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INFLUENCE OF THE GRANULATION AND GRAIN SHAPE OF QUARTZ SANDS ON THE QUALITY OF FOUNDRY CORES

VPLIV GRANULACIJE IN OBLIKE ZRN KREMENOVEGA PESKA NA KAKOVOST LIVARSKIH JEDER

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Several quartz moulding sands were used for the preparation of foundry models. All the moulding sands were similar with respect to their sieving parameters, yet different in terms of some morphological characteristics. Foundry models were analysed with regards to their mechanical properties. It was shown that the flexural strength of the prepared foundry models varied substantially, despite the fact that the grain size distributions obtained by sieving analyses of the moulding sands were very similar. The observed dissimilarities were explained pertaining to some differences in the micro-morphological characteristics of the sands, i.e., the particle shape and the grain statistical parameters. A quantitative morphological analysis of the sands was made on photographs taken with optical and electron microscopy using Zeiss KS 300 software. Crucial morphological parameters were defined by treating the moulding sands in laboratory-scale homogenization equipment and subsequent flexural strength measurements.

Key words: quartz moulding sands, foundry cores, mechanical properties, morphological analysis

Različni kremenovi peski so bili uporabljeni za pripravo livarskih jeder. Pred določitvijo mehanskih lastnosti livarskih modelov so bili vsi peski analizirani s sejalno analizo. Kljub podobnim osnovnim morfološkim lastnostim različnih kremenovih peskov so bile razlike v upogibni trdnosti livarskih modelov relativno velike. Razlike v mehanskih lastnostih livarskih modelov smo razložili z mikromorfološko karakterizacijo peskov. Karakterizacijo mikrostrukture smo izvedli z optičnim ter vrstičnim elektronskim mikroskopom ter kvantitativno analizirali rezultate z uporabo programa Zeiss KS 300. Z medsebojno primerjavo rezultatov se je izkazalo, da se ključni morfološki parametri, kot so oblika ter površina zrn, ter statistični parametri velikosti zrn pri različnih peskih spreminjajo. Izvedli smo tudi obedavo peska na vrtečih se valjih, s čimer smo na preprost način simulirali obdelavo peska na večjih industrijskih napravah, ki se uporabljajo v te namene. S tem je bil demonstriran način obdelave peska z namenom spreminajanja njegovih morfoloških parametrov ter posledično mehanskih lastnosti pripravljenih livarskih jeder.

Ključne besede: kremenov pesek, livarska jedra, mehanske lastnosti, morfološka analiza

1 INTRODUCTION

In foundry practice, sand cores are very extensively used to form various complicated casting cavities. The main ingredients of the moulding sand cores are base sand (i.e., a high-quality silica sand or lake sand), binder (clay binders, organic binders or inorganic binders) and moisture, if clays such as kaolinite are used as binders[1,2]. The ceramic moulding cores should have sufficient mechanical strength, resistance to erosive wear and chemical corrosion of the liquid metal, high refractoriness, low expansion coefficient and superior thermal stability. At the same time, no chemical reactions of the foundry core with liquid metal at high temperatures are allowed[3].

The mechanical strength of the moulding cores prior to pouring the molten metal into the mould is termed "green strength". The key to obtaining optimal sand cores with a high green strength and the desired performance during moulding is a feasible core binder. Therefore, producers and researchers have paid great attention to selecting and developing optimum binders, which can correspond well with the various required properties of the sand cores[4–8]. Such chemically bonded sand cast systems are often used for the moulds in ferrous (iron and steel) and nonferrous (copper, aluminium, brass) castings processes.

When producing cores and moulds, the so-called cold-box method has become increasingly widely used. This method does not require any heating of the moulding sand for hardening. In short, the method is based on the preparation of a mixture of particle-formed material (base sand) and a bonding agent (i.e., a polyisocyanate compound and a polyhydroxy compound), then the mixture is given the form desired and, finally, it is hardened by means of a catalyst. The cold-box method enables accelerated machining of the moulds in large quantities. The raw strength of the moulds, i.e., the strength directly after machining, is high enough to minimize the risks involved in handling the cores and moulds, so they can be used in the casting process shortly after preparation. Moulds and cores prepared by the cold-box method are also characterized by excellent disintegration after the casting of the metal[9].

The mechanical properties of moulds are determined on the basis of strength moduli. The flexural modulus determination is often chosen as the strength parameter, because it can be easily determined experimentally in a practical way[10–12]. However, the mechanical properties of the moulding cores are strongly influenced by the binding mechanism in the moulds' machining process and also by the morphological properties of the sand being used.

The aim of this paper was to demonstrate the relationship between the morphological characteristics of the mould sand and the flexural strength of the prepared moulds. For the first time, crucial morphological parameters were defined and subsequently tested through the tailoring of moulding sands.

2 EXPERIMENTAL PROCEDURE

Six types of silica moulding sands (silica content > 98 %), similar with respect to their sieving parameters, were used in the experimental work. The particle size analysis was carried out on dry samples (110 °C, 2 h) of about 1 kg reduced to a mass of about 100 g using a Jones splitter and a +GP+ mechanical sieve shaker equipped with 12 sieves from 3.000 mm to 0.063 mm. The sieves were shaken continuously for a period of 12 min. After shaking, the sieves were taken apart and the sand left over on each of the sieves was carefully weighed and expressed as a percentage of the total mass.

Prior to the testing of the mechanical properties, mixtures of various sands (5 kg) and bonding agents (50 g of di-isocyanate and benzyl-ether polyole) were prepared, shaped in a sand rammer into bar specimens (18 × 3 × 3) cm and hardened according to the cold-box method with the ethyl-di-methyl-amine catalyst (T = 105 °C, t = 15 s). The flexural strength of the specimens was measured one day after their preparation using +GF+ apparatus and was expressed as an average flexural strength of 11 measurements for each sample.

For the morphological analysis, the sands were first embedded into Technovit resin and polished. After polishing, the samples were analyzed with a Leitz optical microscope (Leitz Wetzlar). The quantitative morphological analysis of the sands was performed on digital images and expressed as the parameters FERET X, FERET Y, FERET MIN and FERET MAX (intercept lengths in the x or y directions and the minimum or maximum intercept lengths, respectively), FERET RATIO as a ratio of the min and max ferrets, PERIM F (perimeter of the filled analysed region), PERIM C (perimeter of the convex shell of the analysed region), D CIRCLE (diameter of the circle with equivalent area as analysed region), F CIRCLE (form factor of the analysed region – sphericity) and AREA (area of the analysed region). The images were digitized into pixels with 255 different gray values using Zeiss KS300 3.0 image-analysis software. To obtain statistically reliable data, 7–10 different images were analysed in each case.

In order to tailor the morphological characteristics of the selected powder, ≈1.5 kg of sand was put into a ball mill's grinding bottle and rotated (≈0.2 r/s) for an extended time (no grinding balls were used).

3 RESULTS AND DISCUSSION

The results of the sieving analysis of the six different silica moulding sands are summarized in **Figure 1** and **Table 1**. It appears that the basic morphological characteristics of all six sands, including the granulometric interval, the mean diameter value $\bar{x}$ and the standard deviation d_s, are very similar and within the range of the morphological requests of silica sands used in a foundry. However, one of the crucial parameters for distinguishing silica sands in the foundry industry is the mechanical strength of the prepared casting model. From this point of view, the six silica sands differ substantially, as indicated in **Table 1**. The highest values of flexural strength were measured in the case of the samples Sand 1 and Sand 2 (777 and 679, respectively), while the lowest values were obtained for the samples Sand 4 and Sand 5 (369 and 317, respectively). Since the basic morphological parameters for the sample pairs Sand 1 and Sand 5, and Sand 2 and Sand 4 are very close, and cannot explain the big difference in the measured flexural strength of the prepared models, a more in-depth morphological analysis of the sands was performed. The optical micrographs and the results of the quantitative morphological analysis are summarized in **Figure 2** and in **Table 2**.

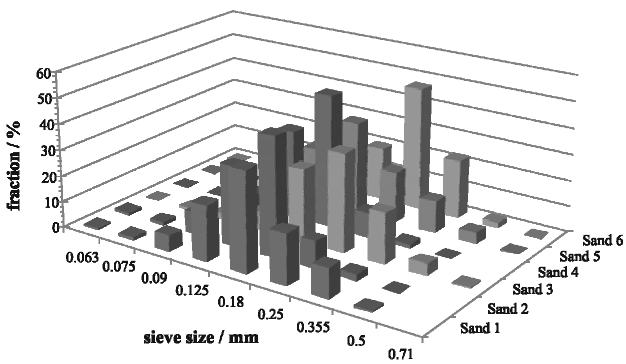

Figure 1: Granulometric histograms of the moulding sands
Slika 1: Histogrami različnih livarskih peskov

Table 1: Basic morphological characteristics of the silica sands and the flexural strengths of the prepared foundry models
Tabela 1: Osnovne morfološke karakteristike kremenovih peskov in upogibna trdnost pripravljenih livarskih jeder

Sample	$\bar{x}$/mm	d_s/mm	σ_{flex}/ (N cm^{-2})
Sand 1	0.196	0.079	777
Sand 2	0.164	0.054	679
Sand 3	0.250	0.095	567
Sand 4	0.167	0.050	369
Sand 5	0.210	0.099	317
Sand 6	0.254	0.081	382

Table 2: Morphological parameters of silica sands
Tabela 2: Morfološki parametri kremenovih peskov

Parameter	Sand sample					
	Sand 1	Sand 2	Sand 3	Sand 4	Sand 5	Sand 6
FERET X / μm	100.785	102.899	143.911	120.273	74.796	123.465
FERET Y / μm	100.221	103.729	140.119	119.183	77.62	122.288
FERET MIN / μm	78.271	80.627	106.389	89.137	56.567	91.705
FERET MAX / μm	117.792	121.547	168.389	143.656	93.003	146.425
FERET RATIO /	0.6645	0.6633	0.6318	0.6205	0.6082	0.6263
PERIM F / μm	368.745	379.89	569.329	467.135	340.922	485.994
PERIM C / μm	314.482	322.784	443.152	375.305	241.109	385.725
D CIRCLE / μm	90.636	92.619	122.214	102.79	63.158	105.489
F CIRCLE /	0.6915	0.6836	0.5402	0.5577	0.4585	0.5531
AREA / μm^2	8799.479	8703.74	15228.13	9298.84	4614.615	10431.86

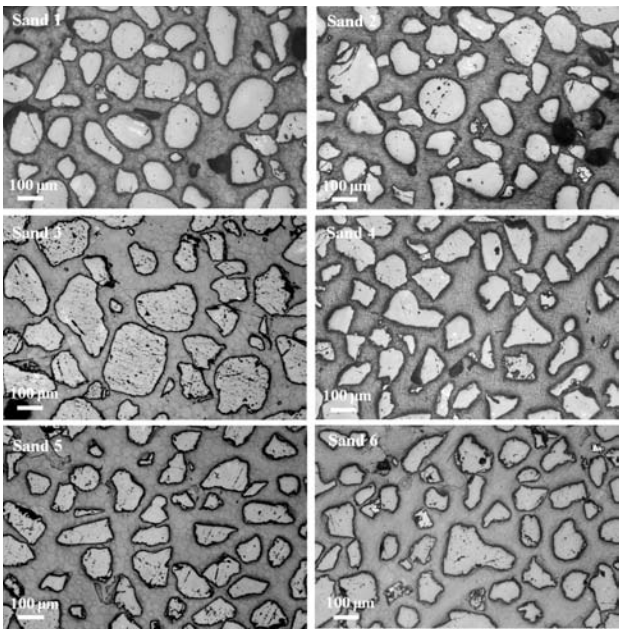

Figure 2: Optical micrographs of silica moulding sands (silica particles were embedded into polymer resin and polished)
Slika 2: Morfološka analiza kremenovih peskov z optičnim mikroskopom (kremenovi peski so bili zaliti v polimerno rezino in polirani)

According to the results summarized in **Table 2**, the FERET X and FERET Y values are very close for each analysed sample. Some differences among the samples can be seen if the values of the minimum or maximum intercept lengths and their ratios (FERET MIN, FERET MAX and FERET RATIO) are compared. The highest FERET RATIO values (close to 0.665) were calculated for the samples Sand 1 and Sand 2. These three values together somehow also indicate the origin of the silica sands. If the silica sands are treated with mechanical processing in crushers, the grains of the finally prepared sands are normally irregularly shaped, meaning that such sands should have fairly different values of FERET MIN and FERET MAX and consequently relatively low FERET RATIO values. A similar deduction may also be used when the parameters PERIM F (perimeter of the filled analysed region) and PERIM C (perimeter of the convex shell of the analysed region) are compared. Both parameters should be dissimilar if the grains are irregularly shaped. Again, by calculating the ratio of PERIM C/PERIM F, a single number is obtained, which indicates in some way the grain shape. The closer the calculated PERIM C to PERIM F ratio is to 1, the more spherical and full (without cavities or large pores) are the silica grains. The highest PERIM C to PERIM F ratios were calculated for the samples Sand 1 and Sand 2 (0.85 in both cases) and the lowest perimeter ratio in the case of the sample Sand 5 (0.71). The parameters D CIRCLE and AREA are not indicative when the morphological characteristics of the sands are compared with the flexural strength of the casting models. These two values describe the size class of an average sand grain. In contrast, the F CIRCLE (sphericity) value is significant for the final mechanical strength of the prepared models. When comparing the values of the measured flexural strength and sphericity, it can be concluded that higher F CIRCLE values also result in a higher flexural strength of the foundry models. More precisely, the highest F CIRCLE values (0.69 and 0.68) were determined for the samples Sand 1 and Sand 2, respectively, which also exhibited the highest flexural strength, while a relatively low flexural strength was characteristic for the prepared foundry model from the Sand 5 sample with the lowest F CIRCLE value of 0.46.

Such a relationship, in which more spherically shaped (less irregular) silica particles also resulted in a higher flexural strength of the prepared foundry models, is in accordance with the principles of the dispersion strengthening of composite materials. Foundry models can be understood as a composite of hard silica particles and softer, more ductile polyurethane, which is formed by the reaction between the di-isocyanate and the benzyl-ether polyole. In such a composite material, any sharp-edged particles locally act as stress intensifiers, reducing the critical stress needed for the mechanical degradation of the tested model.

To confirm that silica particle shape is one of the crucial parameters for controlling the flexural strength of

Table 3: Change of morphological parameters and flexural strength during sand treatment
Tabela 3: Sprememba morfoloških parametrov in upogibne trdnosti med obdelavo peskov

Parameter	Time of sand treatment				
	t = 0	t = 3 d	t = 6 d	t = 10 d	t = 14 d
FERET X / µm	120.273	118.963	111.461	101.811	100.969
FERET Y / µm	119.183	125.086	112.723	103.674	105.883
FERET MIN / µm	89.137	91.304	85.124	79.106	80.856
FERET MAX / µm	143.656	146.075	133.087	123.079	123.951
FERET RATIO /	0.6205	0.6292	0.6396	0.6427	0.6523
PERIM F / µm	467.135	466.154	424.539	382.031	380.529
PERIM C / µm	375.305	381.347	352.102	320.762	323.869
D CIRCLE / µm	102.79	103.319	95.852	85.997	88.268
F CIRCLE /	0.5577	0.5757	0.5897	0.6297	0.6488
AREA / µm^2	9298.84	10462.27	9542.703	7058.766	7416.08
σ_{flex} / N·cm^{-2}	330	/	/	/	

foundry models, silica sand (Sand 4) was rotated in a grinding bottle for several days. Such a treatment of the silica sand should not change its mean particle size considerably; however, it should tailor the shape of the sand grains. The results of the quantitative morphological analysis of the treated silica sand and the flexural strength of the prepared foundry models are summarized in **Table 3**.

The main characteristic of silica-sand treatment is the substantial increase in the flexural strength value if foundry models machined from non-treated and maximally treated sands are compared. However, sand treatment tailors not only the flexural strength of the foundry models but also alters the morphological characteristics of the sand. The parameters that describe the size class of an average sand grain (FERET X, FERET Y, FERET MIN, FERET MAX and D CIRCLE) diminish over time. In this respect, the diameter of the average sand grain (D CIRCLE) was reduced by 14 %. However, strictly from the aspect of grain size, silica sand (Sand 4) is within the range of morphological requirements to be used in the foundry.

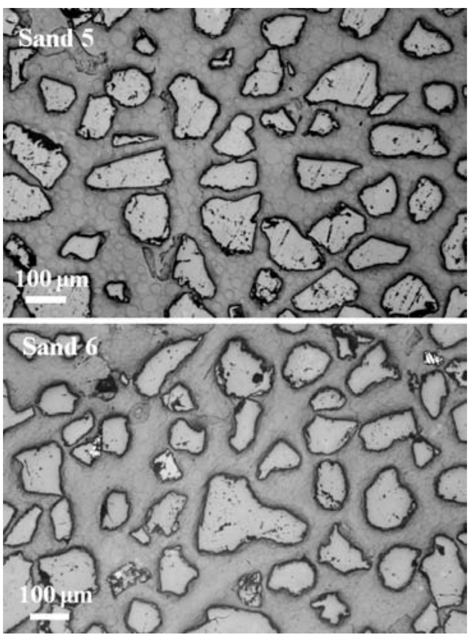

Figure 3: Optical micrographs of the silica sand (Sand 4) before (left image) and after (right image) the sand treatment
Slika 3: Slike optičnega mikroskopa vzorca kremenovega peska (Sand 4) pred obdelavo (levo) in po njej (desno)

In view of the fact that the parameters determining morphological size (if silica grain size is within the range of requests) are not decisive for the foundry model flexural strength, as discussed previously, the increased flexural strength of the foundry model was ascribed to the shape change of the average sand grain. The sand treatment increased the ratio PERIM C to PERIM F from 0.80 to the final value of 0.85. Simultaneously, the F CIRCLE value also increased from 0.56 to 0.65, meaning that the sand grains became increasingly spherical. This change in the sphericity of the particles is also evident from the optical micrographs of the non-treated and treated silica sand (**Figure 3**).

4 CONCLUSION

Foundry models prepared from various silica sands may express quite different values of flexural strength. These differences may be interpreted by the morphological characteristics of silica sands. It was shown that the basic morphological parameters, i.e., the mean particle diameter and the standard deviation, were not sufficient to explain the measured differences in flexural strength. Instead, an in-depth morphological analysis revealed that when the silica grain size is within the range of requests, particle shape is one of the crucial parameters for controlling the flexural strength of the foundry models. More spherically shaped silica particles also resulted in a higher flexural strength of the prepared foundry models. The crucial morphological parameters of the silica sands to predict the flexural strength of prepared foundry models are F CIRCLE (sphericity), the PERIM C to PERIM F ratios (ratio between the perimeters of the convex shell of the analysed region and the filled analysed region, respectively) and the FERET RATIO as a ratio of the ferret min to ferret max.

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