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EFFECT OF THE TYPE OF INORGANIC BINDER ON THE PROPERTIES OF MICROWAVE-HARDENED MOULDING SANDS FOR ABLATION CASTING TECHNOLOGY

The aim of this study is to demonstrate the possibility of using moulding sands based on inorganic binders hardened in a microwave chamber in the technology of ablation casting of aluminium alloys. The essence of the ablation casting technology consists in this that a mould with a water-soluble binder is continuously washed with water immediately after being poured with liquid alloy until its complete erosion takes place. The application of an environmentally friendly inorganic binder improves the ecology of the whole process, while microwave hardening of moulding sands allows moulds to be made from the sand mixture containing only a small amount of binder.

The studies described in this article included microwave-hardened sand mixtures containing the addition of selected inorganic binders available on the market. The strength of the sands with selected binders added in an amount of 1.0; 1.5 and 2.0 parts by mass was tested. As a next step, the sand mixtures with the strength optimal for ablation casting technology, i.e. about 1.5 MPa, were selected and tested for the gas forming tendency. In the four selected sand mixtures, changes occurring in the samples during heating were traced. Tests also included mould response to the destructive effect of ablation medium, which consisted in the measurement of time necessary for moulds to disintegrate while washed with water. Tests have shown the possibility of using environmentally friendly, microwave-hardened moulding sands in ablation casting of aluminium alloys.

Keywords: innovative technologies, ablation casting, moulding sands, microwave hardening, environmentally friendly inorganic binders

1. Introduction

Ablation casting is a relatively new method that has not yet been used in the Polish industry. It involves casting metal into sand moulds with a water-soluble binder. The moulds are intensively washed and cooled with water during casting solidification until they are dissolved completely. This process is applicable to aluminium and magnesium alloys cast into disposable moulds. Sand moulds with water-soluble binders are used in the process. The liquid alloy is poured into a sand mould and while it is still in a liquid state, the mould is washed with a cooling medium (water) fed through a system of nozzles [1-4]. This allows for direct contact of water with the casting surface and prevents the formation of a gas gap. During solidification, casting shrinks and begins to detach from the mould that expands. Then the so-called "gas gap" is formed between the casting and the mould and it effectively blocks heat dissipation from the casting. Thus, more than any other factor contributing to the cooling process, this gap controls the cooling rate, the refinement of casting microstructure and ultimately the casting properties [1]. It occurs in conventional methods of casting, reducing heat release outside the mould. A large temperature gradient across the casting wall cross-section facilitates the elimination of shrinkage porosity, especially in thin-walled castings. Solidification under the conditions of fast heat dissipation results in a very good microstructure. Based on the literature data, it can be concluded that the properties of the resulting casting are comparable to or better even than the properties of a pressure die cast component. The ablation casting technology is intended for castings with varying wall thickness and intricate shape, cast into sand moulds in which a longer time of solidification causes grain overgrowth. The method was patented by Alotech Company in 2006 [5].

Ablation casting technology is based on moulding sands with water-soluble inorganic binders, commonly used in the foundry industry and hardened with organic hardeners. The use of organic hardeners creates environmental hazards and may also deteriorate the quality of the reclaim [6]. Therefore, the use of physical hardening methods (such as thermal or microwave

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hardening) is very advantageous, particularly in the case of ablation casting technology. As studies have shown so far, both methods allow reducing the binder content in the sand mixture, while maintaining sufficiently high strength parameters [7]. In the microwave hardening process shown in Figure 1c, the binder containing water molecules of polar nature (dipoles) is first heated. The electromagnetic wave, penetrating the moulding sand and at the same time increasing the temperature in its entire volume, significantly reduces the duration of the process. Due to the high frequency of vibrations, the energy of the electromagnetic wave is transformed into the thermal energy of the binder, intensifying the formation of a dehydrated layer of glassy sodium silicate [8].

The microwave hardening process has a number of advantages, which include short process duration and low binder content without compromising good mechanical and technological properties [8].

2. Research methodology and discussion of results

As part of this work, strength tests were carried out on moulding sands with four different inorganic binders. Then, the gas forming tendency of the examined sands and their thermal decomposition were determined. The last stage of the research was devoted to the determination of the mould dissolution rate occurring as a result of the ablation process, i.e. testing the speed of mould erosion.

2.1. Bending strength tests

Based on earlier studies [9], it has been established that the optimal strength of the mould used in ablation casting is 1.5÷1.7 MPa. At the same time, this strength allows the transfer of metallostatic pressure of the liquid metal and increases the susceptibility of the mould to the destructive effect of the ablative medium. To speed up the process of mould erosion, the addi-tion of water-soluble binder should be as low as possible. Tests were carried out on sand mixtures containing hydrated sodium silicate R150, modified inorganic binder available on the market (binder B), geopolymer binder and phosphate binder. The physico-chemical properties of the binders are given in Table 1 [10-12]. Sibelco silica sand classified according to the Polish Standard PN-85/H-11001 as medium sand (main fraction 0.20/0.16/0.315) was used as the base material in all moulding sand mixtures.

The following sand mixtures were tested:

Silica sand 100 parts by mass
Inorganic binder 1.0, 1.5 and 2.0 parts by mass
Additive 1.0 part by mass.

The addition of 0.5% distilled water was used to evenly distribute the binder in the moulding sand. It also prevented the detachment of sand particles from the hardened samples taken out of the chamber. After mixing the moulding sand, standard oblong samples with dimensions of 22×22×172 mm were made. The samples were compacted in a vibratory compaction apparatus. The vibration time and amplitude were 20 seconds and

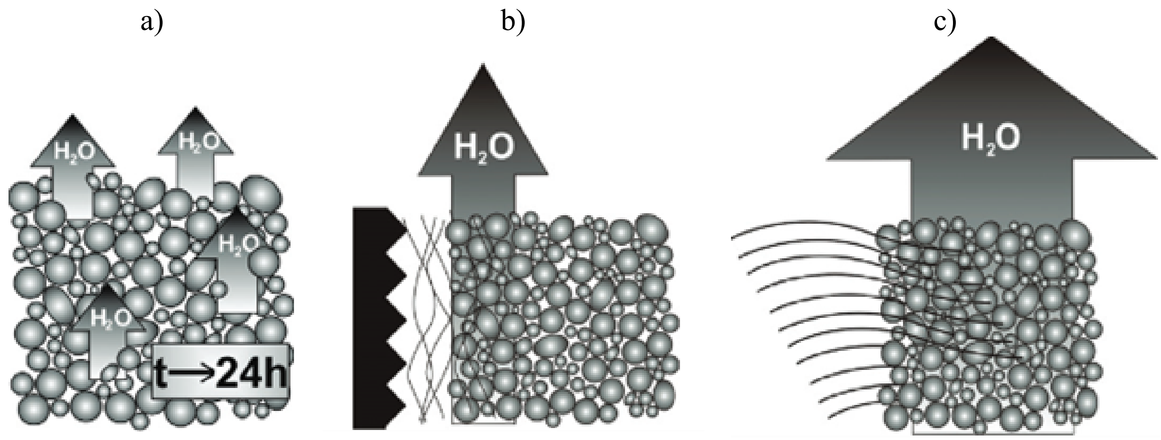

Fig. 1. Schematic representation of systems occurring in different methods of hardening sodi-um silicate moulding sands: a) chemical methods (loose self-hardening sands), b) conventional heating, c) microwave hardening [8]

TABLE 1

Data sheets for physico-chemical properties of inorganic binders based on hydrated sodium silicate [10-12]

Properties, unit	Sodium silicate R150	Binder B	Geopolymer binder	Phosphate binder
Form	Water solution	Water solution	Water solution	Mixture
State of matter	liquid	liquid	liquid	liquid
Colour	white, transparent or translucent	white, transparent or translucent	milky	green
SiO_2/Na_2O	1.9-2.1	2.1-2.4	1.6-2.6	-
pH (20°C)	11-13	11.5-12.5	11-13	3
Density (20°C), g/cm^3	1.50-1.53	1.36-1.47	1.51-1.53	1.6
Viscosity (25°C), mPa·s	20-40	65	250-350	0.6-0.8

1mm, respectively. Then, the samples were hardened with 800 W microwaves at 2.45 GHz for 6 minutes. Previous own research has shown that this is the optimal heating time for moulding sand allows to achieve the highest strength. The final strength of the samples was measured on an LRU-2e apparatus. Samples were tested immediately after removal from the microwave chamber ("hot strength") and 1 hour after completing the hardening process ("cold strength"). The test results are presented in Tables 2-3 and graphically in Figure 2. The results presented in the diagrams are the arithmetic average of three measurements in accordance with the Polish standard PN-83 / H-11073.

TABLE 2

"Hot" bending strength of samples tested immediately after removal from the microwave chamber

Binder content, parts by mass	Bending strength, MPa			
	Sodium silicate R150	Binder B	Geopolymer binder	Phosphate binder
1.0	0.17	0.30	0.17	0.34
1.5	0.18	0.38	0.55	0.00
2.0	0.28	0.36	0.47	0.00

TABLE 3

"Cold" bending strength of samples tested 1 hour after removal from the microwave chamber

Binder content, parts by mass	Bending strength, MPa			
	Sodium silicate R150	Binder B	Geopolymer binder	Phosphate binder
1.0	1.70	2.03	1.47	1.68
1.5	2.10	2.90	2.36	1.40
2.0	2.28	3.74	3.59	1.39

The conducted tests have demonstrated that all tested sand mixtures are characterized by the strength sufficient for foundry application. "Hot" bending strength tests shows the possibilities of unfolding the modeling equipment immediately after being removed from the microwave chamber. The strength of about 0.2 MPa allows safe removal of samples. The temperature of the samples immediately after removal from the microwave chamber is 68°C. Moulding sands based on each of the selected binders allowed the tested samples to achieve the bending strength required for the ablation casting technology. Additionally, microwave hardening allowed achieving these values for a very low content of binder in the sand, which is beneficial for both mould erosion rate and process water quality.

2.2. Testing gas emissions from moulding sands

The amount of emitted gas (gas forming tendency) was determined in accordance with Industry Standard BN-76/4024-05. The measurement was carried out in an electric furnace with a temperature control unit operating in a measuring range of up to 1300°C. An apparatus for the determination of gas emissions is shown in Figure 3.

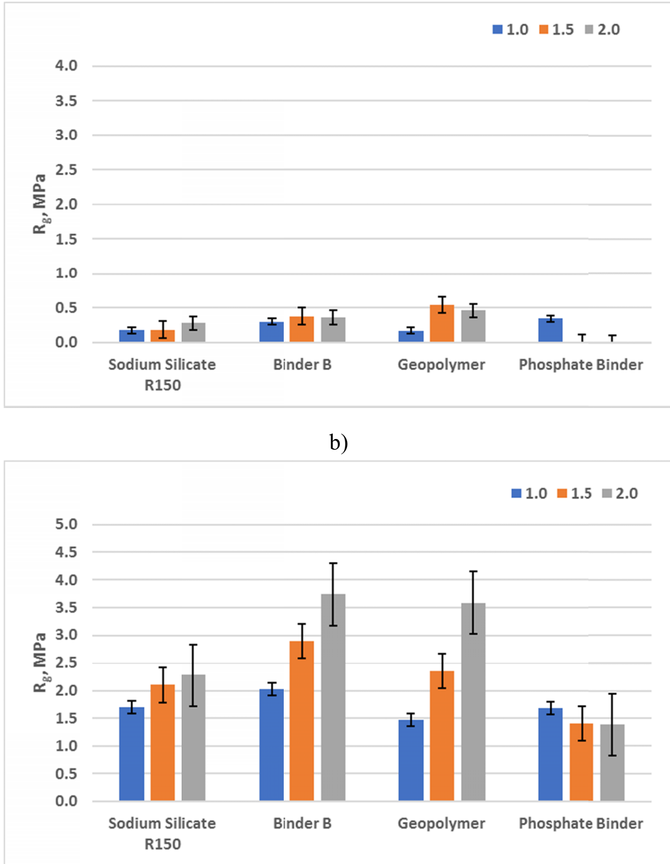

Fig. 2. Bending strength of samples tested: a) immediately after removal from the microwave chamber ("hot strength"), and b) 1 hour after removal from the microwave chamber ("cold strength")

The measurement consists in placing the boat with sample in a furnace heated up to 1000°C. A 1 gram sample of dried material is placed in the boat for the determination of gas forming tendency. The volume of gases emitted is read every 5 seconds. The test is interrupted after 10 minutes or earlier if, within 1 minute after the last reading, the gas volume in the burette does not increase. For the gas emission tests, moulding sands based on inorganic binders with the required bending strength R_g were selected. Two samples of each material were tested and the results were averaged. The composition of moulding sands and test results are presented in Table 4.

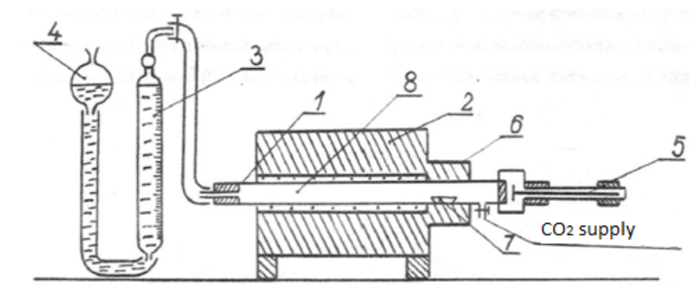

Fig. 3. Apparatus for the determination of gas emissions: 1 – not polished porcelain pipe for combustion, 2 – electric furnace, 3 – 250 cm^3 capacity burette equipped with a three-way tap, 4 – 250 cm^3 capacity equalizing tank, 5 – 12 V electromagnet system for boat movement, 6 – porcelain tube housing, 7 – porcelain boat, 8 – 1000°C temperature zone [13]

TABLE 4

Gas forming tendency of moulding sands selected for testing

Moulding sand composition	Gas emissions, cm^3/g
Silica sand – 100 parts by mass Sodium silicate R150 – 1.5 parts by mass	5.5
Silica sand – 100 parts by mass Binder B – 1.0 part by mass	3
Silica sand – 100 parts by mass Geopolymer binder – 1.0 part by mass	5
Silica sand – 100 parts by mass Phosphate binder – 1.0 part by mass	5

Studies have shown that in all tested sand mixtures, the level of gas emissions during sample heating was very low. Each of the sand mixtures selected for the gas emission tests was characterized by a very low gas forming tendency. The values were negligible, which confirms the ecological nature of the process. The low level of gas emissions is also beneficial for the quality of castings obtained.

2.3. Mould erosion tests

The tests were carried out on four selected sand compositions using the device for ablative removal of moulding sand and controlled cooling of casting (Fig. 4) available at the ŁUKASIEWICZ Research Network – Krakow Institute of Technology.

The device for the removal of moulding sand and casting cooling operates in the following way. The sand mould is placed on a working table extended outside the chamber. By lowering the working table, the mould is introduced into the zone of nozzles operation. The mould is broken down and the duration of this process is measured. An integral part of the device is the BOSCH high-pressure pump producing the liquid flow at a rate of 6.5 l/min and a maximum pressure of 12 MPa.

The following operating parameters were applied in the test:

– number of revolutions – 40 rpm,
– vertical feed – 30 cm/min,
– water pressure – 12 MPa.

Moulds for ablation casting were made from the four selected compositions of microwave-hardened moulding sands.

Each of the moulds was successively placed in the device and the time between switching on the nozzles and full mould erosion was measured. The test results are presented in Table 5.

TABLE 5

The time required for mould erosion

Moulding sand composition	Time of erosion, s
Silica sand – 100 parts by mass Sodium silicate R150 – 1.5 parts by mass	36
Silica sand – 100 parts by mass Binder B – 1.0 part by mass	26
Silica sand – 100 parts by mass Geopolymer binder – 1.0 part by mass	31
Silica sand – 100 parts by mass Phosphate binder – 1.0 part by mass	9

Erosion tests have confirmed that moulding sands with low content of water-soluble inorganic binders undergo erosion in a very short time. This time was the shortest in the case of phosphate binder. In the case of this binder, the duration of the process was three times shorter than in the case of other binders.

a) b)

Fig. 4. Device for ablative removal of moulding sand and controlled cooling of casting: a) general view, b) erosion tests

2.4. Derivatography

To determine the weight loss during heating, thermal analysis of the sand mixtures selected for testing was also carried out. The TG-DTA-DSC-Cp curve was plotted using an STA 449F3 Jupiter thermal analyzer coupled with QMS 403C Aëolos. During thermal analysis, the samples were heated to 1000°C at a constant heating rate of 10°C/min.

The derivatographic studies allowed both thermal differential analysis and thermo-gravimetric analysis to be conducted simultaneously. The changes occurring in the samples during heating were recorded in the form of two curves:

- TG curve – graph showing changes in sample temperature as a function of the heating time
- DTA curve – the differential thermal curve showing thermal effects of exo- and endothermic transformations.

The test results are presented in Figures 5 and 6.

All tested sand mixtures are characterized by a similar course of DTA curves with endothermic transformation taking place at a similar temperature (577, 582, 572, 576°C). Therefore it can be concluded that the occurrence of a peak characteristic of the endothermic transformation, visible in the charts, is caused by the polymorphic transformation of quartz occurring at 573°C, as further confirmed by the literature data [14]. In all samples, the total weight loss is small and does not exceed 0.30%. Thus, it may be due to the evaporation of water contained in the binder. For all binders, the largest weight loss occurs at a temperature of 100-105°C, and this is the temperature at which water evaporates from the moulding sand. The total weight loss occurs at a temperature close to the endothermic point, which means that it does not exceed 600°C.

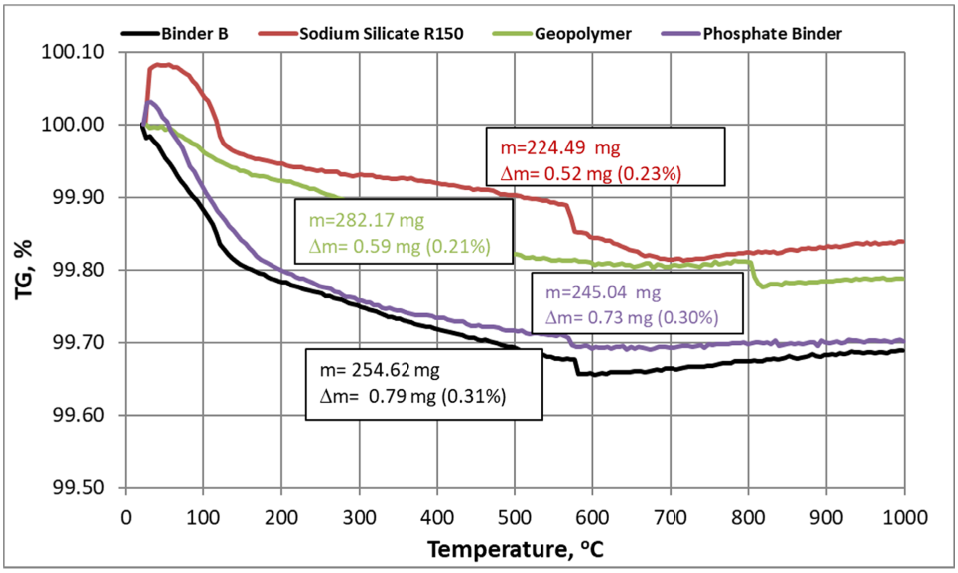

Fig. 5. Weight loss vs temperature (TG) curves plotted for the tested binders

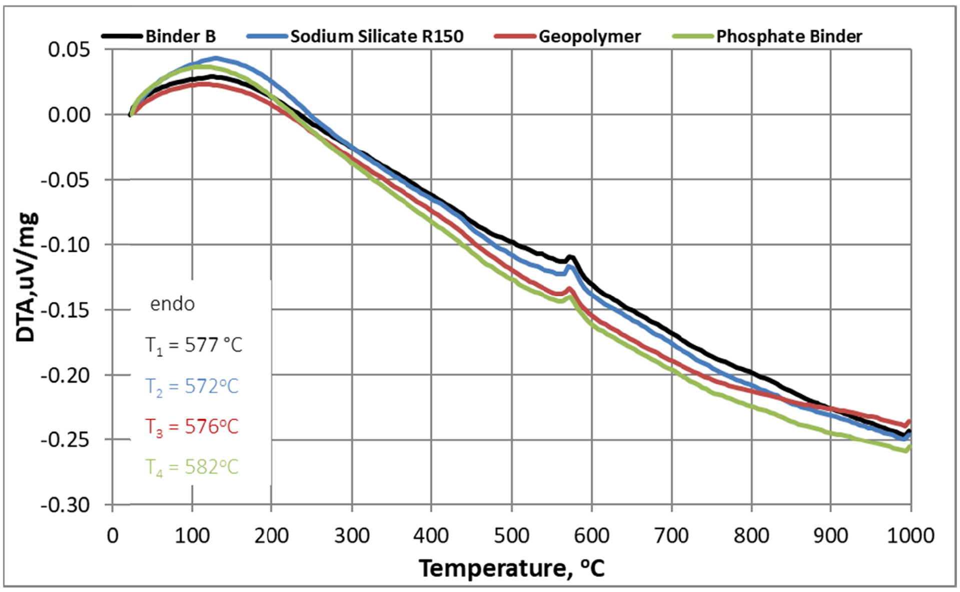

Fig. 6. The DTA curves showing the effect of thermal transformations occurring in the tested binders

3. Conclusions

Based on the literature data and the results of own research, the following conclusions were drawn:

- All binders selected for tests in this study meet the requirements imposed onto moulding sands for ablation casting of Al alloys.
- At a low binder content, microwave hardening allows obtaining the bending strength optimal for ablation casting.
- Microwave-hardened moulding sands based on inorganic binders are characterized by very low gas emissions. This is due to the use of relatively low inorganic binder content in the moulding sand.
- In the temperature range of 0-1000°C, all tested moulding sands are characterized by a total weight loss not exceeding 0.3%, which proves absence of any organic additives in the sand mixture.
- In ablation casting technology, for microwave-hardened sand mixtures based on water-soluble inorganic binders, the process of mould erosion occurs in a very short time, which allows achieving high cooling rates and produces a fine-grained structure in castings. Analyzing the obtained results, the most advantageous parameters from the point of view of the ablation process are characterized by a moulding sand prepared on the basis of phosphate binder.

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