ISSN 0543-5846
METABK 43 (1) 17-22 (2004)
UDC - UDK 621.742:532.58=111

THE INFLUENCE OF MOULDING SAND ON THE COMPRESSIVE STRESSES

Received - Primljeno: 2003-04-12
Accepted - Prihvaćeno: 2003-07-25
Original Scientific Paper - Izvorni znanstveni rad

The aim of this research is to explain how the distribution of moulding sand particles, apart from combination with other components (bentonite and water contents) affects the increase of compressive stresses in the moulding mixture. The granularity of sand and water content have great effect in the increase of compressive stresses. The regression analysis was used to obtain the mathematical model which describes the dependence of the compressive stresses on the mean size of the sand grains and water content in the mould mixture.

Key words: *scabbing, compressive stresses, wet tensile strength, granularity of sand*

Utjecaj zrnatosti kalupnog pijeska na pojavu napetosti u kalupu. Prikaz istraživanja utjecaja zrnatosti kalupnog pijeska u kombinaciji s ostalim komponentama (udjelima bentonita i vode) utječe na pojavu napetosti u kalupu. Provedena ispitivanja pokazuju da veliki udio u porastu tlačnih napetosti ima zrnatost pijeska i udio vode. Regresijskom analizom dobiven je matematički model koji opisuje ovisnost tlačnih napetosti o srednjoj veličini zrna pijeska i udjelu vode u kalupnoj mješavini.

Ključne riječi: *odlupljivanje, tlačne napetosti, rekondenzacijska čvrstoća, zrnatost pijeska*

INTRODUCTION

In moulding of large-size castings, the lack of uniformity in heating results in the deformation of individual mould parts. The resulting deformations cause internal stre-sses in the casting and scabbing in the mould. The main cause of deformation in the mould element is to be found in the α - β transformation of the quartz grains. The allotropic modification of the quartz crystals from α into β quartzite occurs at the temperatures ranging from 575 °C to 580 °C and during this process the quartz grains increase their volume.

The volumetric change causes stresses, which are transferred across the residual of the mould mixture toward the interior of the mould where they cause deformation of the mould cavity face. This transformation is reversible, which means that β - α transformation occurs during the cooling of the quartz grains, and this transformation causes the shrinking of the grains. Figure 1. shows the volumetric changes of different types of quartz sand depending on the temperature.

Since the ratio between the mass and the surface of the grain affects significantly the grain heating rate, the total dilatation time of the mould element is connected with granularity.

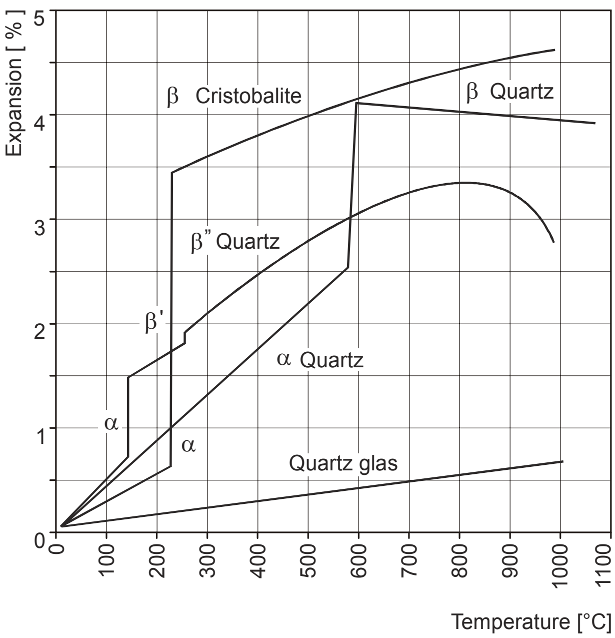

Figure 1. **Volumetric changes of different quartz sands depending on temperature**
Slika 1. **Promjene volumena različitih vrsta kremenog pijeska u ovisnosi o temperaturi**

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EXPERIMENTAL RESEARCH

In order to study the influence of the mould mixture sand granularity on the occurrence of compressive stresses, it is necessary to study the influence of single components which form the mould mixture. Therefore, the following needs to be analysed:

a) influence of granularity,
b) influence of bentonite content,
c) influence of water content.

For the good analysis of the influence of the above-mentioned values on the occurrence of the compressive stresses, it is necessary to choose several mould mixtures, different in composition regarding the granularity, bentonite and water content. For experiment planning, the method of the experiment factor plan was chosen. The limits of every variable have been determined on the basis of minimal and maximal values of the mixtures (Table 1.).

Table 1. **Factor plan of the experiment (range of variables)**
Tablica 1. **Faktorski plan pokusa (raspon varijabli)**

		A (granularity)		
		G3	G3	G3
B	Bentonite [%]	4	4	4
		7	7	7
		10	10	10
C	Water [%]	2.5	2.5	2.5
		4	4	4
		7	7	7

Three different granulometric sand compositions were used in the study. The results of the granulometric analysis have been presented in Table 2.

Table 2. **Results of granulometric analysis**
Tablica 2. **Rezultati granulomenrijske analize**

Size of the holes [mm]	Sample of sand G1 [g]	Sample of sand G2 [g]	Sample of sand G3 [g]
1.5	1.80	0.00	0.00
1.0	12.10	0.00	0.00
0.63	18.50	0.00	0.00
0.4	14.08	0.85	0.00
0.3	5.62	5.90	0.00
0.2	5.85	19.60	1.10
0.15	1.95	23.07	5.05
0.1	0.10	6.45	8.80
0.075	0.00	2.90	10.63
0.063	0.00	0.85	11.28
bottom	0.00	0.38	23.14
Total	60.00	60.00	60.00

After mixing according to Table 1., twenty-seven (27) different mould mixtures were obtained and they were used to make the standard test samples for measuring of the compressive stresses. In order to obtain maximally precise measurements and better repeatability of the measuring results, the design of the measuring device had to be modified. The modification of the measuring device manufactured by Georg Fischer with the accompanying devices is shown in Figure 2.

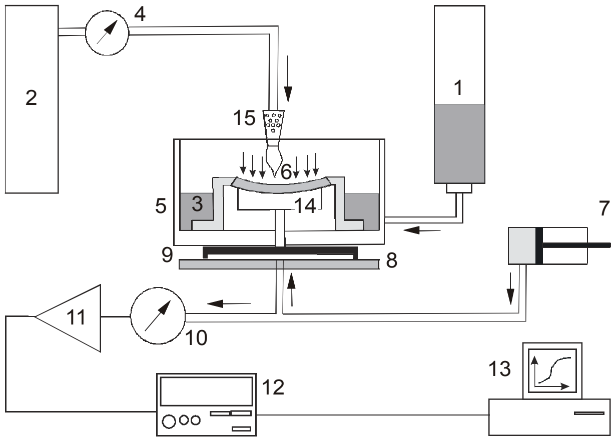

Figure 2. **The modified device for measuring compressive stresses. Components: 1 - vessel with cooling water, 2 - acetylene tank, 3 - sample holder, 4 - manometer, 5 - gauge housing, 6 - test sample, 7 - compressor, 8 - base plate, 9 - counter-plate, 10 - pressure sensor, 11 - amplifier, 12 - measuring switch (A/D converter), 13 - computer, 14 - measuring probe, 15 - burner**
Slika 2. **Modificirani uređaj za mjerenje tlačnih napetosti. Sastavni dijelovi su: 1- posuda sa vodom za hlađenje, 2 - spremnik acetilena, 3 - držač uzorka, 4 - manometar, 5 - kućište mjerilice, 6 - ispitni uzorak, 7 - kompresor, 8 - osnovna ploča, 9 - protuploča, 10 - osjetilo tlaka, 11 - pojačalo, 12 - mjerna centrala (A/D konvertor), 13 - računalo, 14 - mjerno ticalo, 15 - plamenik**

Changing of forces on the measuring sensor results in the change of voltage recorded by the computer. After having introduced changes, it was necessary to record the calibrating diagram (Figure 3.).

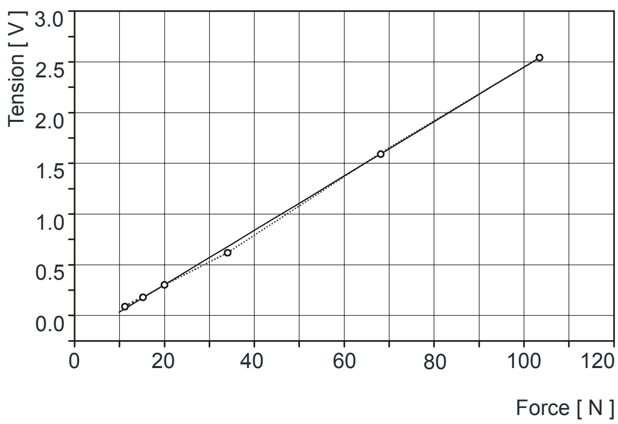

Figure 3. **Calibrating diagram of the modified design of the compressive stresses gauge**
Slika 3. **Baždarni dijagram modificirane izvedbe mjerilice tlačnih napetosti**

From the results obtained by the calibrating diagram, the force on the measuring sensor can be presented by the expression (1):

$$F = \frac{0.23669}{0.02683} + \frac{U}{0.02683} \quad (1)$$

where:

U - the measured voltage [V],
F - force on the measuring sensor [N].

By knowing the sample geometry and the dependence of the measuring sensor force on the recorded voltage value, simple mathematical relations can be used to describe the relation between the compressive stresses (occurring in the test sample) and the measured voltage (recorded by the computer).

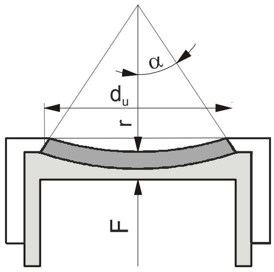

Figure 4. **Test sample on the measuring apparatus**
Slika 4. **Ispitni uzorak na mjernom osjetilu**

The sample used in the measuring features the following dimensions:

r - radius of curvature = 100 mm,
d_u - sample diameter = 50 mm,
s - sample thickness = 5 mm,
α - angle of openness = 15 °.

According to Figure 4., the force F can be described according to [1] as:

$$F = P_\alpha \cdot \sin\alpha \quad (2)$$

where:

F - force measured on the measuring probe expressed in [N] where the test sample is in full contact with the surface of the measuring apparatus,
P_α - force acting along the sample circumference [N],
2α - angle of openness.

From the sample form radius *r*, and its width *d*, the sinus of angle α can be expressed as (3):

$$\sin\alpha = \frac{d}{2\cdot r} = \frac{50}{2\cdot 100} = 0.25 \quad (3)$$

The force P_α which acts along the circumference of the tested sample is the surface which can be expressed as (4):

$$A = s \cdot \pi \cdot d \ \ [\mathrm{mm}^2] \quad (4)$$

where:

s - sample thickness [mm].

From the expressions (5) and (6) follows the relation (7) which enables the calculation of the value of the compressive stresses *Nt* within the sample.

$$Nt = \frac{P_\alpha}{A} = \frac{2\cdot r\cdot F}{d^2\cdot\pi\cdot s} = \frac{2\cdot 100}{50^2\cdot 3.14\cdot 5}\cdot F = 0.005\cdot F \quad (5)$$

$$Nt = 0.005 \cdot (8.82 + 37.3 \cdot U) \quad (6)$$

$$Nt = 0.045 + 0.1865 \cdot U \ \ [\mathrm{N/mm}^2] \quad (7)$$

RESEARCH RESULTS

The measurements yielded 9720 measuring results which cannot be presented here due to the limited space. Graphical presentation of the measurement results for three samples of granularity are shown in Figures 5., 6. and 7.

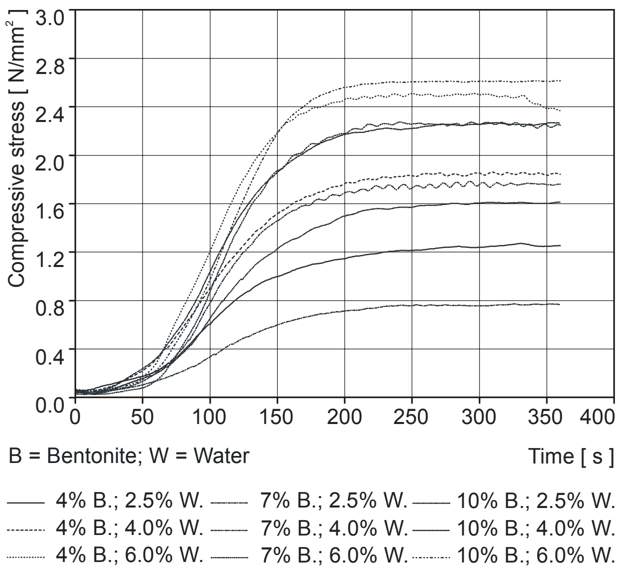

Figure 5. **Graphical presentation of the measuring results for the mould mixture featuring granularity G1**
Slika 5. **Grafički prikaz rezultata mjerenja kalupne mješavine sa zrnatošću G1**

NUMERICAL PROCESSING OF RESULTS

After having obtained the results by measurements, the data were statistically processed. The correlation analysis was used to determine the interdependence of the factors. This analysis has proven the mutual independence of the

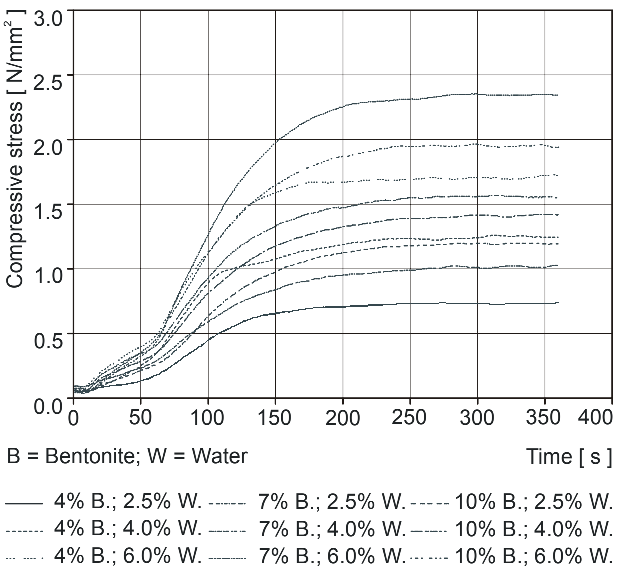

Figure 6. **Graphical presentation of the measuring results for the mould mixture featuring granularity G2**
Slika 6. **Grafički prikaz rezultata mjerenja kalupne mješavine sa zrnatošću G2**

medium-sized grains (SV), bentonite content (B) and water quantity (V). Therefore, these variables have been found independent, whereas the value of compressive stresses *Nt* was found to be a dependent variable. Many different

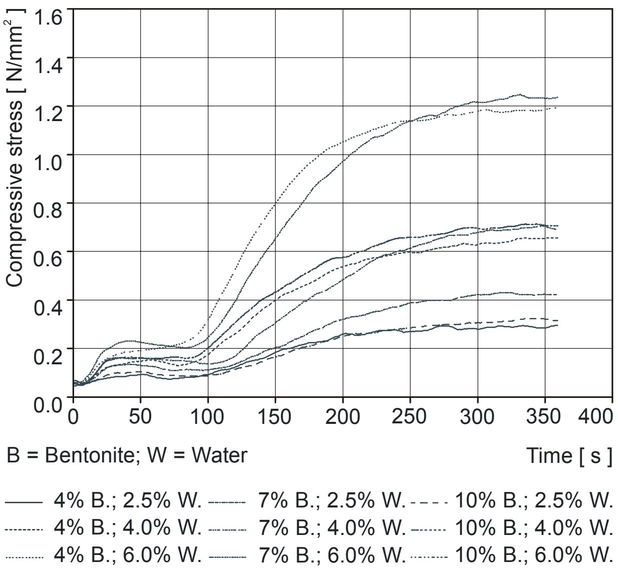

Figure 7. **Graphical presentation of the measuring results for the mould mixture featuring granularity G3**
Slika 7. **Grafički prikaz rezultata mjerenja kalupne mješavine sa zrnatošću G3**

models that describe the occurrence of compressive stresses depending on the studied factors (SV, B and V) were obtained by further statistical processing using the regression analysis. The selected model is presented with expression (8).

$$Nt = - 0.022 + 0.323 \cdot SV + 5.5 \cdot V \qquad (8)$$

Graphical interpretation of the model is presented in Figure 8.

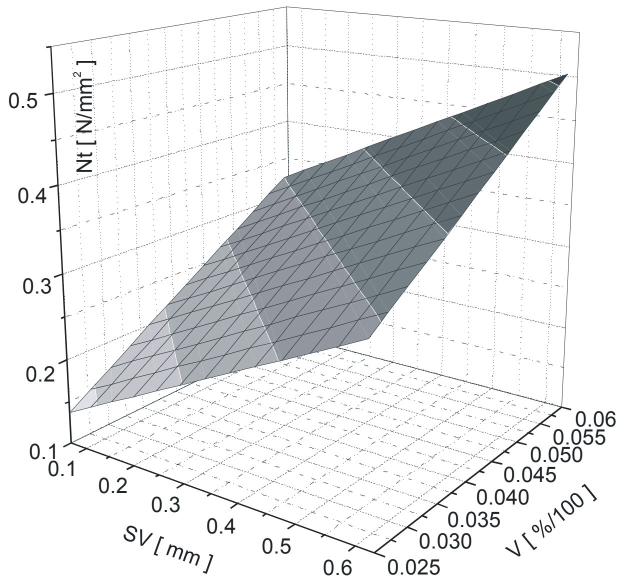

Figure 8. **Graphical presentation of the regression model**
Slika 8. **Grafički prikaz regresijskog modela**

The contour plots that show the dependence of the medium sized grains (SV) on the water quantity (V) are presented in Figure 9.

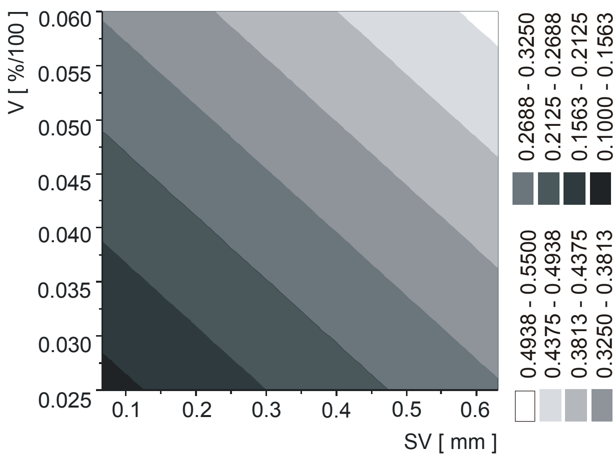

Figure 9. **Regression model - contour plots**
Slika 9. **Regresijski model - konturne plohe**

INFLUENCES OF SINGLE FACTORS

Influence of the medium sized grains

Physically, the influence of the grain size can be explained in the following manner. The difference between the large and the small grains exists in the value of the dilatation force itself. The larger the grain the greater the dilatation forces. The greater resulting dilatation force is explained by the smaller number of contact surfaces, which are the main transmitter of the forces across the interior structure. If the grains are large, the number of contact surfaces is small, the dilatation forces are big, and their resultant is big.

Small grains produce smaller dilatation forces that are transmitted over many contact surfaces. During this transmission, great changes occur in the acting direction of the dilatation forces, and they can be partly also annulled during transmission through the interior structure of the mould mixture. A lot of small holes that occur in the contact of two sand grains also alleviate the action of the force, and compensate for their expansion.

The difference in the heat spreading rate in small and large sand grains is also of great significance. Smaller grain will heat sooner up to the transformation temperature than a large one. If the mould mixture is considered, during the heating of the small grain in the surface layers (layers closer to the heat source) the temperature of allotropic modification is reached relatively fast and the dilatation occurs very rapidly. After that, the heat spreading is decelerated by passing through the water bentonite barriers, so that the sand grains heat up more and more slowly in the layers more remote from the mould face. Due to their large volume, larger grains need to be heated over a longer period of time, and their dilatation is therefore delayed. The larger the grain, the greater its dilatation, but it takes longer to occur. The heat passage through the large-grained structure is facilitated due to the smaller number of water - bentonite barriers.

Influence of water content

With a certain content of water and bentonite, the sand grains are bonded, that is, water provides bentonite with the properties of bonding and plasticity. The stronger the bond of the sand grains, the more directed the action of the dilatation forces, and the greater the value of the compressive stresses. The direction of the action of the force can be achieved only when the sand grains are strongly bonded and do not move. Possible movement of the sand grains will occur in case when the connecting bonds are not sufficiently strong. In that case the movement of grains represents a certain effect of “adjustment”, which compensates for the action of the dilatation force.

Another reason due to which water plays a very important role is the fact that the presence of greater quantities of water in the mould mixtures increases the capability of heat conduction. The moulding procedure results in a certain manner of fitting (positions) of the sand grains. Here, the space which is present in the contact of two sand grains, is determined by the geometry of the outer grain surface. This space can be filled by air, bonding medium, water, small particles, or other impurities. The spaces between the grains can significantly increase or decrease the thermal flow and influence the heat spreading rate within the mould.

Influence of bentonite

The influence of bentonite in these experiments did not prove to be significant. The insignificance of bentonite content can be explained by excessive compression of the samples used in the measuring of compressive stresses. Due to the great compression, the sand grains came into direct contact which transmits the dilatation force.

CONCLUSION

The allotropic modification from α into β phase of the mould parent material, i.e. quartz sand, occurs as the basic source of compressive stresses. Sudden volumetric change of the quartz grains during the α - β transformation results in the forming of dilatation force, occurrence of compressive stresses, deformation of the mould cavity and causes stresses in the castings. Apart from the change in the mould geometry, the deformation of the mould cavity causes also the stresses in the layers closer to the mould face, and due to the occurrence of the recondensation zone, this results in the reduced strength of the mould mixture and in scabbing. The resulting stresses spread more towards the interior of the mould because the dilatation forces are blocked towards the external side of the mould. In studying the dilatation force in the mould mixtures made of the same type of sand but of extremely different granularity, the following may be concluded:

The grain size of the mould parent material, i.e. quartz sand, has significant influence on the value of the compressive stresses. The total change of the larger grain is greater than with the smaller grain. This produces greater dilatation forces and their direction. The size of the grain of the parent material, i.e. quartz sand, influences the rate at which compressive stresses occur. Large grains need much more heat to achieve α - β transformation, so that the dilatation occurs much later than with small grains.

Apart from the granularity of the parent material, the influence of other components is shown, which form the mould mixture. The regression analysis determined that the value of compressive stresses is greatly influenced also by the water content. Water provides bentonite with plasticity and bonding properties. If the bonding forces between two grains are greater, the dilatation force can be transmitted faster towards the interior of the mould. With the greater content of water in the mould mixture, the value of compressive stresses is greater as well.

Except for the water and the medium-sized grains, the bentonite content was not significant in the occurrence of the compressive stresses. The reason lies probably in the excessive compression of the sample. The sand grains came into direct contact pushing out bentonite in the contact zone. Therefore, the dilatation force that acts on the contact surfaces was transmitted as if there were no bentonite. The increase in the compressive stresses with the increased water content in the mould mixture provided a greater amount of bentonite with grain bonding. Due to excessive compression, bentonite filled the gaps between the grains and thus made them rigid. Such bonding enabled the spreading of the dilatation force which caused the increase of the compressive stresses. If there is not enough water, bentonite does not feature its bonding property but in the mould mixture plays the role of the basic mould material of very fine fraction (small particles).

Different times and values of dilatation forces with different grains indicate that if we want to reduce the phenomenon of sudden dilatation, then the parent material that has *variable* grains should be used. By determining the mathematical model which describes the value of the dilatation force depending on the composition of the mould mixture, the dilatation force can be determined in advance. This opens up the possibility of adjusting the granularity of the mould mixture, and of alleviating the action of certain components on the occurrence of compressive stresses.

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