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Investigations Concerning Improvements of the Knock Out Property of Ceramic Moulds Applied in the Investment Casting Technology

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Abstract

In lost wax technology, self-supporting ceramic moulds are made, which must have adequate strength after being filled with liquid metal. The final structural strength is determined by such factors as the thickness of the individual layers applied to the wax model resulting from the viscosity of the liquid mass, the specific strength of the layers formed, and the heat treatment of the moulds. The development of technology and materials is moving in the direction of increasing the specific strength of self-supporting ceramic moulds. The consequence of this is that the final strength of these moulds is too high, making it difficult to knock castings out of the moulds. Removing mould remnants from holes, closed spaces of the casting, corners, sharp edges, variable cross sections and etc. is cumbersome. In order to remove mould remnants from the casting, a method is used to dissolve them in heated solutions of suitable chemical composition and reaction.

The paper presents the results of research on a new solution, the essence of which is the production of layers in a ceramic mould, in the middle zone of the mould, characterized by a significantly reduced final strength, achieved after firing. These layers are produced using a different liquid ceramic mass than the base one, based on an organic binder. As a result, thanks to the embedded layer, very good knock-out of castings is achieved and separation of residual ceramic mass. Special layers can be incorporated over the entire surface or only in those places where the bonding of the casting surface and ceramic mass occurs.

Keywords: Ceramic moulds, Lost wax technology, Knock-out properties, Colloidal silica, Wax model

1. Introduction

Modern casting technology using investment castings is one of the basic technologies in producing precision castings. The precision of castings, with reference to maintaining the geometry and dimensions as well as a high surface smoothness, has determined its majority over other casting methods [1, 2]. Investment casting technology is applied in the production of small and medium castings that are mainly made of ferrous alloys, steel castings, and special alloys that are used in the aviation, motorisation, machine, and armament industries. Multilayer ceramic moulds are poured at high temperatures – even those above 1000°C. Silicate binders that are based on colloidal silica are applied in investment casting; these provide high strengths at high temperatures (which are necessary in self-supporting moulds). The silica binder is not thermally destructed after making a casting, while the ceramic shell undergoes only crumbling and cracking. In other technologies of expendable moulds, the binder is destructed by means of either gasification (organic binders) or dehydration (inorganic binders). The mould and its elements (cores) lose cohesion and decompose, while the moulding sand sometimes undergoes total disintegration [3-5].

The practice of utilising silica binders in investment casting indicates that such a mould relatively easily separates from some parts of a casting surface while being simultaneously difficult to separate in other parts of the casting. Small steel castings that are produced by the investment casting are presented in Figure 1. The external surfaces of these knocked-out castings are 'clean' – the ceramic moulding sands are completely removed from these surfaces, while the leftovers of the not-knocked-out sands still remain in the internal sections of the castings (in closed corners and any openings).

Fig. 1. Steel castings produced by investment casting

A similar situation occurs in classic technologies, where not-knocked-out sands very often remain in closed spaces. However, the mechanism of sands that remain in corners and channels in the cases of classic technologies is quite different than in the cases of ceramic moulds. The difficulties in knocking out moulding sands in classic technologies are related to the sintering of the sands, which leads to a high retained strength. The high strengths of ceramic moulds are achieved during their production (at roasting, before their pouring with liquid metal). Ceramic moulds are roasted at temperatures of 700° to 1100°C [6-8].

When looking for the reasons and mechanisms of sand tightening in closed spaces, cavities, and the openings of ceramic moulds, attention should be directed to the changes in the dimensions that are caused by the thermal contraction. The processes of expansion and shrinkage are of concern in castings as well as in ceramic moulds when their temperatures change. The thermal expansion of casting alloys is much greater than that of ceramic materials that are applied for multilayer shell moulds. The values of the coefficients of the thermal expansions of selected alloys and ceramic materials are listed in Table 1.

Table 1.
Coefficients of thermal expansion of selected materials

Materials	Alloyed steel	AK9	Fe	ZrO_2	Al_2O_3
$\alpha[1\cdot10^{-6}/K]$	18,9-20,0	24,0	13,4	10,0	5,5-8,4

After pouring a mould with liquid alloy and after the solidification of the casting, the cooling procedure starts; in parallel, the casting and ceramic mould also start to shrink as a result. Ceramic moulds with high compression strengths should also be treated at high temperatures as to not be susceptible such shrinkage [9, 10]. A ceramic shell in a closed space is 'tightened' due to the differences in the coefficients of the thermal expansionof a casting alloy and of a ceramic shell. This is shown in Figure 2 [11, 12]. Strength/stresses tighten a shell in a closed space; in casting openings, between walls, etc., this will be the higher. The greater the difference between the thermal expansion of the alloy and the ceramic mould, the higher the cooling range of the casting will be (from the transfer of a solid state to the surrounding temperature). It should be expected that, in the cases of steel castings, ceramic moulds are tightened the most due to their high melting temperatures.

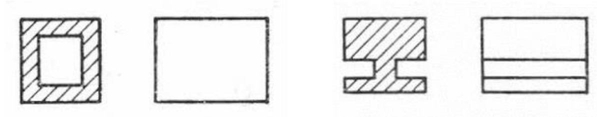


Fig. 2. Sketches of castings in which hindered thermal shrinkage occurs

When analysing the process of metal shrinkage in a ceramic mould on the external sides of castings, it should be noticed that the described differences in the values of the thermal expansions of an alloy and ceramic mould favour the mould's separation from the casting. When the ceramic mould is cooled, it shrinks less than the casting that is inside it. Thus, the conditions are formed for the intrinsic separation of the shell from the casting. This is confirmed in practice, where a cracked external ceramic shell easily separates from the external surface of a casting.

The idea of solving the problem of 'tightening' ceramic shells in closed cavities and openings is reduced to technological operations that are aimed at lowering the strengths of the near-surface layer of the ceramic moulds. This strength-lowering concerns parts of the mould where the shrinkage effects lead to its strong tightening. This can be realised by building one or more layers into the structure of multilayer mould that will be characterised by a low strength after roasting the ceramic mould and after cooling the metal that is poured into it. An idea for this solution is presented in Figure 3. For the formation of such a weakening layer, ceramic sand with a binder should be used that does not influence the high strengths of the layers with colloidal silica on the one hand and is subjected to thermal degradation during the annealing on the other [13].

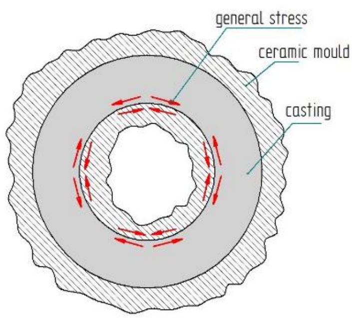


Fig. 3. Cross-section of ceramic mould with ceramic core in its middle part

An aqueous binding agent that fulfils the mentioned criteria is polyvinyl alcohol (PVA), which polymerises in the presence of silicates and borates. By the means of aqueous solutions of sodium silicate or sodium borate, the cross-linking reaction of PVA provides polymers with such properties (depending on the amounts of the applied silicates or borates). Small amounts of cross-linking agents result in small amounts of silica or borate ions being able to joining the polyalcohol particles to provide a weak but quite elastic polymer that can be stretched into nearly transparent thin foils. The application of higher amounts of these ions leads to obtaining less of the elastic polymer but allowing it to be formed into various shapes [14].

In the cases of ceramic moulds in which one or more layers are made of ceramic sand contain PVA as a binder, the polymerisation process of the alcohol will be initiated by colloidal silica. This will contribute to joining the neighbouring layers: one with the silica binder, and another with the polyvinyl alcohol binder. The verification of such a concept of producing multilayer ceramic moulds requires the investigations that are described below; these contain the production of ceramic moulds with additional layers with PVA as a binder as well as their roasting. To verify the influence of the additional layers on the knock-out properties of moulds and on the ease of separating them from the corners and cavities in castings, bushing-shaped iron castings and small toothed wheels were made. Then, an assessment of the ease of removing the ceramic mould's left-overs from the cavities and the developed surfaces of the castings was performed.

2. Own research

Producing test ceramic moulds

Four kinds of wax patterns of different shapes were used to produce multilayer ceramic moulds. In all of the tests, six-layered ceramic moulds were made. Photographs of the wax models and ceramic moulds can be seen in Table 1. The ceramic moulds were made in a standard way: depositing a layer of liquid ceramic sand on the wax model, then depositing a granular layer (the so-called powder topping), drying the mould, and producing the next layer. This cycle was repeated six times, a part of the layers was made of silica liquid ceramic sand, while another part was made of liquid sand with an aqueous solution of polyvinyl alcohol (PVA).

The heat-treatment process of the moulds was based on the sintering and mutual joining of previously loose grains. This caused increasing surfaces of the joints between the powder topping grains (related to the shrinkages of the grains) and the elimination of the closing empty spaces (pores) between the grains. During the solidification of the metal that was poured into the shell mould, the strong joining of the ceramic mould with the casting surface occurred on the selected surfaces; this rendered the knocking out of the casting difficult. In order to increase the effect of the joining the moulds with the castings, the castings in which this effect is very common were selected for the test castings. These were castings of a bushing with a bottom and castings of toothed wheels. In the case of the bushing with the bottom, the problem of sand being knocked out occurred at the internal side in the vicinity of this bottom. In the case of the toothed wheels, problems concerning the sands being knocked out and their separation from the casting occurred in the corners and in the vicinities of the sharp edges. Other wax models (beam and plates – shown in Table 2) were used for making ceramic moulds in order to determine the beam's bending strength and the permeability of the multilayer ceramic moulds (plates).

Table 2.
Test wax models and ceramic moulds

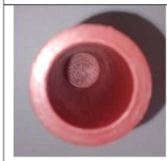
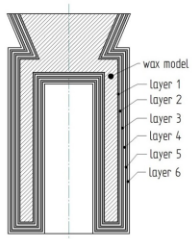
Wax model/ ceramic mold after wax melting/ sleeve	Wax model/ ceramic mold after wax melting /gear wheel	Wax model/ ceramic mold after wax melting / Rg bending strength tests	Wax model/ceramic mold after wax melting / permeability tests P
			
			
MOULD I	MOULD II	MOULD III	MOULD IV

Table 3 presents descriptions of the structures of the individual layers of the ceramic moulds. Two kinds of liquid ceramic sands were applied in the investigations: "Ludox AM ceramic sand" (which was made on the base of the colloidal silica with an addition of aluminium oxide powder [Al_2O_3]), and "X ceramic sand" (which was made on the base of the organic PVAL binder [in a 4:1 ratio to water]). The PVAL (a polymer of vinyl alcohol) was either in the form of a white powder or a granular material that was dissolved in water. The main aim of the ceramic sand being prepared in such way was the weakening of the final structural strength of the ceramic mould (after roasting). This built-in X layer was coloured black in order to contrast with the other layers.

Table 3.
Structures of individual ceramic layers

Layer number	CERAMIC MOULD 1	CERAMIC MOULD 2	CERAMIC MOULD 3	CERAMIC MOULD 4
1	CERAMIC MASS Ludox AM+ Mullite „1”	CERAMIC MASS Ludox AM+ Mullite „1”	CERAMIC MASS Ludox AM+ Mullite „1”	CERAMIC MASS Ludox AM+ Mullite „1”
2	CERAMIC MASS Ludox AM+ Mullite „2”	**CERAMIC MASS X** + Mullite „2”	CERAMIC MASS Ludox AM + Mullite „2”	CERAMIC MASS Ludox AM + Mullite „2”
3	CERAMIC MASS Ludox AM+ Mullite „2”	**CERAMIC MASS X** + Mullite „2”	**CERAMIC MASS X** + Mullite „2”	**CERAMIC MASS X** + Mullite „2”
4	CERAMIC MASS Ludox AM+ Mullite „2”	CERAMIC MASS X Ludox AM+ Mullite „2”	**CERAMIC MASS X** + Mullite „2”	**CERAMIC MASS X** + Mullite „2”
5	CERAMIC MASS Ludox AM+ Mullite „2”	CERAMIC MASS X Ludox AM+ Mullite „2”	CERAMIC MASS Ludox AM+ Mullite „2”	**CERAMIC MASS X** + Mullite „2”
6	CERAMIC MASS Ludox AM+ Mullite „3”	CERAMIC MASS X Ludox AM+ Mullite „3”	CERAMIC MASS Ludox AM+ Mullite „3”	CERAMIC MASS Ludox AM+ Mullite „3”



For each wax model, the ceramic moulds were made in four variants: I, II, III, and IV (described in Table 3). The moulds in Variant I were made in a traditional way as the reference ones were this means that the sand that was based on the colloidal silica (trade name – Ludox AM) being deposited on each layer. On the other hand, the moulds in the three remaining variants contained only the matrix. Each layer was sprinkled with granular refractory material, which was used as a matrix of the layer as well as to increase the final strength of the mould. The grain sizes were as follows: Mullit I da - 108.51 μm; Mullit II da – 326.46 μm; and Mullit III da –

624.99 μm. After depositing all of the layers and preliminarily drying the mould, a wax model was removed (melted). Next, the mould was dried for 4 hours at a temperature of 50°C and then annealed in stages in a silite furnace within a temperature range of 400°-1100°C for 8 hours altogether.

Investigations of test moulds properties

Since investigations of the permeability of ceramic layers are not standardised and normalised, a new measuring methodology that was developed in AGH's Laboratory of Foundry Moulds Technology of the Faculty of Foundry Engineering was applied. The investigations were performed on the apparatus for testing the permeability of the foundry sands. Figure 4 shows the sampler with the mounted ceramic mould for the permeability testing. The applied methodology allowed for a fast and easy measurement, utilising the simple shapes of the sample and the universal laboratory device.

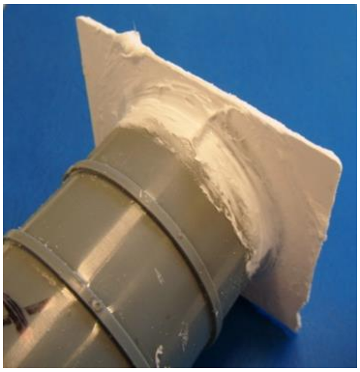


Fig. 4. Sampler with glued ceramic mould readied for permeability tests

The sampler with the tested flat sample (ceramic mould) was situated in the place of measuring the bushing in the LPiR1 device. This sampler consisted of a plastic joint with a diameter of d = 50 mm and the tested ceramic mould in the shape of a plate being glued to it. Investigations of the bending strength were performed on the testing machine by means of the three-point test. A diagram of the denotation of the bending strength is presented in Figure 5. In this case, the sample shape was standardised, and the bending strength was defined as the maximum tensile stress in the sample bending test.

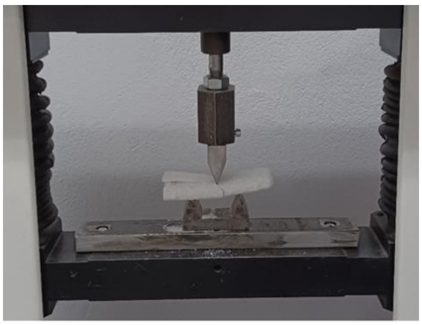


Fig. 5. Investigations of bending strength

Results of investigations

The results of the permeability and strength tests of the ceramic moulds that were made in four variants are presented. Each tested sample was characterised by a different structure in its multilayer structure. The results of the permeability investigations of the ceramic moulds that were obtained for the moulds that were built with six different layers are shown in Figure 6, while the results of their bending strengths are shown in Figure 7. The highest strength value that was achieved was the Variant III mould (in which two layers with the PVAL binder were built-in).

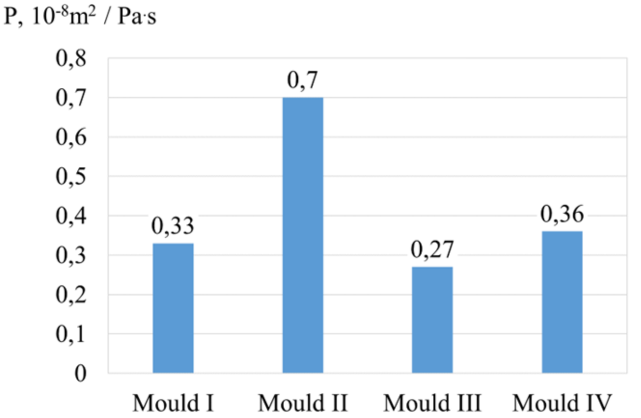


Fig. 6. Permeability of six-layered ceramic moulds

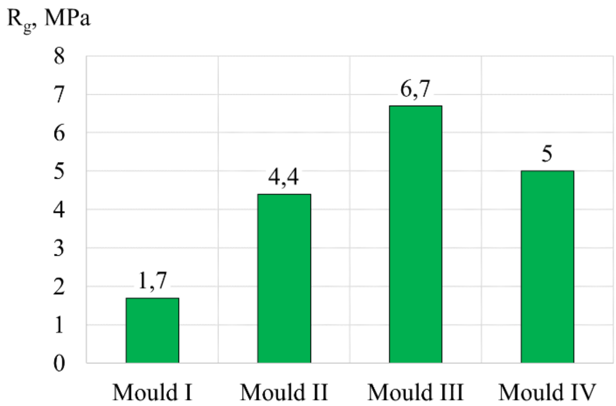


Fig. 7. Bending strengths of ceramic moulds

The layers of the ceramic mixture that are formed on wax model surfaces are – in practice – never uniform in their thickness. This is caused, among others, by the heterogeneous preparation of thin layers (of a thickness of approx. 1 mm) that make the mould as well as by different sizes of refrectory matrix grains. In order to obtain reliable values, the results that are presented in this paper are the averages of three measurements. The highest permeability value ($0.7\ 10^{-8} m^2/Pa*s$) was obtained in the ceramic Mould II, which had two built-in layers that were made on the basis of the X ceramic sand.

Testing knocking-out properties of shell moulds

The last stage of the investigations constituted assessments of the knocking-out properties of the bushings as well as the toothed wheels. After the annealing, the moulds were heated to a temperature of appr. 500°C and then poured with a liquid alloy (cast iron). After the castings reached the surrounding temperature, the assessments of the knock-out properties started. Separating the shells from the castings was performed on a vibratory table for 1 and 3 minutes after placing the sample on the table plate. Observations were realised at certain intervals of the vibration time. The castings of the bushings were subjected to vibrations for 1 and 3 minutes (Fig. 8), while the toothed wheels were vibrated for 1 minute (Fig. 9).

The three-minute-long vibration of the castings allowed for the complete removal of the ceramic shell from the external surfaces of the bushings. However, the ceramic sand that was on the internal side (in the opening) was not removed (Fig. 9) – a visible difference can be seen in the photograph. The casting, which was made by pouring the traditional Mould I by cast iron, was characterised by the lack of a knock-out property. Inside the bushing (in the place of the opening), the 'trapped' ceramic sand could be seen. This sand can be removed either by an additional finishing treatment (chipping) or by chemical dissolving. In many cases, the chemical treatment is not efficient, it can lead to casting corrosion, and it is costly.

The ceramic moulds that were made in Variants II, III, and IV were characterised by much better knock-out properties and by their ease of separation from the castings. The best effect was obtained at making Mould III, in which the third and fourth layers were made of X ceramic sand (which was based on an organic binder). After annealing the ceramic mould at a temperature of 1000°C, between mould layers, being near the model and external layers the space filled with powders and grains – which formed the X layer – was developed.

a)

b)

Fig. 8. Test castings subjected to knocking-out on vibratory table – external side of bushing casting: a) view of castings after 1 mammoth treatment on vibrating table; b) view of castings after 3 mimytes processing on vibrating table

a) b)

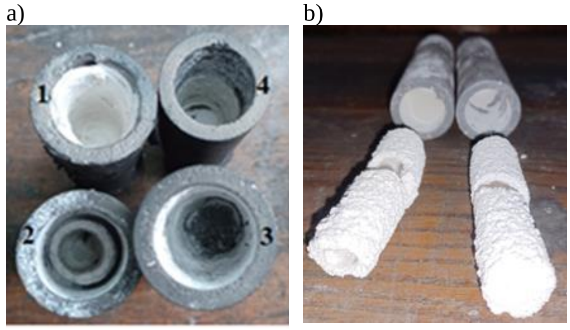
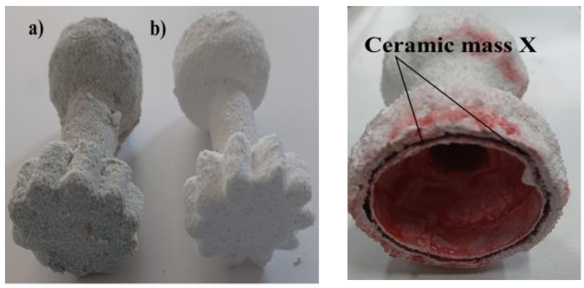


Fig. 9. Test castings subjected to knocking-out on vibratory table: (a) internal side of bushing casting; (b) ceramic mould knocked out from opening of bushing (ceramic core)

The binder was gasified. Such an effect occurred in both the bushing and toothed-wheel forms. The X ceramic sand that was used in the tests that were made on the basis of the organic binder disintegrated, as the binder burned away under the temperature's influence in the annealing process. As the final effect, it caused the weakening of the selected layers and structures of the multilayered ceramic moulds. Such an effect provided significant improvements in the knock-out properties of the shell moulds (even those with complicated shapes).

Similar effects concerning the improvements in the knocking-out properties of the ceramic moulds that were applied in the investment casting technology were achieved for the other castings (e.g., the toothed wheels). In the cases of these castings, the "jamming" of the ceramic sands occurred between the teeth of the wheel. The performed tests confirmed this effect. The ceramic moulds that were used for the castings of the toothed wheels are shown in Figure 10.

The castings of the toothed wheels after being subjected to the knocking-out on the vibratory table are presented in Figure 11. It can be noticed that, after the three-minute treatment of vibrations, the separation degree of the shell from the casting was significantly greater in the cases of the moulds with the built-in layer/layers with the organic binder (X ceramic sand).



(a) Applied layer of ceramic compound X - gray color, (b) Applied layer of Ludox AM ceramic compound

Mould after wax melting, visible embedded layer X

Fig.10. Ceramic moulds of toothed wheels

Ludox AM Ceramic mass X

Fig. 11. Castings of toothed wheels after 1 minute of vibrations

3. Conclusions

Very often, models with complex surface geometries are produced in investment casting. Knocking out such castings from ceramic moulds is not efficient – especially in closed spaces, openings, and corners. It is not possible to separate ceramic sand from a casting; the mechanism of this effect of 'clinging' to the casting in the aforementioned spaces can only be explained on the basis of shrinkage effects. Castings that are made of alloys with much higher shrinkage potentials than ceramic moulds clamp the leftovers of sand in openings and corners, making it difficult to separate them from the casting.

The performed investigations indicated that building in layers that weaken a mould is a correct action when striving to improve a casting's knocking-out from a ceramic mould when applied in investment casting. When applying the proposed solution, it is possible to either weaken the whole multilayer ceramic mould by building in an X layer on the whole surface of a wax model or to weaken only those points in which the sand 'clings' and is difficult to remove.

Being only at the present stage of a preliminary character, the performed investigations also indicated that built-in layers of organic binders cause higher permeability values in multilayer ceramic moulds (which is a favourable effect). Out of the group of the compared structure variants of ceramic moulds, the best knock-out properties were characterised in moulds with built-in layers with organic binders as Layers 3 and 4.

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