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Application of a New Innovative Ceramic Material for Investment Casting Technology

Z. Stefański [a]*, I. Izdebska- Szanda [a], M. Angrecki [a]
[a] Foundry Research Institute, Zakopiańska 73, 31-418 Cracow, Poland
* Corresponding author's e-mail: zbigniew.stefanski@iod.krakow.pl

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Abstract

The article presents the research results of a new ceramic material, in which olivine sand was used as the matrix. This new ceramic material was studied at the angle of its application in the investment casting technology. This material will be mainly used for preparing self-supporting moulds for castings made of aluminium and magnesium alloys, replacing the expensive material – molochite which has been used so far.

The article presents the results of mineralogical research of olivine sand, as well as thermophysical research of the new ceramic material made on the olivine sand matrix. Comparative research of both materials was conducted, i.e. with the olivine and molochite matrix, then the assessment of the quality of the new ceramic material was made. What is more, the research results of the developed ceramics and its usefulness for the production of castings are presented.

Key words: Innovative foundry technologies and materials, Olivine sand,Self-supporting mould, Investment casting technology,

1. Introduction

In the production of castings in line with the investment casting method, a specifically significant problem, connected with achieving high technological properties of castings, is directional and quick solidification of castings in a casting mould, instead of slow and volume solidification. Directional solidification enables to attain a solid and fine-grain structure of castings, without casting defects like shrinkage voids, microshrinkage, and as a consequence high technological properties. It is especially important in case of castings with complex designs, with differentiated wall thickness and high technological requirements. This issue is of utmost importance in case of producing castings of aluminium and magnesium alloys. Ensuring directional solidification in this method is difficult due to a low temperature of solidification of these alloys (approx. 700^{o}C) and a technological necessity to bake the prepared ceramic moulds at a high temperature, i.e. 900-1200 ^{o}C (the temperature of moulds higher than the temperature of alloy solidification). In this method hot casting moulds, after baking are directly poured with molten metal. In this case there occurs unfavourable, slow, the so-called volume solidification of castings.

In the technology of producing castings, mainly made of cast iron and cast steel, with the use of the investment casting the most commonly utilised ceramic material is cheap quartz, which is used for preparing self-supporting moulds, which due to its physical properties, must be poured with molten metal after baking the moulds, when their temperature is 900-1200^{O}C.[1]

This principle is not useful while producing castings of aluminium and magnesium alloys because of too high temperature of moulds. Lowering the temperature of moulds before pouring, in case of using quartz, causes their cracking and damaging during pouring. It is connected with considerable dimensional changes of quartz ceramics, and transformations in the crystallographic arrangement of the quartz matrix, which take place when the temperature is decreased. That is why, in case of making responsible, complex designs of castings, casting moulds are made of a different material, much more expensive than quartz, such as zircon, fused alumina, or molochite. After being baked ceramic moulds are cooled to the temperature required by the technology (most often approx. 300 ^oC), without any damage.

The production of castings of magnesium alloys according to this technology in quartz moulds has further barriers, due to magnesium affinity for oxygen contained in silica. While pouring the moulds there occur chemical reactions, the decomposition of quartz, the possibility for magnesium to burn, moreover there is uptake of silicon by the alloy, which deteriorates the properties of the alloy.

The proposed new ceramic composition, in case of its application for casting moulds does not have any of the above-listed drawbacks; it enables to decrease the temperature of moulds after their baking, and before pouring with molten metal, without concerns about damage. It allows more favourable, directional solidification and cooling of castings. The content of quartz in olivines is approx. 40%, which prevents magnesium alloy from burning.

2. The aim and the scope of the research.

The presented subject matter was realised within the Targeted Project, entitled “The development of technology and production start-up of a new type of high quality ceramic materials intended for moulds and castings made with the precision casting method.”

An assumption was made that a new ceramic material made on the olivine sand matrix should achieve high physico-chemical and technological properties, especially with aluminium and magnesium alloys. Recently, the development of the production of this group of castings has been very intensive.

To realise the subject matter is was necessary to:

- conduct mineralogical research of selected samples at the angle of their usefulness for foundry needs,
- conduct research of thermophysical properties of olivine and ceramic sands which contain this material,
- develop an experimental technology to produce moulds and castings with the application of the new ceramic material
- prepare experimental casting moulds with the application of the new matrix on the basis of olivine,
- prepare experimental castings with the application of new ceramics and control their quality.

3. The description of the research and the achieved results

3.1. Mineralogical research of selected samples of olivine sand in the aspect of their usefulness for the foundry industry.

Olivines belong to a group of minerals referred to as the island silicate group, which means that they contain independent, not connected with oxygen bridges complex $[SiO_4]^{4-}$ anions. The representatives of olivines are: forsterite $Mg_2[SiO_4]$ and fayalite $Fe_2[SiO_4]$ (very rare), which create a continuous isomorphous series [2-4].

For the purposes of the research imported were olivine samples which came from a quarry in Italy. The research of the phase composition was conducted with the use of an X-ray diffractometer KRISTALLOFLEX 4H manufactured by Siemens. The phase analysis was carried out using characteristic X-radiation of a copper cathode CuKa = 0.145 nm. The research w conducted with 30 kV voltage and 25 mA current. The qualitative research of studied samples was made in the Bragg-Brentano geometry.

As the achieved results of the phase composition research were not decisive during the quantitative assessment of particular phases present in the studied samples, the analysis of phase composition was repeated and additionally research of their grain and chemical composition was conducted.

The analysis of the chemical composition of studied olivine samples was made with inductively coupled plasma optical emission spectrometry (ICP OES) with the use of an ICP OES Optima 2100 spectrometer manufactured by Perkin – Elmer.

Additionally, the analysis of the chemical composition of a selected population of grains was made during the microscopic analysis conducted with the use of a NOVA 200 NANOSEM scanning microscope manufactured by FEI Europe Company in the secondary electron system (SE), coupled with a EDS microanalyser manufactured by EDAX

The chemical analysis proved that as regards the content of iron, magnesium and silicone the studied samples were closely homogenous. In all samples aluminium, calcium, sodium and chrome were present in the amount not exceeding 1%.

The achieved results of the analysis of the chemical composition of studied olivine samples made with optical emission spectrometry were proved during the microscopic research. It was stated that in samples there are neither grains which are made only of silicone and iron (100% fayalite), nor only of magnesium and silicone (100% forsterite).

In all studied samples the majority of grains were made of iron, magnesium and silicone, which proves that the majority of grains, from the point of view of the phase composition, are olivine – isomorphous form of forsterite – magnesium silicate, in which a few percent of magnesium were substituted by iron and/or chrysolite. Moreover, in all six studied samples of olivine the presence of grains was proved in which apart from Fe, Mg and Si there is aluminium in the amounts from 1.19% to 0.038%.

During the research of the microstructure in the analysed olivine samples proved was also the presence of grains, in which apart from Fe, Mg, Si and Al there were calcium, sodium, potassium and chrome. The presence of chrome was stated in the research, at the same time verifying the results of the chemical analysis. Figure 1 presents an example of olivine microstructure.

The above-presented results of chemical analyses enable to state that the studied olivines contain in their phase composition, first and foremost, forsterite and other minerals which are either products of their transformations or accompanying minerals.

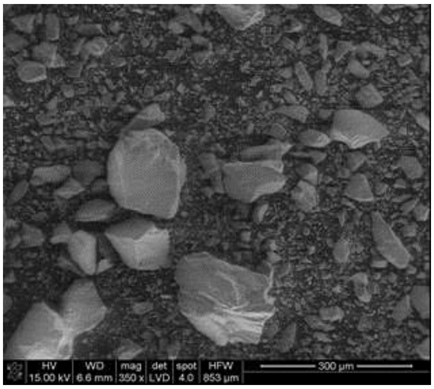

Fig. 1. The microstructure of studied olivines - magnification 350x.

These observations prove the results, presented below, of phase composition research – X-ray diffraction.

On the basis of diffractograms of studied olivine samples the content of particular phases was estimated. In all analysed samples the dominating phase is forsterite (Mg_2SiO_4.) The second phase, when it comes to the content, constitutes chrysolite, a mineral, in which the content of iron calculated into the content of $FeSiO_4$ in moles can be even three times higher. The following phase identified during olivine research, except for sample 5, was enstatite, magnesium silicate with the chemical formula $MgSiO_3$. Similarly to Mg_2SiO_4, it is not found in unsubstituted form and it is not regarded as a mineral which belongs to the olivine group (pyroxene group). In the samples small amounts of tremolite were identified, a mineral with the formula $Ca_2Mg_5Si_8O_{22}$ $(OH)_2$ (amphibole group), as well as fayalite.

Table.1. The percentage content of forsterite and fayalite in studied olivines samples.

Olivine sand samples	1	2	3	4	5	6
$C_{Forsterite}$,[%]	62.32	32.70	31.24	72.26	26.83	33.37
$C_{Fayalite}$, [%]	14.31	16.01	24.97	20.89	7.27	26.88

Data in Table 1 indicate that in olivine samples 1 and 4 the content of forsterite exceeds 60%, and in other olivine samples the content of this phase is by 50% lower. In turn, the content of fayalite in studied samples does not exceed 27% (sample 6). The above-mentioned properties of samples were used during the selection of olivine grain composition to prepare ceramic moulds for wax patterns.

The grain composition of studied samples was tested with the use of a Mastersizer 2000 apparatus manufactured by Malvern Instr. The research results of the grain composition of studied olivine samples carried out with the laser diffractometry method are presented in the form of grain distribution curves (Fig. 2).

Grain distribution curves, except for the curve for sample 2 are monomodal maximums (D_{domin}.) within the range 41.76 µm-170.22 µm.

Sample 2 next to the maximum which is close to $D_{domin.}$ = 112.47 µm has another wide maximum near the value of the dominating diameter 10.74 µm and at the same time it is characterised by the narrowest grain distribution, which indicates the most homogenous sizes of grains.

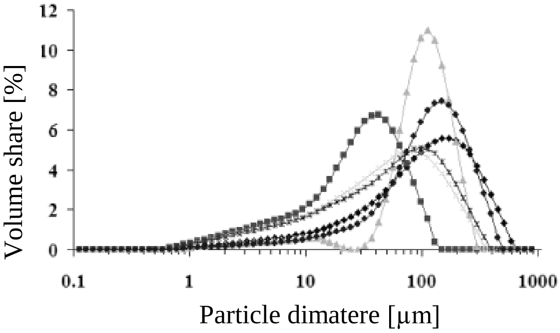

Fig. 2. Curves presenting grain distribution in studied samples of olivines.

3.2. The research of thermo-physical properties of ceramics made on olivine and molochite matrix

The achieved results of thermo-physical research are utilised in developing technologies for producing castings, and especially during conducting simulations of cooling and solidification of castings. The aim of conducting simulations is to achieve castings with good quality without casting defects.

3.2.1. Dilatometric research

On the basis of dilatometric research it is possible to determine temperature courses for the following thermo-physical values:

- relative change in linear dimension $\Delta L/L$,
- physical and average (technical) coefficient of linear expansion β and β_m.

The research of samples was conducted with a DIL 402C/4/G dilatometer manufactured by NETZSCH, which is used to measure thermal expansion of metals and alloys, ceramic materials, polymers and composites within the range from the ambient temperature to 1550°C.

Two types of samples made of ceramics were studied, which differed with respect to the applied ceramic matrix. The first matrix being olivine, and the second – as a reference material molochite, which is commonly used in foundries as the matrix for ceramic moulds. The binder was liquid colloidal silica. After preparing samples, melting wax, drying and burning them at 900°C, samples were tested. Figures 3 and 4 present the thermal expansion of studied ceramic materials. On this basis it can be stated that with a temperature rise, thermal expansion of ceramics made on the olivine matrix increases, as compared to thermal expansion of ceramics made on the molochite matrix. At 1000ºC, ceramics made of olivine has twice as big thermal expansion as ceramics made of molochite.

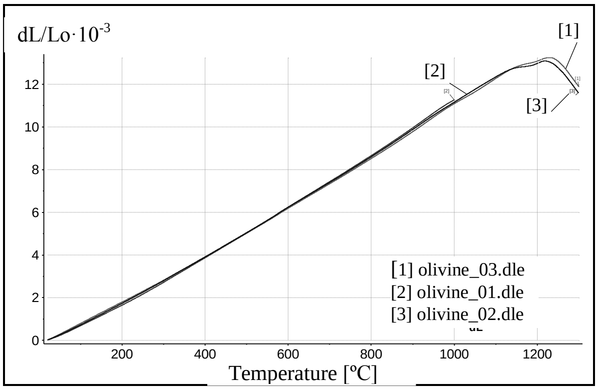

Fig.3. Thermal expansion of olivine sand.

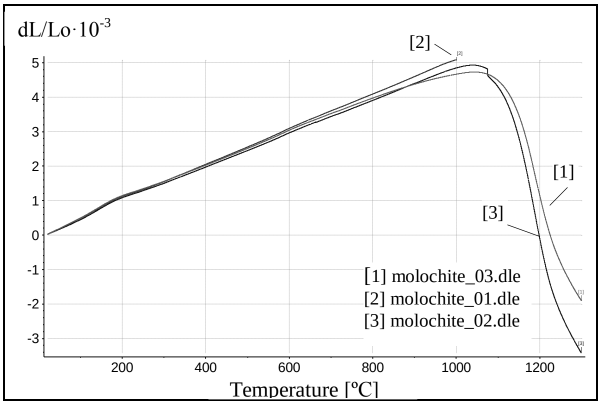

Fig. 4. Thermal expansion of molochite.

3.2.2. Calorimetric research

Differential Scanning Calorimetry was used to conduct the research. This is a method of thermal analysis, which uses the technique measuring the difference in heat flowing to the studied sample and the reference sample. The flow is forced by a controlled change in the temperature of the system. The research was conducted with the use of a DSC 404 C/3/G Pegasus high-temperature differential scanning calorimeter. After obtaining the data from the colorimeter, specific heat c_p = (dH/dT)/m was calculated on the basis of the equation:

$$C_{sample} = c_{reference}\,(m_{reference}/m_{sample})(D_{sample}/D_{reference}) \qquad (1)$$

Ceramic material made on the basis of olivine had higher specific heat than ceramics made of molochite, which at 1200ºC for ceramics made on the olivine matrix was 1.5 J/gK, and for ceramics made of molochite 1.2 J/gK.

3.2.3. The research of thermal conductivity

Netzsch Laser-Flash LFA 427/4/G apparatus was used for measurements. This device is used to test temperature diffusivity and thermal conductivity in metals and alloys in the solid and liquid state, metals, ceramic minerals and powdered materials. The applied impulse technology enables to measure the coefficient of temperature diffusivity (compensation) “a” within the range 0.001 ÷ 10 m^2/s, and within the temperature range 20 ÷ 1500 °C,

Using the software of the LFA 427 device the value of thermal conductivity (λ) was calculated on the basis of previously measured values of temperature diffusivity. The research was conducted under 10^{-5} mbar vacuum within the range from the ambient temperature to 1200 °C.

Diagrams in fig. 5 and 6 present the changes of thermal conductivity “λ” and temperature diffusivity ”a” for olivine and molochite sand within the temperature range from 0º÷1200ºC.

Up to 400ºC the ceramic material made on the matrix of olivine sand had higher thermal conductivity than ceramics made of molochite. Within the range 400÷1000ºC both materials have similar thermal conductivity, whereas above 1000ºC ceramics made on the olivine matrix definitely conducts heat better than the ceramic material made of molochite.

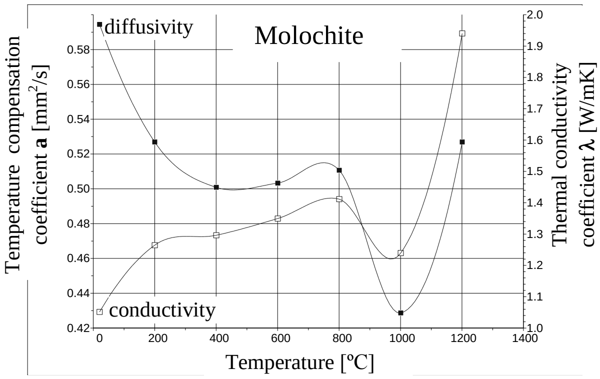

Fig.5. Thermal diffusivity and conductivity of molochite.

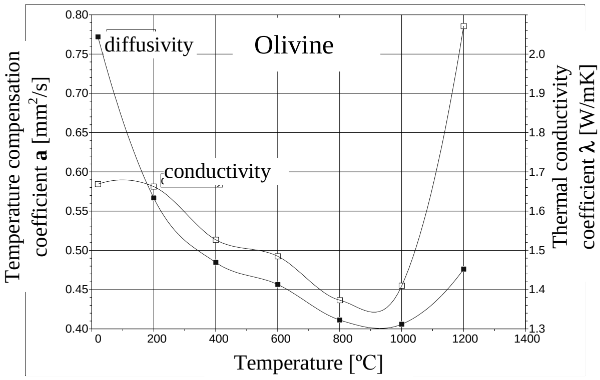

Fig.6. Thermal diffusivity and conductivity of olivine.

4. The research of technological properties of ceramics made on the olivine matrix.

In order to develop optimal quality of ceramics designated for producing moulds and castings, technological research was carried out, typical for investment casting: research of rheological properties of liquid ceramic bodies, determination of the wetting angle of a wax pattern by liquid ceramic body, and determination of flexural strength at changeable temperature.

Within the scope of the research determined was the influence of the granulometric composition and the chemical composition of studied ceramic materials on the stability of rheological properties of studied liquid ceramic bodies in time function.

The result of conducted rheological research and research of the wetting angle should be assessed as positive. No significant differences were found between ceramic materials currently used in foundries on the basis of molochite and the studied material on the basis of olivine.

4.1. The determination of bending strength

The bending strength test of ceramic body was conducted for comparison purposes on three types of samples, i.e. on the quartz, molochite and olivine matrix. Bending strength tests of ceramic body were carried out at the ambient temperature and after heating to 900ºC, with the application of a special apparatus. The achieved test results at the ambient temperature are presented in table 4, whereas results at high temperatures in table 5. Exemplary samples after carrying out the tests are presented in fig. 7.

Table 4. Bending strength Rg of samples after removing them from an autoclave (ambient temperature).

	Quartz	Molochite	Olivine
	Rg [MPa]		
Average from 10 samples	2.02	1.35	1.27

Table 5. Bending strength Rg of ceramic samples at 900ºC.

	Quartz	Molochite	Olivine
	Rg [MPa]		
Average from 10 samples	5.69	4.43	5.44

Test results at the ambient temperature showed that ceramics made of quartz had the highest bending strength, whereas ceramics made of molochite and olivine had comparable strength.

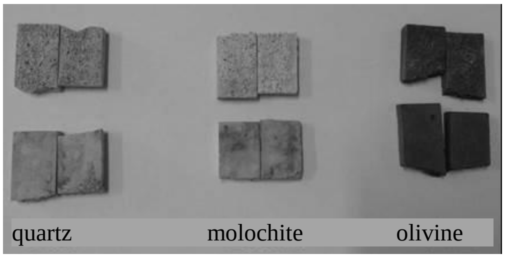

Fig.7. Samples made of studied ceramic bodies.

While in case of tests at high temperatures strength of ceramic samples containing olivine should be assessed as positive and comparable to quartz samples; samples containing molochite had the worst results.

5.2. Preparing experimental ceramic moulds

In order to select proper granulometric parameters of the grain matrix of the new material, a series of wax patterns was made, and then ceramic moulds were prepared. Attempts to make ceramic moulds were made in the Foundry Research Institute, with the application of technologies and devices typical for the semi-technical scale, these attempts were made for three types of patterns. Fig. 8 shows a ceramic experimental mould.

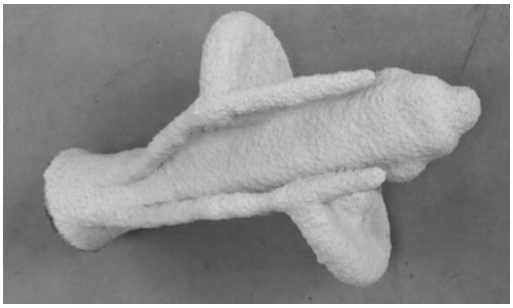

Fig.8. A ceramic mould made with the application of the new ceramic material on the olivine matrix.

The prepared ceramic moulds were burnt within the temperature range from 600 to 900ºC, and then poured with different alloys, i.e. aluminium alloy, magnesium alloy, cast steel, cast iron and copper alloys.

The moulds poured with aluminium and magnesium alloys were, after burning, and before pouring, cooled to 200ºC. The decrease of temperature was forced by the temperature of alloys solidification. It was also checked how the decrease of temperature of a mould after burning would influence the durability of the casting mould. Both while pouring and solidification the moulds were not damaged. Castings obtained in this way were characterised by good surface quality. Figure 9 presents an exemplary casting after knocking out of the ceramic mould made of ceramics on the olivine matrix.

Fig.9. Castings made of magnesium AZ91 alloy in a mould made with the application of the new ceramic material.

5. Conclusions

On the grounds of the achieved results of the presented research, the following conclusions may be formulated:

1. At 900ºC ceramics made of olivine has twice as big thermal expansion as a ceramic material made on the basis of molochite.
2. A properly selected ceramic material made on the olivine sand matrix, due to its chemical composition, i.e. lower content of silica is especially predestined for preparing ceramic moulds for castings of magnesium alloys.
3. New resources are utilised to prepare ceramic moulds for castings of magnesium, aluminium, copper and iron alloys, including cast iron and alloy cast steel.
4. The high quality of developed resources of the new type and their proportions, with a precisely selected composition, will allow a considerable decrease in temperature of burning moulds, at the same time ensuring their proper quality, as well as the quality of castings, which allows a decrease of energy consumption, as compared to energy currently consumed by this technology.
5. The application of the developed resource for the production of casting moulds enables to pour them with molten metal at low temperatures, for example approx. 200^0C, which allows directional solidification of castings, achievement of their fine-grain structure and high quality.
6. The price of the new resource is considerably lower than the price of currently utilised materials of this type in the investment casting technology.

Acknowledgements

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