:4. A ceramic filter measuring 50x50x10 mm was placed under the gate peg. Simultaneously, a casting of the ridge block was poured (Fig. 2) of the same material; two thermocouples were placed into the casting at a depth of 100 mm, as follows: 1st thermocouple T1 lies in the middle of the casting, 2nd thermocouple T2 lies 5 mm from the surface.

The following mechanical properties of the ridge block were measured in the metallographic laboratory of ŠKODA AUTO a.s.: hardness, strength, structure (Tab. 1). The structure was analyzed at 4 points: t1, t2, t3, t4 (Fig. 2).

3. SIMULATION OF THE CASTING OF A CYLINDER HEAD COVER

In order to optimize the casting of the cylinder head cover (Fig. 1) a computer simulation of the casting, using the MAGMAsoft, as well as experimental casting were performed. Fig. 1 shows the location of the thermocouples at points T4 and T5. For the measurement of temperature field, type K (NiCr-Ni) sheathed thermocouple probes were used (sheath diameter 1.5 mm). A DaqBook 100 analog
Table 1: Mechanical properties, chemical composition, and structure of the ridge block
Tabela 1 Własności mechaniczne, skład chemiczny i struktura bloku.

<table>
<thead>
<tr>
<th></th>
<th>t1, t2</th>
<th>t3, t4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_m$ [MPa]</td>
<td>420 - 431</td>
<td>412 - 421</td>
</tr>
<tr>
<td>HB [5/750]</td>
<td>161 - 166</td>
<td>162 (t3), 166 - 168 (t4)</td>
</tr>
<tr>
<td>Structure</td>
<td>t1: ferrite-pearlite, 10-20%P</td>
<td>t3: ferrite-pearlite, 20-30%P</td>
</tr>
<tr>
<td>Chemical composition</td>
<td>C = 3.74; Mn = 0.265, Si = 2.69; P = 0.03; S = 0.012; Cr = 0.045; Ni = 0.031; Mg = 0.018; Cu = 0.117</td>
<td></td>
</tr>
</tbody>
</table>

To digital converter with the DBK 19 high-accuracy thermocouple card of the firm OMEGA was used to digitize the signal. The temperature values measured were currently saved in the data file on a PC disk by means of the DaqView 7.0 software. Thermocouple T4 was set 20 mm deep, 5 mm from the wall; T5 was set 35 mm deep in the middle of the wall (see Fig. 1). These are the actual depths of the thermocouples, which were located such as to enable us to follow the solidification process of both the thicker and the thinner walls. A comparison of the curves acquired experimentally and those acquired by simulation shows Fig. 3.

From the perspective of stress in operation, much emphasis is put on the mechanical properties of castings (Fig. 1). The simulation of casting was therefore calculated for minimum tensile strength, hardness HB, degree of ductility, and pearlite and ferrite in the cylinder head cover.

For a comparative evaluation of the simulated values with the actual mechanical properties, we chose to compare ultrasound speeds $V_L = f(R_m)$. It should be noted that the values of the mechanical properties acquired from the ridge block merely give us an idea about the actual values in the casting (different rate of cooling, different wall thickness, different solidification).

In the two cylinder head covers the speed was measured of ultrasound passage in locations 1 to 16 (Fig. 4). The measuring points were specially prepared by grinding. The measuring was done with ECHOMETER 1060, Deutsch, acoustic oil medium, probe HB2 - 10 MHz $\phi 10$ mm. The results of measuring with ultrasound waves are shown in Table 2. The $R_m$ calculation was based on the equation $R_m = 555.8 \cdot v_r^{3.18}$ [2]. Table 2, also shows the values acquired by simulation, see Fig.4. At most of the measured points, the $R_m$ values acquired by simulation were slightly lower than the calculated $R_m$ values(max. difference was 15.9 MPa). The speed of ultrasound waves in the casting decreases after heat treatment (B). After calculation in $R_m$, the tensile strength was 13 MPa higher in the as-poured casting than in the as-annealed one.

Likewise, measuring the speed of ultrasound waves is sensitive to the type of heat treatment. In the future, it would be a good idea to set up the dependence
4. EXPERIMENTAL MEASURING AND CALCULATION OF INTERNAL STRESS USING SIMULATION PROGRAM MAGMASoft

To measure internal stress in the casting, we chose 5 points of measurement. Point M1 was situated 6 mm deep in the thicker part; points M2 and M3 were in the ribs (Fig. 4). The values of solidification were calculated at 98% solidification and correspond to the temperature levels. Internal stress was measured both after pouring and after heat treatment (annealing) to remove internal stress. Cylinder head covers are subjected to heat treatment: annealing 6 hours, followed by cooling 8 hours down to approx. 250°C. For the actual measuring of internal stress, we used Mathar’s strain-gauge method, M120 rosettes, and a DMD 20A compensator. For calculating the E module, we used the ultrasound method based on the speed of ultrasound waves ($E = \frac{R_m}{v_\text{ultrasound}}$).
178,200 MPa – result from 4 measurements). The results of internal stress measurement are shown in Tables 3 & 4.

Table 3: Internal stress measurements in as-poured state
Tabela 3. Naprężenia wewnętrzne mierzone w stanie surowym

<table>
<thead>
<tr>
<th>Measured point</th>
<th>( \sigma_1 ) [MPa]</th>
<th>( \sigma_2 ) [MPa]</th>
<th>( \sigma_r ) [MPa]</th>
<th>( \alpha ) [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>48.5</td>
<td>41.6</td>
<td>45.2</td>
<td>-40</td>
</tr>
<tr>
<td>M2 (drilled-through rib)</td>
<td>176.5</td>
<td>40.2</td>
<td>160.3</td>
<td>-5</td>
</tr>
<tr>
<td>M3</td>
<td>160</td>
<td>71.6</td>
<td>138.9</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 4: Internal stress measurements after heat treatment
Tabela 4. Naprężenia wewnętrzne mierzone po obróbce cieplnej

<table>
<thead>
<tr>
<th>Measured point</th>
<th>( \sigma_1 ) [MPa]</th>
<th>( \sigma_2 ) [MPa]</th>
<th>( \sigma_r ) [MPa]</th>
<th>( \alpha ) [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>57.7</td>
<td>54.4</td>
<td>56</td>
<td>-15</td>
</tr>
<tr>
<td>M2 (drilled-through rib)</td>
<td>27.7</td>
<td>-12.7</td>
<td>35.8</td>
<td>-25</td>
</tr>
<tr>
<td>M3 (drilled-through rib)</td>
<td>73.1</td>
<td>28.5</td>
<td>63.8</td>
<td>-29</td>
</tr>
</tbody>
</table>

Table 3 shows that the two main internal stress measurements (\( \sigma_1 > \sigma_2 \)) in all the points measured in poured state were in the tensile stress category. This corresponds to the fact that stress caused by shrinkage inside the engineering component (drilled hole with dia 6 mm or drilled-through rib) appears in the form of tensile stress, while on the surface, it appears in the form of compressive stress. As to internal stress values, these reached about \( 1/3 \) \( R_m \) of the given alloy.

Heat treatment (Tab. 4) reduces tensile stress (except point M1, where the values remained roughly the same – from the viewpoint of solidification this is a place with larger material volume). At point M2, tensile stress changes into compressive stress, which can be explained by that due to change in the yield strength tensile stresses are reduced in heat treatment while in thin-wall areas (ribs), tensile stress is longitudinally stretched. Due to the adjacent thick parts, which are connected with the ribs, subsequent cooling induces compressive stresses in the ribs.

Simultaneously with the simulation of filling and solidifying, internal stresses were calculated in the cylinder head cover casting. The magnitudes of stress are summarized in Table 5.

Table 5: Magnitudes of internal stress calculated in as-poured state
Tabela 5. Wielkości naprężeń wewnętrznych obliczonych w stanie surowym

<table>
<thead>
<tr>
<th>Point</th>
<th>Tension along axis x (( \sigma_1 ))[MPa]</th>
<th>Tension along axis y (( \sigma_2 ))[MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>-14 ÷ 64</td>
<td>0 ÷ -25</td>
</tr>
<tr>
<td>M2</td>
<td>-14 ÷ -43</td>
<td>-14 ÷ 64</td>
</tr>
<tr>
<td>M3</td>
<td>-14 ÷ -43</td>
<td>-14 ÷ 64</td>
</tr>
</tbody>
</table>
A comparison of Tables 3 and 5 shows a certain difference between the values measured experimentally and those obtained by simulation. Measurements taken with the aid of the strain-gauge method show stress values after drilling a hole (to a depth of 6 mm, in the case of ribs drilling through).

In general it can be said that the drilled-hole method and internal stress simulation using the MAGMASoft give a fairly good idea of the stress values. The interpretation of the results leads to the fact that all maximum stress values are way below the acceptable tolerance limits for internal stress for the given alloy. This can be regarded as a positive quality feature when casting components.

5. CONCLUSION

The MAGMASoft enables design engineers and technicians to predict the mechanical properties and the microstructure of components. Prediction tensile strength \( R_m \), combined with measuring the speed of ultrasound waves, \( V_L, V_R = f(R_m) \), leads to very good results that are applicable in practice. Relatively satisfactory results were also obtained in hardness comparison [2]. On the other hand, ductility values showed a higher degree of scatter [2].

By measuring internal stress with the aid of strain-gauges and subsequently by simulation, the technician and design engineer can verify the effectiveness of heat treatment (annealing) and test dangerous parts of a casting from the perspective of internal stress.

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Bibliography:
Fig. 1: Casting of a cylinder head cover, with the gating system and thermocouples T4 & T5

Rys. 1. Odlew pokrywy głowicy cylindrów z układem wlewowym i termoparami

Fig. 2: Ridge block with thermocouples T1 & T2. Points used for structural Analysis are: t1, t2, t3, & t4

Rys. 2. Blok z termoparami T1 I T2. Miejsca analizy struktury t1, t2, t3 i t4
Fig. 3: Cooling curves for points T4 and T5
Rys. 3. Krzywe stygnięcia w punktach T4 i T5

Fig. 4: Minimum tensile strength ($R_m$) in the casting of a cylinder head cover
Rys. 4. Minimalna wytrzymałość na rozciąganie ($R_m$) odlewu pokrywy głowicy cylindrów
PRZEWIDYWANIE WŁASNOŚCI MECHANICZNYCH, STRUKTURY I NAPRĘŻEŃ WEWNĘTRZNYCH W ODLEWACH SAMOCHODOWYCH.

STRESZCZENIE

Artykuł opisuje eksperymentalne i symulacyjne metody zastosowane do testowania grawitacyjnego odlewu pokrywy głowicy cylindrów z żeliwa sferoidalnego. Przewidywanie wytrzymałości na rozciąganie połączone z pomiarem szybkości fal ultradźwiękowych daje bardzo dobre wyniki, co umożliwia praktyczne zastosowanie tej metody. Analiza mikrostruktury pokrywy cylindra pokazuje, że zawartość perlitu i ferrytu koreluje z wartościami uzyskanymi z symulacji. Wartości określające ilość sferoidów na 1mm$^2$ dla materiału korelują z wartościami zmierzonymi. Poprzez pomiar naprężeń wewnętrznych z zastosowaniem metody tensometrycznej i późniejsza symulację, technicy i projektanci mogą weryfikować efektywnie procesy obróbki cieplnej i sprawdzać niebezpieczne miejsca z perspektywy naprężeń wewnętrznych.

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