ARCHIVES
of
FOUNDRY ENGINEERING
10.24425/afe.2025.155363
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2025
Issue 3/2025
141 – 148
16/3

An Innovative Method for Producing Ceramic Moulds with Enhanced Knock-Out Properties Using Lost-Wax Casting Technology

J. Kolczyk-Tylka
AGH University of Krakow, Poland
Corresponding author: E-mail address: kolczyk@agh.edu.pl

Received 18.02.25; accepted in revised form 09.06.25; available online 25.07.2025

Abstract

This paper presents an innovative ceramic mould manufacturing technology aimed at improving the driftability of particularly difficult castings, which are characterised by complex geometry and a high tendency to bake/clog the mass in critical areas of the mould (holes, closed casting spaces, corners, sharp edges, variable cross-sections). Traditional ceramic moulds, despite their strength, often create problems during the casting knockout process, leading to casting damage and increased cleaning costs.

The new technology is based on the use of a hybrid mould structure, the essence of which is the production of layers in the ceramic mould, in the central zone of the mould, characterised by a significantly reduced final strength, achieved after firing. These layers are made on the basis of an organic binder. As a result, excellent driftability of the castings and effective separation of ceramic residues from the surface of the castings is achieved due to the embedded layer. The special layers can be incorporated over the entire surface or only in the areas where fusion of the casting surface with the ceramic mass occurs.

Tests conducted have shown that the developed technology significantly improves the driftability of ceramic moulds, especially for castings with complex geometries, where traditional methods fail. The introduction of this innovation has the potential to be widely applied in various industries where the requirements for precision and quality of castings are very high, such as the aerospace, energy and automotive industries.

Keywords: Ceramic moulds, Lost wax technology, Colloidal silica, Wax model, Strength

1. Introduction

The production of precision castings is dominated by pattern-melting technology. This method is characterized by a very high degree of shape accuracy, even for complex geometries, along with high surface smoothness and excellent dimensional precision. These features make pattern-melting technology competitive with other casting production methods. Using this technology, we primarily produce small- to medium-sized castings of moderate weight [1, 2].

For environmental reasons, the primary component of the ceramic slurry used in this technology is colloidal silica. After the ceramic moulds are fired, this provides them with high strength at elevated temperatures [3, 4]. During the annealing process of the ceramic mould, which takes place at approximately 1100°C, the water from the colloidal silica evaporates. The silica particles, together with the matrix applied to the ceramic mould, form a vitrified, thermally resistant structure that remains intact and does not degrade.

When knocking out technologically complex castings (with intricate surface geometries) from ceramic moulds made entirely of silica binders, it is relatively easy to separate the shell from the outer flat surfaces of the castings. However, sensitive areas such as holes, cavities, and enclosed sections inside the casting remain difficult to separate. The ceramic mould is completely removed from the external surfaces of the castings, but in internal zones with enclosed surfaces, remnants of ceramic material persist, making mechanical removal challenging. In such areas, the ceramic mass becomes mechanically trapped due to the shrinkage processes of both the casting and the shell [5–7].

When analyzing the causes and mechanism of material clamping (Figure 1) in confined spaces, cavities, and holes, it is important to consider the dimensional changes resulting from the thermal contraction of the mould and casting. The process of expansion and contraction affects both the casting and the ceramic mould during temperature changes. Casting alloys exhibit much higher thermal expansion/contraction compared to the ceramic materials used in multilayer shell moulds.

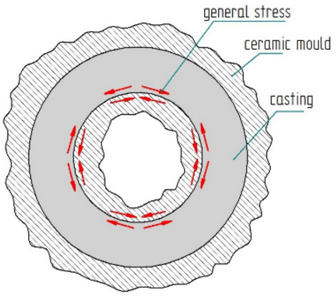


Fig. 1. Cross-section of the ceramic mould with ceramic core in its middle part

Once the mould has been flooded with liquid alloy and the casting has solidified, simultaneous cooling and associated shrinkage of both the casting and the ceramic mould begin. Ceramic moulds, characterized by their high compressive strength even at high temperatures, should therefore be regarded as resistant to the shrinking of the casting. Inside the casting, in confined spaces, the ceramic shell is "clamped" due to differences in the thermal expansion coefficients of the casting alloy and the ceramic mould. The compressive force or stress on the ceramic moulds in confined spaces, such as the casting holes or the spaces between walls, increases in proportion to the difference between the thermal expansion of the alloy and the ceramic mould, as well as the cooling temperature range of the casting—from solidification to ambient temperature. In the case of steel castings, due to their high melting point, the strongest clamping of the ceramic mould is to be expected [8, 9].

When analyzing the process of metal shrinkage in the ceramic mould on the outside of the castings, it should be noted that the differences in thermal expansion of the alloy (high shrinkage) and the ceramic mould (low shrinkage) promote their mutual separation. During cooling, the ceramic mould shrinks less than the casting inside it, which creates the conditions for the spontaneous separation of the shell from the casting surface. This phenomenon is confirmed in practice—the cracked outer ceramic mould easily detaches from the casting surface. In confined spaces, as shown in Fig. 1, the situation is the opposite, with excessive shrinkage of the alloy leading to the crimping of the shell, whose shrinkage is less [10, 11].

The solution to the problem of "clamping" of the ceramic mould in closed cavities and holes lies in applying appropriate technological measures to reduce the strength of the near-surface layer of the ceramic mould. This applies to areas where metal shrinkage leads to strong clamping of the mould. In practice, this can be achieved by incorporating one or more layers with reduced strength into the structure of the multilayer mould. These layers will be more susceptible to cracking after the mould has been fired and the metal has cooled [12]. Ceramic masses with a binder that does not reduce the strength of the remaining colloidal silica-containing layers, while thermally degrading during annealing, can be used to create such weakening layers [13, 14].

An aqueous binder that meets these requirements is polyvinyl alcohol (PVA), which undergoes polymerization under the influence of silicates or borates. Crosslinking of PVA using aqueous solutions of sodium silicate or sodium borate leads to the formation of polymers, the properties of which depend on the amount of crosslinking agents used. Small amounts of silicate or borate ions, which bind the polyalcohol molecules, create a fragile but flexible polymer that can be stretched into thin, almost transparent films. In contrast, higher amounts of these ions result in a polymer that is less flexible but can be formed into various shapes [15].

In the case of ceramic moulds, where one or more layers are formed from a ceramic mass using PVA as a binder, the polymerization process of the alcohol is initiated by colloidal silica. Through this mechanism, the bonding of adjacent layers—one containing a silicate binder and the other with a PVA binder—is achieved. Verification of this concept required studies, the details of which are described below.

The precision casting process requires the use of high-quality ceramic moulds, which must exhibit adequate mechanical strength during casting while allowing the casting to be easily removed (knocked out) after solidification. This is particularly important for so-called "difficult" castings, such as thin-walled castings with complex geometry.

The present work focuses on the development of an innovative ceramic mould manufacturing technology that aims to increase driftability, especially for complex-shaped castings, while maintaining high surface quality and resistance of the moulds to mechanical and thermal damage.

2. Self-Study

Making test ceramic moulds

As part of the research, multilayer ceramic moulds were produced in which additional layers with PVA alcohol as a binder were incorporated and then annealed. To determine the effect of these layers on the driftability of the moulds and the ease of removing their residues from the interior and hard-to-reach areas of the castings, iron castings were made in the form of smooth sleeves and sleeves with holes. An analysis of the ease of eliminating ceramic mould residues from both the interior and exterior surfaces of these castings was then carried out.

Two types of wax sleeve models were used to manufacture multilayer ceramic moulds: a smooth sleeve and a sleeve with holes, to assess the driftability of the moulds. Additionally, a flat rectangular shape (beam) was used to test the bending strength of the ceramic moulds. Six layers of ceramic mould were applied to all models along with the matrix. Figures 2 and 3 show the models and the ceramic moulds made from them.

Fig. 2. Wax moulds and ceramic molds sleeves

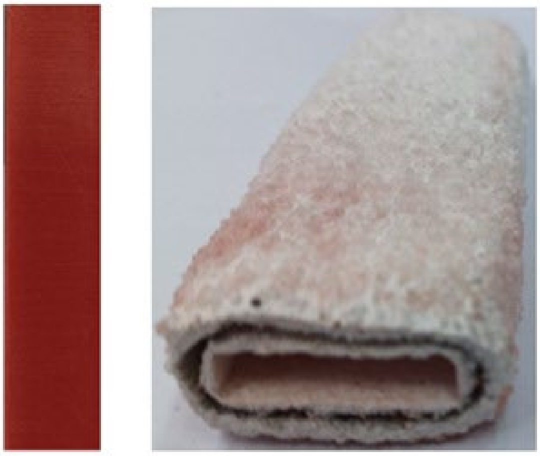


Fig. 3. Wax moulds and ceramic mold for flexural strength testing

The ceramic moulds were made in a standard manner: applying a layer of liquid ceramic mass to the wax model, followed by a granular layer (known as sprinkling), drying the mould, and repeating the process for subsequent layers.

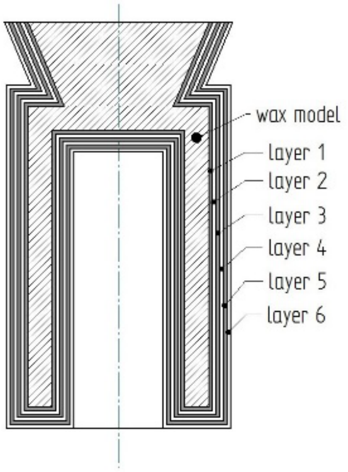
This cycle was repeated six times, except that some of the layers were formed from molochite-based liquid ceramic, while others were formed using a liquid ceramic mass with an aqueous solution of polyvinyl alcohol (PVA). The heat treatment process of the ceramic moulds involves sintering and interlocking of the initially free-flowing grains, which increases the contact area between the granular particles. This is accompanied by shrinkage of the binder bridges and the elimination or closing of voids (pores) between them. During the solidification of the metal in the flooded shell mould, strong bonding of the ceramic mould to the casting surface occurs in some areas, which hinders the knock-out process.

To better investigate this phenomenon, castings prone to such issues were selected for testing. These included smooth-bottomed bushing castings and bushings with holes in the side walls. In the case of bushings with a bottom, difficulties in removing the ceramic material occurred inside the sleeve, near the bottom, and around the holes.

Table 1 describes the structure of the individual layers of the fabricated ceramic moulds.

Table 1.
Structure of the individual layers of ceramic moulds

Layer number	CERAMIC MOULD 1	CERAMIC MOULD 2	CERAMIC MOULD 3	CERAMIC MOULD 4	CERAMIC MOULD 5
1	CERAMIC MASS Ludox AM+ Molichite	CERAMIC MASS Ludox AM+ Molichite	CERAMIC MASS Ludox AM+ Molichite	CERAMIC MASS Ludox AM+ Molichite	CERAMIC MASS Ludox AM+ Molichite
2	CERAMIC MASS Ludox AM+ Molochite	**CERAMIC MASS X** + Molochite	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molochite
3	CERAMIC MASS Ludox AM+ Molochite	**CERAMIC MASS X** + Molochite	**CERAMIC MASS X** + Molochite	CERAMIC MASS + Molochite	**CERAMIC MASS X** + Molochite
4	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS + Molochite	**CERAMIC MASS X** + Molochite	**CERAMIC MASS X** + Molochite	CERAMIC MASS Ludox AM+ Molochite
5	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molochite	**CERAMIC MASS X** + Molochite	CERAMIC MASS Ludox AM+ Molochite
6	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molichite	CERAMIC MASS Ludox AM+ Molochite	CERAMIC MASS Ludox AM+ Molochite



The liquid ceramic mass (CMC) used in this study was prepared in two types: the first, "Ludox AM ceramic mass," based on colloidal silica with the addition of molochite meal, and the second, "X ceramic mass," based on an organic binder—poly(vinyl alcohol) (PVA)—soluble in water at a 4:1 ratio (water to binder). Ceramic mass X was prepared by mixing PVA, in the form of a white powder, with molochite meal. Its main purpose was to weaken the strength of the ceramic mould in the middle thickness of the layers after firing. To facilitate identification, the "X" layer was deliberately colored black to distinguish it from the other mould layers.

For each wax model (sleeves, beams), ceramic moulds were made in five variants: 1, 2, 3, 4, and 5, as described in Table 2. The moulds in Variant I were made in the traditional way (reference), with each layer consisting of colloidal silica-based ceramic mass (Ludox AM). Moulds in Variants 2, 3, 4, and 5 were experimental and made using two types of ceramic mass, combined with the same granular matrix. For the final (sixth) layer, a high-strength granular material with the largest grain size (0,5-1mm) was applied to reinforce the mould structure. After all layers were applied and the mould was pre-dried, the wax models were removed (rendered).

The moulds, now without the wax model, were dried at 50°C for 4 hours and then annealed in stages in a sylvite oven. The temperature range during annealing was 400–1100°C over a total duration of 8 hours.

Testing strength properties of the moulds

The bending strength of the six-layer ceramic moulds was tested using a three-point testing method. The test setup is illustrated in Figure 4. The bending strength is defined as the ratio of the bending moment at fracture to the simplified section strength index (rectangle).

Fig. 4. Bending strength of ceramic moulds

Figure 5 presents the results of the bending strength tests for the ceramic beam moulds.

The ceramic layers applied to the surface of the wax model are usually not uniform in thickness. This is due, among other reasons, to the uneven application of thin layers (approximately 1 mm thick) and variations in the grain size of the refractory matrix. To obtain reliable results, the values presented in this study are the averages of three measurements.

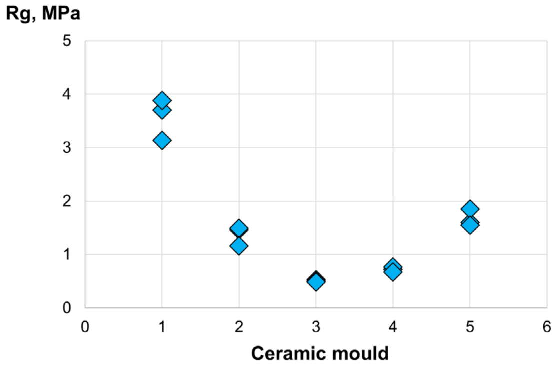


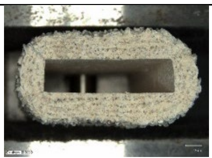
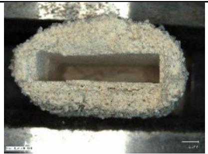
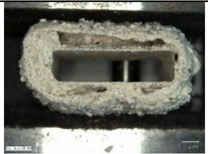
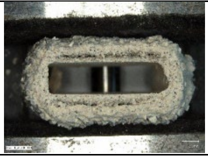
Fig. 5. Bending strength of ceramic moulds

The highest flexural strength value, approximately 4 MPa, was achieved by the traditional ceramic mould (Variant 1). Test moulds 2, 3, 4, and 5 displayed lower strength values. In all four experimental cases, ceramic mass was introduced to weaken the structural strength of the mould. Details of the "X" layer construction are shown in Table 1. The lowest flexural strength value, 0.5 MPa, was observed for mould 3. This lower strength value is directly related to the improved driftability of the ceramic moulds.

Table 2 provides photographs of the ceramic moulds at the fracture site after the bending test. The images were captured using a confocal microscope. The table includes a structural analysis of the ceramic moulds at different magnifications (10x and 50x) to assess their fabrication quality. Cross-sectional images reveal macroscopic structural details, including porosities, cracks, grain size, and other features of the ceramic material.

In the images of ceramic moulds numbered 3 and 5, layers with visible voids left by the organic binder can be observed, indicating a weakened structure. Moulds 3 and 5 contain an embedded weakened layer of ceramic mass X. In the case of mould 3, the weakening occurred at the 3rd and 4th layers, whereas for mould 5, it was at the 3rd layer. In both cases, a distinct loss of the applied layer within the multilayer ceramic mould structure is visible.

Table 2.
Images taken with a confocal microscope at 10x and 50x magnification

No	Zoom 10x	Zoom 50x
1		
2		
3		
4		
5		

The introduction of a polyvinyl alcohol (PVA)-based binder into selected layers of the ceramic mould allows for structural weakening after firing, facilitating its removal during the knockout process in hard-to-reach areas of the casting. Research has confirmed that PVA undergoes controlled thermal degradation, leading to the formation of a porous layer with reduced mechanical strength, which promotes easier separation of the mould from the casting. Figures 6 and 7 show cross-sections of ceramic mould 3.

Figures 6 and 7 provide a clear view of the material's cross-section, which exhibits an irregular and porous structure. In the central part of the sample, a larger empty space is visible, indicating cavity formation, porosity, and degradation during the annealing process of the ceramic moulds. In Figure 7, the color map indicates surface height variability:

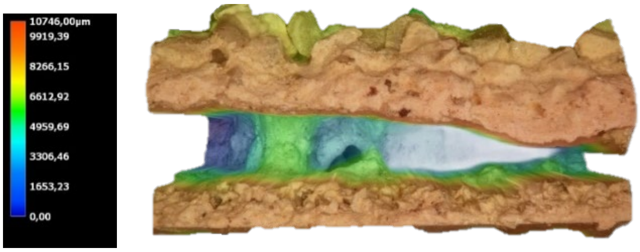


Fig. 6. View of ceramic mould No. 3

- Red and orange: Areas with the highest height (~9337 µm).
- Yellow and green: Areas with lower height (~1400–5000 µm).
- Blue and dark blue: The lowest structures (~0 µm), indicating deep pores or channels.

The upper and lower layers have a rough structure with numerous irregularities and pores. The inner area appears more recessed, indicating heterogeneity in the production process of the ceramic mould. Figure 7 consists of two panels:

1. Left Panel: A three-dimensional visualization of the ceramic sample surface. The color depth map shows:
    - Red and orange: Highest points (~9337 µm).
    - Blue and green: Lower areas (~0–4309 µm).

Visible depressions and a porous structure indicate the material's susceptibility to chipping. The reference grid aids in assessing the surface shape and depth of the analyzed areas.

2. Right Panel: A 50x magnification view of the internal structure. The images reveal porosity and voids formed after firing, significantly affecting the quality and knock-out performance of the ceramic moulds.

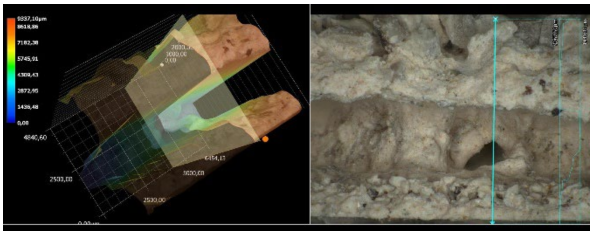
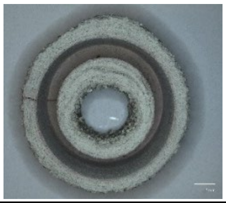
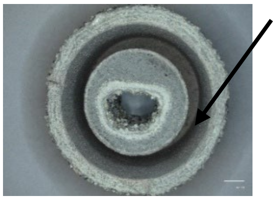
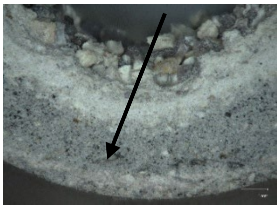


Fig. 7. Cross-section of ceramic mould no. 3, 3D visualization

Photographic analysis of ceramic moulds and castings

Table 3 shows cross-sections of ceramic moulds used to assess knock-out properties, comparing traditional moulds (A) with weakened moulds (B).

Table 3.
Photos of ceramic moulds after melting the wax

A	
	
B	
	

A: Traditional ceramic mould made with colloidal silica, molochite flour, and a matrix.
B: Weakened ceramic mould made with ceramic mass X, comprising PVA alcohol, molochite flour, and a matrix

Evaluation of sleeve castings

The final stage of the research involved evaluating the knock-out process of sleeve castings. Table 4 provides images of cast iron sleeve castings during various knock-out stages.

Ceramic moulds for the sleeves were prepared by applying six layers of ceramic mass to the wax models. A specific coating, intended to weaken the mould structure, was applied only to the inner parts of the sleeves and around the holes. The weakened layer was varied according to the configurations in Table 1. After melting the wax, the moulds were dried at 50°C for 4 hours, annealed at ~700°C, and poured with molten cast iron. Once the castings cooled to ambient temperature, the knock-out process was initiated.

The shell was separated from the casting on a vibrating table, and observations were made at vibration intervals of 1 minute and 6 minutes.

- Six-Minute Vibration: Ceramic moulds of variants 2, 3, 4, and 5 were fully removed from both the outer and inner surfaces of the sleeve castings (Table 4, items 3 and 4).
- One-Minute Vibration: For variant I, the ceramic moulds was removed only from the outer surface of the casting. After six minutes, remnants of the shell were still present on the inner surface (e.g., inside the hole, as shown in Table 4, item 3).

Figure 8, clear differences are visible:

- Left Casting: Made with the traditional mould (Variant I) and characterized by incomplete knock-out. Ceramic material remains trapped inside the sleeve, particularly near the hole, requiring additional finishing (e.g., chiseling or chemical dissolution). These methods are often costly, inefficient, and may lead to casting corrosion.

- Right Casting: Made with the weakened mould (Variant 3), demonstrating much better knock-out properties and easier separation of the ceramic shell.

The best results were obtained using mould 3, in which layers 3 and 4 were made of ceramic mass X. Similarly, mould 5 (with layer 3 made of mass X) performed well. After annealing at ~1000°C, the X-layer created a powder-filled space between the inner and outer mould layers, facilitating easier knock-out.

The castings produced using traditional and weakened-layer technologies were identical in terms of shape and dimensions. The weakening did not compromise the geometry of the final castings.

Table 4.
Castings at Different Knock-Out Stages

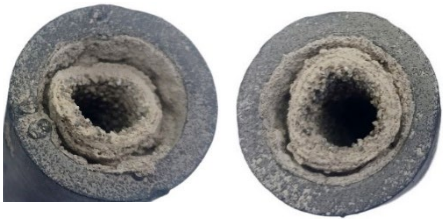
No.	Sleeve castings
1	
	Sleeve castings (after initial knockout) - 1 minute of vibration
2	
	View of the inside of the sleeve with visible baked/crimped ceramic mass – 1 minute of vibration
3	
	From the left: sleeve no. 3 after knocking out the casting – 6 minutes of vibration, sleeve no. I after knocking out the casting – 6 minutes of vibration
4	
	Sleeve with knock-out holes - 6 minutes of vibration and sandblasting

Fig. 8. Comparison of Castings: Traditional Mould (Left) vs. Weakened Mould (Right)

2. Analysis of ATR-FTIR Spectra

In this study, the methodology was extended to include ATR-FTIR (Attenuated Total Reflectance - Fourier Transform Infrared Spectroscopy) tests to analyze the chemical composition of materials used in the production of liquid ceramic masses and finished ceramic masses. Figure 9 presents the ATR-FTIR spectra.

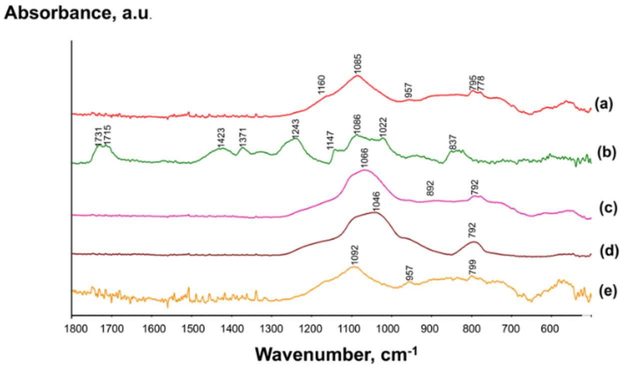


Fig. 9. ATR-FTIR spectra: (a)Ceramic mass X (b) Pure PVA alcohol in powder form (c) Ludox AM ceramic mass (d) Ludox AM binder without additives (e) Molochite in pure powder form

Comparing the ATR-FTIR spectra reveals the influence of the PVA additive on the structure of the ceramic mould produced using the colloidal binder. One of the most characteristic bands is observed in the range of 1100–1000 cm^{-1}, corresponding to the vibrations of Si-O-Si oxygen bridges in silica structures [16].

In the ATR-FTIR spectrum for ceramic mass X (Figure 9a), a broad band in this range, characteristic of Si-O vibrations, overlaps with a band characteristic of C-O groups present in the PVA alcohol [17, 18]. In the ATR-FTIR spectrum for PVA alcohol (Figure 9b), the band originating from C-O vibrations appears at a frequency of 1086 cm^{-1}. Meanwhile, in the ATR-FTIR spectrum for ceramic mass X, this band is slightly shifted to 1085 cm^{-1}. This band shift may indicate interactions between PVA and the silica or molochite surface. However, the influence of other factors, such as specific measurement conditions or microstructural differences, cannot be completely ruled out.

Additionally, when analyzing the bands in the range of 900–780 cm^{-1}, chemical changes in the material structure become apparent. In the ATR-FTIR spectrum for ceramic mass X (Figure 9a), two overlapping bands are observed at frequencies of 795 cm^{-1}

and 778 cm^{-1}. These bands, characteristic of tetrahedral SiO_2 structures, are shifted compared to the ATR-FTIR spectra for the reference samples (Figures 9 c, d, e). Such spectral changes likely result from interactions between PVA and silica.

3. Conclusions

After conducting research, it can be concluded that:

- ceramic moulds based on colloidal silica are characterized by high mechanical resistance, which positively affects their durability and strength. However, this same property makes their removal difficult after the pouring process. Optimizing the composition of the liquid ceramic mass can improve its knock-out properties under specific technological conditions. In precision casting, models with complex surface geometries are often produced. Removing such castings from ceramic moulds becomes particularly problematic in closed spaces, holes, and nooks, where the ceramic mass does not effectively separate from the casting. The mechanism of this "sticking" can be explained by the phenomenon of shrinkage: castings made of alloys with significantly greater shrinkage than the ceramic mould tend to trap remnants of the ceramic mass in hard-to-reach areas, making their removal challenging.
- Ceramic mould is an effective solution to improve knock-out properties in precision casting using the lost-wax method. Introducing such layers can weaken the multilayer ceramic mould throughout its volume by covering the entire surface of the wax model or by applying it selectively to areas where the mass becomes "jammed" and is difficult to remove.
- Research and practical tests have demonstrated that ceramic moulds with a single layer of PVA binder incorporated into specific locations (e.g., as the third and fourth layers) exhibit improved knock-out properties compared to traditional moulds. The PVA binder intentionally introduces localized weakening within the ceramic mould layers, facilitating cracking and crumbling during the knock-out process. As a result, the casting can be separated more efficiently without risking damage. Although ceramic moulds with a built-in weakened layer have better knock-out properties, their mechanical strength remains at the intended level. These moulds maintain sufficient structural stability, allowing the alloy to be poured and the casting process to proceed correctly.
- The results obtained using the ATR-FTIR technique clearly indicate changes in the chemical structure of the starting materials used to build the multilayer ceramic mould. The addition of PVA affects the structure of the bonds in the ceramic material, as evidenced by band shifts and overlapping in the vibration ranges characteristic of C-O groups and Si-O-Si oxygen bridges. The observed changes in the ATR-FTIR spectra suggest possible interactions between PVA and the silica or molochite surfaces, leading to modifications in the silica network and alterations in the structure of organic bonds.

Funding

The research was performed within the framework of the statutory work number 16.16.170.654/B507.

References

[1] Małek, M., Wiśniewski, P., Matysiak, H., Nawrocki, J. & Kurzydłowski, K. J. (2013). Yttrium (III) oxide application for manufacturing prime coat of ceramic shell moulds used in investment casting. *Szkło i Ceramika*. *64*(6), 8-11. (in Polish).

[2] Matysiak, H., Ferenc, J., Lipiński, Z., Grabarz, K., Michalski, J. & Kurzydłowski, K.J. (2009). Characterization and monitoring of technological parameters of ceramic slurries used in the investment casting process of aircraft turbine elements using the Bridgman technique. *Inżynieria Materiałowa*. 30(4), 239-244. (in Polish).

[3] Karwiński, A. (2014). Technological parameters of the process of making moulds of ceramic with the participation of water silicate binder. In K. Swiatkowski (Eds.)., *Polish Metallurgy in 2011-2014* (pp. 529–541). Kraków: AKAPIT. (in Polish).

[4] Karwiński, A. & Żółkiewicz, Z. (2014). The research of properties of experimental ceramic layers. *Archives of Metallurgy and Materials*. 59(2), 703-705. DOI: 10.2478/amm-2014-0115.

[5] Liu, W. H., Jia, X., Song, L. & Li, Y. M. (2023). Effects of binder components and PVA modifier on bonding performance of phosphate binder for sand core-making. *China Foundry*. 20(2), 134-138. https://doi.org/10.1007/s41230-023-1021-1.

[6] Pattnaik, S.R. (2017). An investigation on enhancing ceramic shell properties using naturally available additives. *The International Journal of Advanced Manufacturing Technology*. 91, 3061-3078. https://doi.org/10.1007/s00170-016-9975-4.

[7] Soroczyński, A., Haratym, R. & Biernacki, R. (2019). The role of recycled ceramic material obtained from the ceramic layered moulds used in the investment casting. *Archives of Foundry Engineering*. 19(1), 71-74. DOI: 10.24425/afe.2018.125194.

[8] Kolczyk, J., Zych, J. & Jamrozowicz, Ł. (2017). Influence of the Al2O3 solid phase on the kinetics of binding ceramic moulds. *Archives of Foundry Engineering*. 17(4), 91-96. DOI: 10.1515/afe-2017-0136.

[9] Kolczyk, J. & Zych, J. (2013). Kinetics of hardening and drying of ceramic moulds with the new generation binder – colloidal silica. *Archives of Foundry Engineering*. 13(4), 112-116. DOI: 10.2478/afe-2013-0093.

[10] Tabor, A., Rączka, J.S. (1998). *Casting design and mould technology*. Kraków: Fotobit. (in Polish).

[11] Skarbiński, M. (1957). *Casting construction*. Warszawa: Państwowe Wydawnictwo Techniczne. (in Polish).

[12] Kolczyk-Tylka J., Zych J. (2023). Investigations concerning improvements of the knock out property of ceramic moulds applied in the investment casting technology. *Archives of*

Foundry Engineering. 23(4), 1-6. DOI: 10.24425/afe.2023.146676.

[13] Lu K, Liu X & Duan Z (2019). Effect of firing temperature and time on hybrid fiber-reinforced Shell for investment casting. *International Journal of Metal Casting*. 13, 666-673. https://doi.org/10.1007/s40962-018-0280-x.

[14] Pająk, J., Ziemski, M. & Nowak, B. (2010). Poly (vinyl alcohol) – biodegradable vinyl material. *Chemik*. 64(7-8), 523-530. (in Polish).

[15] Rohini, Kumar, D.B., Rami, Reddy, M., Mulay, V.N. & Krishnamurti, N. (2000). Acrylic co-polymer emulsion binders for green machining of ceramics. *European Polymer Journal*. 36(7), 1503-1510. DOI: 10.1016/S0014-3057(99)00199-8.

[16] Assefa Aragaw T. & Kuraz F. (2019). Physico-chemical characterizations of ethiopian kaolin for industrial applications: case study WDP propoxur formulations. *Advances of Science and Technology. ICAST*. 274, 122-134. https://doi.org/10.1007/978-3-030-15357-1_10.

[17] Kharazmi, A., Faraji, N., Hussin, R. M., Saion, E., Yunus, W. M. M., & Behzad, K. (2015). Structural, optical, opto-thermal and thermal properties of ZnS–PVA nanofluids synthesized through a radiolytic approach. *Beilstein Journal of Nanotechnology.* 6(1), 529-536. https://doi.org/10.3762/bjnano.6.55.

[18] Sumer Gaaz T., Bakar Sulong A., Niaz Akhtar M., Amir H A.. Abu Bakar Mohamad K. & Al-Amiery A. (2015). Properties and applications of polyvinyl alcohol, halloysite nanotubes and their nanocomposites. *Molecules*. 20(12), 22833-22847; https://doi.org/10.3390/molecules201219884.