

# Innovative Microwave Hardening of Water-Glass Containing Sandmixes in Technical-Economic Approach

A. Malachowska<sup>b\*</sup>, M. Stachowicz<sup>a</sup>, K. Granat<sup>a</sup>

<sup>a</sup> Foundry and Automation Team, Wrocław University of Technology, ul. Łukasiewicza 5, 50-371 Wrocław, Poland

<sup>b</sup> Welding Technology Team, Wrocław University of Technology, ul. Łukasiewicza 5, 50-371 Wrocław, Poland

\*Corresponding author. E-mail address: [aleksandra.malachowska@pwr.wroc.pl](mailto:aleksandra.malachowska@pwr.wroc.pl)

Received 01.02.2012; accepted in revised form 28.03.2012

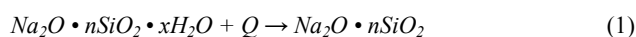
## Abstract

In recent years, an increasing interest in sandmixes containing inorganic binders has been observed. These binders, including water-glass, are harmless for the environment, neutral for humans, and relatively cheap. In spite of numerous advantages, their wide application is restricted by poor knock-out properties and problems related to rebonding. Therefore, numerous researches aimed at eliminating the disadvantages of water-glass binders are directed, among others, to modifying the structure of hydrated sodium silicate or to applying new hardening techniques. An innovative method of rapid hardening by microwave heating, permitting the restriction of the quantity of binder used and thus improving knock-out properties, meets the expectations of present-day foundries. In this paper, available information is compiled on microwave hardening of water-glass containing sandmixes; furthermore, the costs of practical application of this technology are evaluated on the grounds of the authors' own research.

**Keywords:** Innovative foundry technologies, Microwave hardening, Water-glass, Moulding and core sands

## 1. Introduction

The hardening of water-glass containing sandmixes consists in converting sol to gel, which can be chemically or physically initiated. Chemical (irreversible) methods are based on replacing the stabilising solution of alkaline ions by other ions include, among others, the CO<sub>2</sub> process and the Floster process. Physical methods include traditional drying, as well as the Hot-Box and the Warm-Box process [1,2]. In these processes, water-glass is transformed to anhydrous, vitreous silicate film binding the matrix grains, which can be described as the following reaction [2]:



where:  $n, x$  – stoichiometric factors.

Depending on the applied drying technology, the reaction rate is different, which can influence the strength of the created bridges. In the authors' own research [4,5], the best properties were obtained for sandmixes dried by the innovative method of microwave heating.

Physical hardening permits reaching higher strengths of water-glass containing sandmixes due to the significant reduction or complete absence of secondary reaction products like sodium carbonate created in the CO<sub>2</sub> process, sodium acetate solidifying in the form of longitudinal precipitates breaking the gel continuity and multihydroxide alcohol in sandmixes hardened with esters or dicalcium silicate in the case of hardening with self-decomposing

slag U-10 [1,3,4]. Figure 1 shows a moulding sand structure obtained by hardening with CO<sub>2</sub> and with microwaves. In the image of a binder bridge obtained by innovative microwave hardening (Fig. 1a), a homogeneous vitreous structure is visible, guaranteeing high strength. In contrast to this, in Fig. 1b the cracks of the bridges created by hardening with CO<sub>2</sub> that reduce the strength of the bridges [6] are visible.

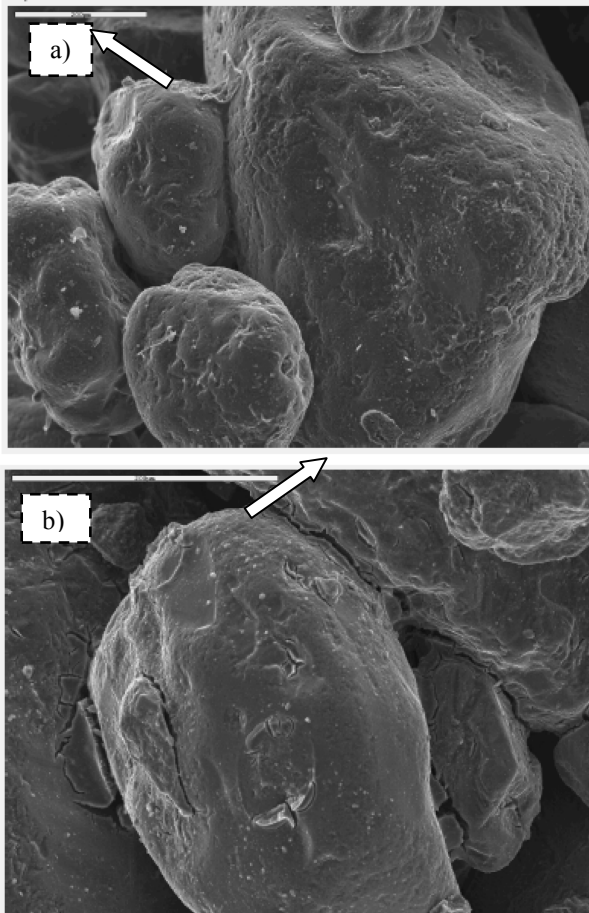


Fig. 1. View of linking bridges in moulding sand: a) microwave-hardened, b) hardened in CO<sub>2</sub> process [6]

Because of the optimum structure of the linking bridges, the sandmixes hardened by microwave heating can be – according to BN-76/4020-01 – classified as 1<sup>st</sup> class sandmixes when containing 1.5 % of water-glass only [7]. So, it is possible to obtain much better knock-out properties after heating to the critical temperature range of 600 °C to 950 °C. Irrespective of the water-glass grade used, after heating to 600 °C the strength  $R_c^{tk}$  does not exceed 1 MPa. For comparison's sake, in the Flodur or CO<sub>2</sub> technologies this strength ranges from 3 to 5 MPa [8].

Considering the strength aspect, it is only the hardening of moulding sands by traditional drying that permits obtaining strength parameters comparable with those obtained by

microwave heating. However, the traditional drying method requires relatively long drying times and thus large energy expenditure [4]. In comparison to traditional drying, the alternative method of microwave heating, based on high-frequency polarisation of water molecules, permits obtaining uniform, equal temperature increase in the whole volume and thus reducing dehydration [7].

On the other hand, the method of hardening with esters is widely applied in industry and other areas because of its relatively good strength parameters and ease of dosing with liquid hardener. However, a basic disadvantage of this method is the long time of evaporating water bound in the sandmix that in industry practice can reach even 24 hours. It often happens that, depending on atmospheric conditions, this time does not guarantee complete removal of water bound in the binder. This can result in problems manifesting themselves as casting defects [9,10].

## 2. Object of the research

The research was aimed at comprehensive technical and economic evaluation of microwave hardening in comparison to other methods with respect to industrial manufacture of moulds of loose self-setting moulding sands. In default of data concerning the application costs of this new method, a simplified cost analysis was carried-out. The data on mechanical properties were taken from literature. The microwave method of hardening moulding sands with water-glass was proven at the Foundry Department of DFM ZANAM-LEGMET in Legnica. The manufactured casting core for crusher hammers was characterised by a wall thickness reduced from 45 mm to 21 mm, which significantly improved its knock-out properties. The quantity of binder was reduced by 30 % and the quantity of high-silica matrix by ca. 60 %. After casting the hammers, no significant differences could be found on cast surfaces in the places where the cores were used, and thus the possibility of applying the microwave method in industrial practice was confirmed [6,11].

## 3. Materials used in the research

To compare the costs, casting cores were prepared using a water-glass containing sandmix, hardened in four ways: traditional drying, microwave heating, CO<sub>2</sub> purging, and with Flodur 1 in the Floster process.

The sandmix was composed of:

- high-silica sand from the Nowogrod Bobrzanski mine, with main fraction 0.40/0.32/0.20,
- water-glass from the Chemical Plant "Rudniki", with the properties given in Table 1,
- liquid ester hardener Flodur 1, with the properties given in Table 1.

Table 1.

Physico-chemical properties of sodium water-glass and ester hardened used in the research

Water-glass grade	Molar modulus $\text{SiO}_2/\text{Na}_2\text{O}$	Oxide content $(\text{SiO}_2+\text{Na}_2\text{O})$ [%]	Density (20 °C) $[\text{g}/\text{cm}^3]$	$\text{Fe}_2\text{O}_3$ max. [%]	CaO max. [%]	Dynamic viscosity (P)
145	2.4 ÷ 2.6	39.0	1.45 ÷ 1.48	0.01	0.1	1
Hardener (commercial name)		Gelation time [min]	Density (20 °C) $[\text{g}/\text{cm}^3]$	Flash-point [°C]	Acid value	Content of ethylene glycol diacetate
Flodur 1		40	1.104	91	20	85

Depending on the hardening method, the cores were made as either "solid" or innovative "economical" ones, possible thanks to high strength obtained by microwave heating. Dimensions of both types of cores are shown in Fig. 2. below.

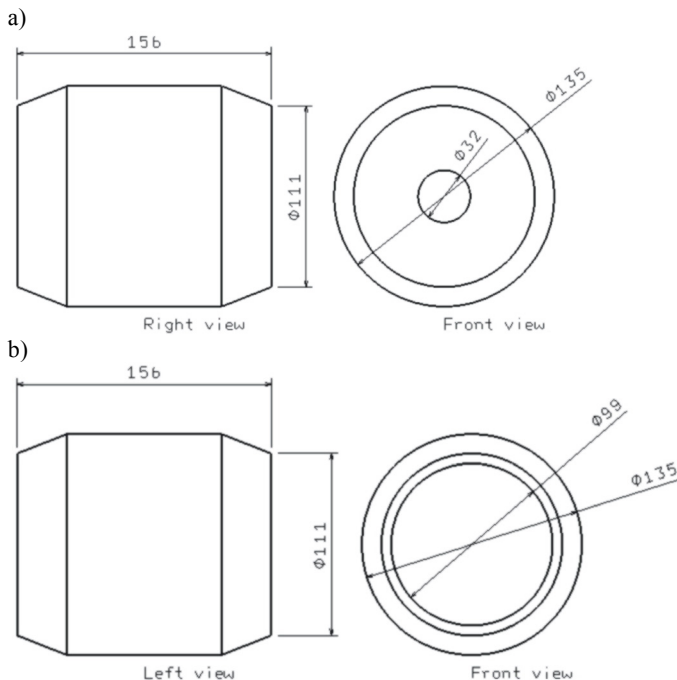


Fig. 2. Dimensions of cores used in the research: a) "solid" core hardened with  $\text{CO}_2$  and Flodur, b) "economical" core to be hardened with microwaves

The innovative cores were hardened using a microwave oven permitting stepless adjustment of the magnetron operation. For traditional drying, a popular chamber drier was used. The core box was made of a material permitting penetration of electromagnetic wave deep into the box. Design of the Polytetrafluoroethylene (PTFE) box allowed removing the created steam through special gaps. All the cores were made of three kinds of sandmixes with various water-glass content. Their compositions are given in Table 2.

Table 2.

Composition of the applied sandmixes

Sandmix type	Sandmix 1	Sandmix 2	Sandmix 3
Component	(1.5 %)	(3.5 %)	(3.5 %)
High-silica sand [kg]	6	6	6
Water-glass 145 [ml]	54.55	127.27	127.27
Water [ml]	15	15	0
Flodur [ml]	0	0	24

Sandmix 1 with 1.5 % of water-glass was applied for manufacture of the cores hardened both with microwaves and the traditional method; Sandmix 2, with 3.5 % of water-glass, was used for hardening the cores with  $\text{CO}_2$ , and Sandmix 3 was hardened using the ester process. To facilitate spreading the binder on the matrix grain surface and to intensify the absorption of microwaves, an addition of water was introduced.

The sandmixes were prepared in a laboratory runner mixer LM-2e. After pouring sand into the mixer, water was added and the sand was stirred for 60 s. Next, water-glass was dosed, and the stirring continued for another 180 s. In the case of the sandmix with Flodur, at the beginning high-silica sand was mixed with the hardener for 120 s, then the binder was added and stirred for another 120 s. Next, the previously assembled moulding box was filled-up and the sandmix was vibration-compacted. The time of these operations was 98 s.

The cores were hardened in four ways:

- using microwaves – the "economical" core was placed in the microwave oven chamber and dried for 300 s at power setting of 1000 W.
- traditional method – the oven was preheated to 110 °C and after placing the cores the process lasted for 1110 s. Power consumption during heating was 1882 W. After preheating, power consumption fluctuated just to maintain the set temperature.
- by purging with  $\text{CO}_2$  – the core was hardened by purging with  $\text{CO}_2$  for 60 s.
- hardening with Flodur – the provisionally hardened core was taken-out from the core box and left for 23 hours for further water removing.

### 3. Results of the research

With respect to the use of research in laboratory conditions, the prototype cores were manufactured individually and the costs were extrapolated to a production lot. Salaries of workers were

accepted as gross 12.10 PLN/h. Labour cost was settled proportionally to the operation time. Omitted was the manufacturing cost of the core box; due to thermal conductivity similar to that of wood, identical core boxes were used for both types of cores. The purchase cost of mixers, thickeners etc., assuming that these type machines belong to standard foundry equipment, was also omitted. Considered in capital allowances was a microwave oven MKT 6.4 made by German company Linn High Therm, available from their Polish distributor, Wichary Technologies. It is a chamber oven with the following specifications:

- microwave power: 6.4 kW
- number of megatons: 8
- chamber dimensions: 800 x 1200 x 800 mm (W x H x D)
- net price: EUR 35 000 [12].

The Czech LAC SV 650/25 was selected to be used as the conventional oven with a similar chamber size to that of the

microwave. It is a low-temperature oven/chamber drier equipped with a trolley, with the following specifications:

- power: 6 kW
- max. temperature: 250 °C
- chamber dimensions: 1000 x 800 x 800 mm (W x H x D)
- net price: EUR 8 280 [13].

For capital allowances the rate of 10 % was accepted, based on depreciation tables. With the currency rate EUR/PLN = 4.20, the monthly allowances are:

- PLN 1225.00 for the microwave oven,
- PLN 271.17 for the conventional oven.

Table 3 includes direct manufacturing costs of a single core. As can be seen, microwave hardening is characterised by relatively low direct costs of materials and electricity.

Table 3.  
Specification of costs for various hardening methods

Designation	Unit	Unit price [PLN]	Core hardened with microwaves		Core hardened in traditional way		Core hardened with CO <sub>2</sub>		Core hardened with Flodur	
			Quantity	Value [PLN]	Quantity	Value [PLN]	Quantity	Value [PLN]	Quantity	Value [PLN]
<b>Total costs</b>				<b>1.4186</b>		<b>2.2492</b>		<b>1.8725</b>		<b>1.6611</b>
1. High-silica sand	kg	0.0768	1.5	0.1151	3.2	0.2456	3.2	0.2456	3.2	0.2456
2. Water-glass	ml	0.0007	13.6375	0.0092	29.0933	0.0197	67.8773	0.0458	67.8773	0.0458
3. Electricity										
- stirring	kWh		0.0233	0.0114	0.1750	0.0854	0.1750	0.0854	0.1750	0.0854
- compacting	kWh	0.4880	0.0008	0.0004	0.0008	0.0004	0.0008	0.0004	0.0008	0.0004
- hardening	kWh		0.1218	0.0595	1.3834	0.6751	-	-	-	-
4. CO <sub>2</sub>	l	4.1678	-	-	-	-	0.0694	0.2891	-	-
5. Flodur	l	0.0061	-	-	-	-	-	-	12.8000	0.0776
6. Labour incl. surcharges	PLN/h	12.10	0.1011	1.2230	0.1011	1.2230	0.0997	1.2062	0.0997	1.2062

As results from analysis of cost simulation, because of depreciation costs, profitability of microwave hardening in a monthly cost balance-sheet is strictly related to the number of manufactured cores. On the assumption that the cores are manufactured in small numbers, e.g. 2000 pcs. per month, the methods not requiring high capital expenditures become somewhat more profitable, see Fig. 3. However, with increasing production volume, the profit from material savings starts favouring the innovative solution, which can be observed already at the quantity of 5000 pieces per month, see Fig. 4. Cost of microwave hardening, slightly higher than that of the other two methods, could be reduced by buying an oven of lower cost (second-hand or post-exhibition equipment). In the case of mass production, however, it seems reasonable to buy an automated continuous microwave oven that would considerably rationalize the manufacturing process.

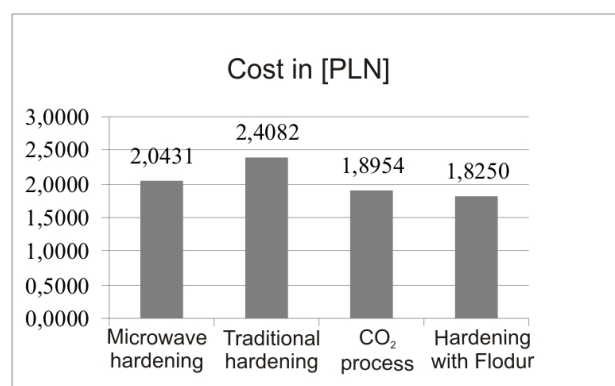


Fig. 3. Unit cost of a core for production level of 2000 pieces per month

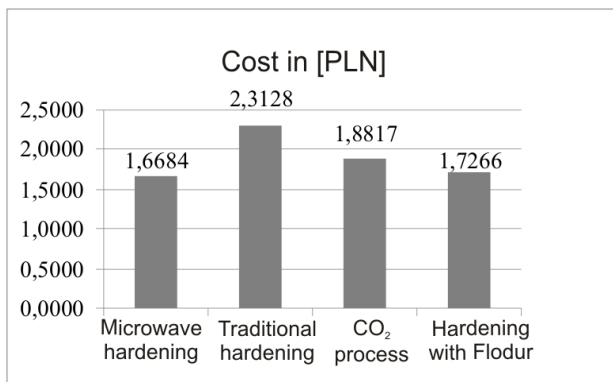


Fig. 4. Unit cost of a core for production level of 5000 pieces per month

In comparison to the other hardening methods, the high fixed costs of microwave drying can be also observed by analysing the break-even point (BEP).

Table 4. Assumption data for a microwave-hardened core

Category	Value
Unit variable cost (VC)	1.42
Fixed cost (FC)	1248.93
Sale with complete use of production capacity (PC)	2000
Change of unit price (P) in PLN/pc.	2.50 → 2.25
BEP1 – price PLN 2.50 = 57.75 % of PC = 1155 pcs. = PLN 2887.50	
BEP2 – price PLN 2.25 = 75.15 % of PC = 1503 pcs. = PLN 3381.75	

In Table 4 above, change in BEP is shown, resulting from a lower unit price for the specifications given in Table 3. As can be seen, the BEP value is relatively high, and the unit price of PLN 2.50 amounts to 57.75 % (BEP1). This is evidenced by the high level of fixed costs. Reduction of price increases the BEP value to 75.15 % (BEP2). The calculated values are within acceptable limits. However, an increase of BEP over 70 % is a warning signal and enforces obeying the organizational discipline, including, e.g. limitation of idle times. For comparison, analysis of BEP of the CO<sub>2</sub> process is shown below, with the assumptions given in Table 5.

Table 5. Assumption data for a core hardened in the CO<sub>2</sub> process

Category	Value
Unit variable cost (VC)	1.87
Fixed cost (FC)	45.72
Sale with complete use of production capacity (PC)	2000
Change of unit price (P) in PLN/pc.	2.50 → 2.25
BEP1 – price PLN 2.50 = 3.65 % of PC = 73 pcs. = PLN 182.50	
BEP2 – price PLN 2.25 = 6.10 % of PC = 122 pcs. = PLN 274.50	

The BEP value for the CO<sub>2</sub> process is very low because of low fixed costs of PLN 45.72 only. With the lowest price in the table above, the BEP value is 6.10 % of production capacity, i.e. 122 pieces, significantly lower than that for microwave hardening. And thus, manufacture is practically profitable from the first piece, but expenses for removing a waste core in the knock-out process are much higher.

## 4. Conclusions

This paper presents a comparison of the four basic methods of hardening cores: traditional drying, microwave heating, hardening with CO<sub>2</sub> and the ester process.

From the viewpoint of foundry reason, the "economical" cores hardened in a microwave oven are characterised by the best properties:

- they are characterised by the best bending, compression and tensile strengths already at 1.5 % of water-glass content [5],
- low water-glass content guarantees good knock-out properties and easy reclamation of sandmix,
- they have the best knock-out properties that are, acc. to the author of [14], decisive for wide application of this kind inorganic binder,
- are characterised by low friability, ca. 15 times lower than in the case of CO<sub>2</sub> hardening [5].

From a technological point of view, the innovative hardening process by microwave heating has a significant advantage over the other methods considered here:

- guarantees full control and repeatability of the process, which permits producing cores perfectly adapted for very high requirements posed to these responsible components of a casting mould,
- thanks to very good technological parameters, it is possible to reduce the quantity of the applied sandmix.

With regard to costs, analysis of the results indicates the following:

- because of low break-even point, the most profitable for short series of cores are the methods characterised by low fixed cost level, i.e. the recommended hardening method is the CO<sub>2</sub> process and the next in the sequence of increasing costs is hardening with liquid hardeners,
- on a large production scale, the methods of traditional drying and of microwave heating become more profitable, although the latter is characterised by a high, disadvantageous break-even point.

It should be noted that the above analysis does not consider the significant costs of cleaning castings and the reclamation of sandmix which in the case of microwave hardening would be much lower than for the other methods, and thus the total cost of the process would be reduced. It seems that this problem should be subject to further investigation.

An important question seems also to be the potential usefulness (because of very good technical parameters) of this innovative microwave hardening method for a wide range of more geometrically complex cores that makes the possibility of extending its application with respect to CO<sub>2</sub> hardening.

## References

- [1] Jelinek, P. (2005). Development of inorganic binders for dehydration microwave hardening. In VIII Foundry Conference Technical. (in Polish).
- [2] Lewandowski, J. L. (1997). *Materials for casting moulds*, , Cracow: Akapit. (in Polish).
- [3] Baliński, A. (2000). *Selected problems of technology of moulding sands with inorganic binders. Structure of hydrated sodium silicate and its effect on binding of sandmixes*. Cracow: Foundry Research Institute (in Polish).
- [4] Jelinek, P & Polzin, H. (2003). Strukturuntersuchungen und Festigkeitseigenschaften von Natrium-Silikat-Bindern. *Giesserei-Praxis*. 2, 51-60.
- [5] Granat, K., Nowak, D., Pigieli, M., Stachowicz, M. & Wikiera, R. (2007). The influence of hardening method on basic properties of water glass molding sands. *Visnik Chmel'nickogo Nacional'nogo Universitetu*. 1 (4), 98-104.
- [6] Granat, K., Nowak, D. & Stachowicz, M. (2010). Application of innovative microwave hardening method in manufacture of cast-steel castings for machine-building industry. *Archives of Mechanical Engineering and Technology*. 30 (1), 19-27. (in Polish).
- [7] Stachowicz, M., Granat, K. & Nowak, D. (2010). Studies on the possibility of more effective use of water glass thanks to application of selected methods of hardening. *Archives of Foundry Engineering*. 10 (spec. iss. 2), 135-140.
- [8] Stachowicz, M., Granat, K. & Nowak, D. (2011). Influence of water-glass grade and quantity on residual strength of microwave-hardened moulding sands. Pt. 1. *Archives of Foundry Engineering*. 11 (spec. iss. 1), 93-98.
- [9] Granat, K., Nowak, D., Pigieli, M., Stachowicz, M. & Wikiera, R. (2009). Determination of application possibilities of microwave heating in the curing process of water glass molding sands with fluid esters. Pt. 1. *Archives of Foundry Engineering*. 9 (spec. iss. 1), 45-50
- [10] Granat, K., Nowak, D., Pigieli, M., Stachowicz, M. & Wikiera, R. (2009). Determination of application possibilities of microwave heating in the curing process of water glass molding sands with fluid esters. Pt. 2. *Archives of Foundry Engineering*. 9 (1), 51-56.
- [11] Stachowicz, M., Granat, K & Nowak, D. (2010). Application of microwaves for innovative hardening of proecological sandmixes with water-glass used in manufacture of cast-steel castings. *Archives of Mechanical Engineering and Technology*. 30 (1), 19-27. (in Polish).
- [12] Retrieved 15.06.2011, from <http://wichary.eu/>.
- [13] Retrieved 15.06.2011, from <http://www.lac.cz/produkty/katalogove-pece-susarny/prumyslove-pece-susarny-plastikarstvi-gumarenstvi-povrchove-nizkoteplotni-pece-susarny-komorove-zavazecim-vozikem-sv/>.
- [14] Strumps, E. (2009). Den anorganischen Bindersystemen gehört Zukunft. *Giesserei*. 7, 59.