Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(8), 451–461
https://doi.org/10.12913/22998624/221788
ISSN 2299-8624, License CC-BY 4.0

Received: 2026.03.25
Accepted: 2026.06.01
Published: 2026.07.01

Hybrid ceramic shell system for manufacturing thin-walled steel investment casting

Jacek Nawrocki[1*], Kamil Dychton[1], Mirosław Tupaj[2], Piotr Garbien[3]

[1] Department of Materials Science, Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-029 Rzeszów, Poland
[2] Faculty of Mechanical Engineering and Technology, Rzeszów University of Technology, ul. Kwiatkowskiego 4, 37-450 Stalowa Wola, Poland
[3] SPECODLEW Innovative Foundry Company Ltd., ul. Witolda Pileckiego 3, 32-050 Skawina, Poland
* Corresponding author's email: jaceknaw@prz.edu.pl

ABSTRACT

In the present research work, an attempt was made to develop a casting shell mould that would enable the manufacturing of thin-walled investment castings from nano-bainitic steel. Nano-bainitic steels have unique properties, offering a very favourable strength-to-plasticity ratio. Thus, the use of nano-bainitic steel enables the production of lighter components with reduced wall thickness. However, the manufacturing of thin-walled castings is often accompanied by the formation of hot-tear defects. One of the reasons for the formation of hot tears is the high mechanical strength of the shell mould. The aim of the present work was to investigate the possibility of reducing the shell mould strength while simultaneously maintaining its other functional properties. To achieve this objective, different types of pore-forming materials were added to shell moulds based on fused silica. Metallic and organic materials were selected for shell mould property modification, including brass micro-powder, wood pellets, spelt husk, buckwheat husk, sliced barley, and oat flakes. All modifiers were introduced into the shell mould as stucco materials. Analysis of the mechanical test results, such as flexural strength tests, Weibull modulus and Young's modulus determination, as well as porosity and permeability measurements, showed that all the investigated materials effectively reduced the mechanical strength of the shell moulds. The flexural strength was reduced by 58–62%. It was also observed that the hot permeability of the modified shell moulds did not change significantly, except in the case of brass micro-powder, which completely blocked gas flow inside the mould.
Based on the results of the research, thin-walled demonstration castings were successfully manufactured.

Keywords: investment casting, shell system, thin-walled casting.

INTRODUCTION

Over the last several years, the development of bainitic steel in the metallurgical industry has been intensively pursued. Initially, Harry Bhadeshia [1–3], followed by other researchers [4–9], defined the standard characteristics of bainitic microstructures and the properties of novel steel alloys. Their main advantage is greater durability compared to alloys used previously. The applicability of these new materials for producing thinner sheets and components for the automotive and railway industries has been demonstrated.

The availability of improved materials encourages their broader application, including in investment casting technology. If structural elements intended for various applications can be made lighter and thinner while maintaining comparable mechanical strength, they could also be manufactured as investment castings. The production of thin-walled investment castings remains a challenge for many foundries [10–11]. Shell permeability is a key property of investment moulds and may be responsible for casting defects such as cold shuts and misruns. Misruns and hot tears found in thin-walled castings are among the most common causes of low production efficiency and high scrap rates [12–14]. Misrun defects may be eliminated by increasing the melt or mould temperature. However, defects such as hot tears are resistant to changes in casting process parameters [15].

During the solidification of castings with complex geometries, differences in the solidification time between thinner and thicker sections generate tensile stresses. Thin-walled areas hinder the free contraction of the casting during solidification and cooling. As the casting cools and shrinks, its mechanical strength increases once the casting body has fully crystallized. At the same time, the mechanical strength of the mould resists free contraction, generating constrained shrinkage stresses [16–17]. If the mechanical strength of the solidified casting is lower than that of the mould, hot tear defects occur. A moderate reduction in hot tearing can be achieved through process temperature adjustments, such as decreasing the cooling rate of the casting. However, when technological temperature limits are reached and the expected effects are not achieved, the area of intervention becomes the modification of mould mechanical strength. Investment casting moulds consist of several layers. Each layer is composed of a slurry coat (a liquid mixture) and a stucco coat (loose sand). Methods for modifying mould mechanical strength, such as reducing the number of mould coats or using various slurry additives or metal powders, are well known [18–28]. Previous research has focused mainly on increasing mould mechanical strength. In the present study, a method for decreasing mould mechanical strength was developed. The concept involved introducing modifier materials into the mould as stucco materials. The new stucco material should reduce mould mechanical strength while simultaneously having only a limited effect on other mould properties, such as permeability.

Considering global trends promoting sustainable consumption and production as the preferred direction of industrial development, it was assumed that the material used as a shell mould modifier should be renewable and biodegradable. Monitoring of the nano-bainitic steel casting process indicated that the maximum mould temperature occurring during the process is approximately 1100 °C. Based on the obtained data and the adopted assumptions, two groups of materials were selected as potential modifiers. The first group consists of plant-based materials, which are expected to burn out during the process and create pores within the mould structure. Natural materials are readily available and reproducible within a short time. The second group consists of metallic micro-powder characterized by a liquidus temperature below 1100 °C, allowing them to remain in a liquid state inside the mould during pouring and the initial stage of casting solidification. Metallic materials can potentially be recycled and reused. Both types of modifiers are expected to reduce mould mechanical strength to varying degrees. The focus of this work is an industrial challenge related to future applications.

EXPERIMENTAL

As a reference material for comparison in this study, a mould system based on a colloidal silica binder and fused silica as filler/stucco material was selected. The basic back-up coats of the moulds were prepared using a binder containing 24 wt.% colloidal silica and fused silica sand with grain sizes of 200 Mesh and 20–50 Mesh as the filler and stucco materials, respectively. A filler load factor of FL = 60 wt.% was applied. Both modified and non-modified moulds consisted of a face coat, five back-up coats, and a seal coat. The modifiers were applied as stucco materials in the third back-up coat. The following materials were used as modifiers: brass micro-powder (BP) with an average grain diameter of 63 μm and a liquidus temperature of 1027 °C, as well as various organic materials, including wood pellets (WP), spelt husk (lat. *Triticum spelta*) (SH), buckwheat husk (lat. *Fagopyrum esculentum* Moench) (BH), and oat flakes (lat. *Avena sativa*) (OF).

The following bulk properties of the modifiers were measured using a Bettersize Instruments BT-1001 analyzer and AccuPyc 1330 (gas) and GeoPyc 1360 (quasi-liquid) pycnometers: internal friction angle, angle of repose, bulk density, and specific density. Mould porosity was calculated as the difference between bulk and specific density values. Thermal effects of the materials were evaluated using differential scanning calorimetry (DSC), differential thermal analysis (DTA), and thermogravimetric analysis (TG).

The moulds were dried under controlled conditions (21 °C, relative humidity RH = 45%), dewaxed using steam pressure (8 bar, 20 min cycle time), and fired to remove residual wax (500 °C, 4 h cycle time). The following mould properties were tested: porosity, permeability, flexural strength, and tensile strength. Young's modulus and Weibull modulus were also calculated for comparison of shell mould properties. The test results were analyzed with reference to both the basic fused silica mould and moulds used in industrial foundry production based on aluminosilicate and quartz materials. Different types of samples were prepared for mould testing (Figure 1), including flat samples with a rectangular cross-section for flexural strength testing and spherical "ping-pong" samples for permeability and porosity measurements.

Three-point flexural strength tests of the fired ceramic mould samples were performed using an INSTRON 5982 testing machine with a 1 kN load cell, in accordance with ASTM International ASTM D790, using a span length of 25 mm and a crosshead speed of 1 mm/min. Tensile tests were conducted on an INSTRON 3381 testing machine with a 1 kN load cell at an elevated temperature of 1050 °C. To analyze the potential influence of pore morphology on mould properties, the samples used for permeability measurements were scanned using computed tomography (CT). The following scanning parameters were applied: lamp voltage 220 V, lamp current 200 µA, exposure time 131 ms, and voxel size 50 µm. Stereological parameters, including mean chord length and anisotropy coefficient, were measured.

a)

b)

Figure 1. Shell moulds with different types of testing samples: (a) for mechanical properties, (b) for permeability and TC scanning

RESULTS

Modifiers properties

The physical properties of modifiers have been collected in Table 1 and Figure 2. Except BP which is micrometric size, all others organic modifiers can be classified as fine. Values of angle of repose bigger than 40° for WP and OF modifier demonstrate sluggish flow. Remaining modifiers as SH, BH and BP are characterized by average flow. Loosing factor of materials has been calculated using formula:

$$K_P = \frac{SG}{BD} \quad (1)$$

where: SG – specific gravity, BD – bulk density.

Taking in to consideration K_p factor has been shown which modifier is more applicable as stucco material to manufacturing of investment casting mould using rainfall sander or fluidized bed sander. OF, WP and BP demonstrate K_p value similar to standard sands [29] and could be use in rainfall sanders. While SH and BH with high K_p value required application of fluidized bed sander. Organic modifiers present differences in particle morphology. OF, WP and BH modifier have elongate shape with similar anisotropy factor in range 1.5–1.6 but they differ from each other in size characterized by equivalent circle diameter – 6.5 (coarse), 3.7 (middle) and 2.5 (fine) respectively. The SH modifier is more extended and larger than all others modifier. In contrast to organic modifiers BP particles are regular, very fine round shape.

To sum up, all organic modifiers are characterized by burn temperature in range of 598–709 °C. This means that all organic modifier will burn during casting process and creates pores. Metallic powder has *liquidus* at 1027 °C. This confirms that powder going to change state from solid to liquid in casting process (Figure 3). It can be assumed that both phenomena will decrease mechanical strength of mould.

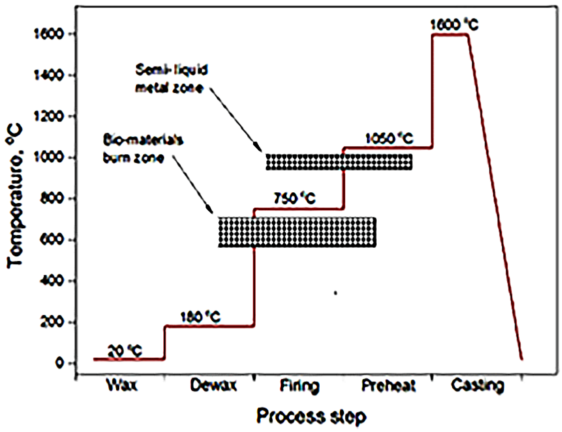


Figure 3. Liquid and burn zones of modifiers in reference to casting process temperature

Mould porosity

As a result of using modifiers with different particle morphologies, moulds with various porosity values, shown in Figure 4, were produced. The standard fused silica (FS)-based mould without modification is characterized by a relative pore volume of 4.8%. All applied organic modifiers significantly increased mould porosity, reaching values from 10.6% to 22.4%. In the case of the mould modified with metal powder, the relative pore volume was 5.0%. The moulds with known porosity values were subsequently subjected to mechanical testing.

Table 1. Stereology and bulk properties of modifiers. OF-oat, WP-wood pellet, SH-spelled husk, BH-buckwheat husk, BP-brass powder

Property	Modifiers				
	OF	WP	SH	BH	BP
Internal friction angle, °	48.1	51.8	39.7	46.2	35.5
Angle of repose, °	45.2	48.3	30.6	28.7	28.7
Bulk Density – loose. g/cm^3	0.49	0.33	0.12	0.16	3.96
Specific Gravity,. g/cm^3	1.07	1.01	0.98	0.95	8.50
Loosing factor - K_p	2	3	8	6	2
Equivalent circle diameter, mm	6.5	3.7	6.9	2.5	0.06
Anizothropy factor	1.6	1.5	2.5	1.5	1.0

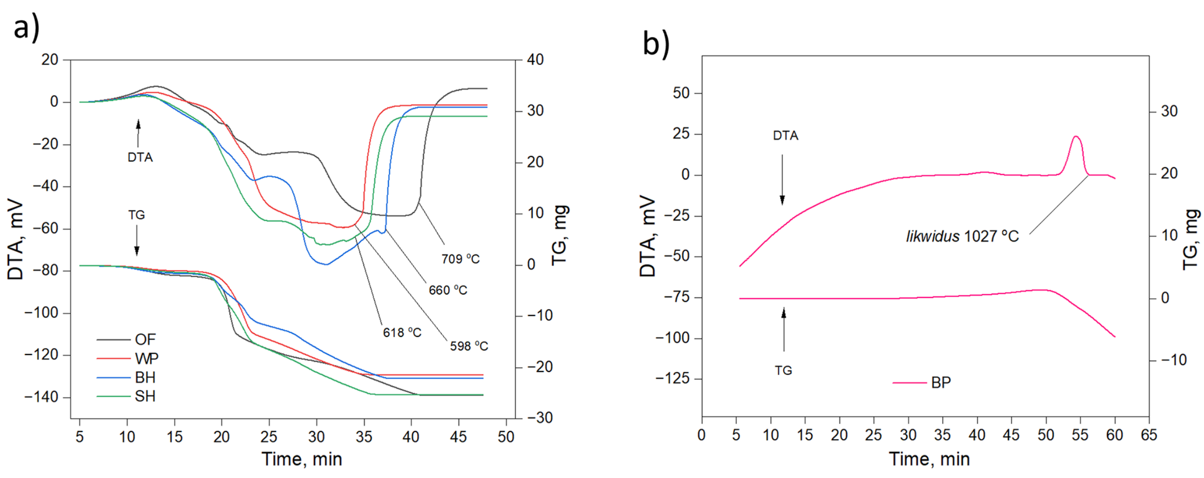


Figure 2. DTA diagrams: (a) organic modifiers, (b) metal powder

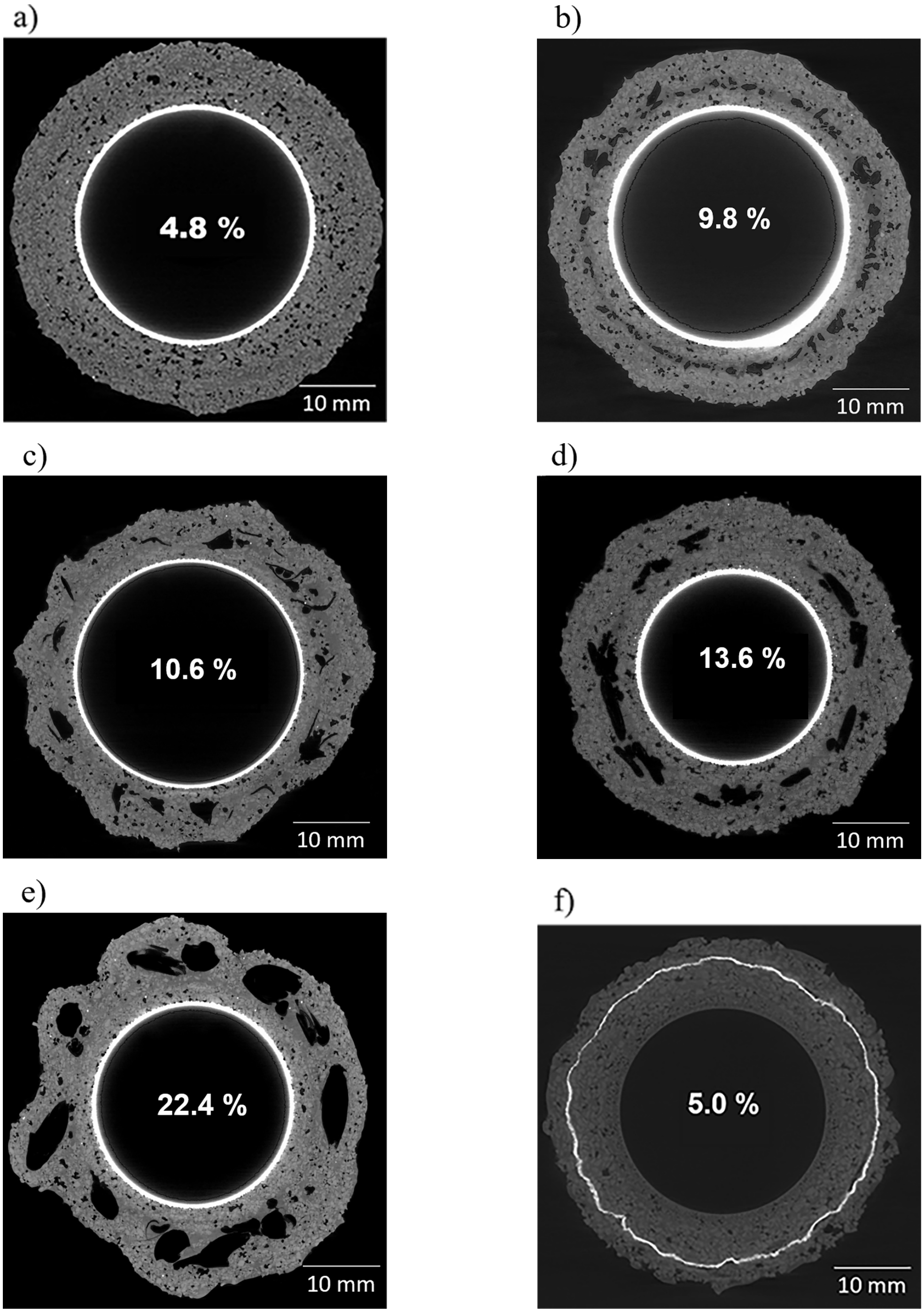


Figure 4. Computed tomography scans of moulds cross section with porosity value: (a) standard fused silica, (b) wood pellet, (c) buckwheat husk, (d) oat flakes (e) spelled husk (f) brass powder

Mould mechanical properties

Flexural strength of moulds has been calculated using formula:

$$\sigma = \frac{3FL}{2bh^2} \quad (2)$$

where: F – force, L – length of support span, b – sample width, h – sample thickness, and deformation using formula:

$$\varepsilon = \frac{6fh}{L^2} \quad (3)$$

where: f – deflection arrow. Using Hook's law, moulds Young's modulus was calculated using formula:

$$E = \frac{\sigma}{\varepsilon} \quad (4)$$

To better characterize the distribution of flexural strength values, the Weibull statistical distribution was applied. According to the Weibull theory, the probability of failure of samples subjected to stress is described by the following relationship:

$$P = 1 - exp(-(\sigma/\sigma_0)^m) \quad (5)$$

where: σ – failure stress, σ_0 – constant, m – Weibull modulus.

After linearization of the relationship using a logarithmic transformation, the slope coefficient of the approximating line obtained from the experimental results (presented in coordinates ln(ln(1/1–P)) and h(σ/σ_0) corresponds to the Weibull modulus, *m*. The Weibull modulus describes the degree of strength dispersion in the ceramic material and the probability of defects being retained within the material structure. For the analysis, a constant value of $\sigma_0 = 1$ was assumed, meaning that the probability of failure remained constant throughout the analysis. A higher value of *m* indicates lower strength dispersion and a lower probability of mould failure. All results are presented in Table 2.

As can be observed, the modification of the moulds had a significant influence on their mechanical properties. In comparison with the basic fused silica (FS) mould, a reduction in flexural strength was observed for all modified moulds. The greatest reduction, amounting to 65%, occurred in the mould modified with brass powder (BP), while the smallest reduction, 57%, was observed in the mould modified with spelt husk (SH).

Analysis of the Weibull modulus revealed a significant increase in the probability of failure of the modified moulds under lower stress levels. Young's modulus analysis indicated a greater reduction in the mechanical properties of moulds modified with buckwheat husk (BH), brass powder (BP), and spelt husk (SH) compared to moulds modified with oat flakes (OF) and wood pellets (WP), amounting to reductions of 73–91% and 22–65%, respectively.

Based on the mechanical test results, Weibull statistical equations (Equations 6–13) were determined for all modified shell moulds, industrial shell moulds used in foundries (FM1 and FM2), and the newly developed fused silica-based shell mould (FS). The graphical representation of the Weibull statistics confirmed that all applied modifiers significantly reduced the probability of shell failure (Figure 5).

$$\text{FM1: } y = 3.1375x - 3.4603;\ R^2 = 0.75 \quad (6)$$

$$\text{FM2: } y = 4.246x - 5.1075;\ R^2 = 0.89 \quad (7)$$

$$\text{FS: } y = 6.684x - 8.791;\ R^2 = 0.96 \quad (8)$$

$$\text{OF: } y = 1.7872x - 2.9424;\ R^2 = 0.89 \quad (9)$$

$$\text{WP: } y = 1.6026x - 2.5301;\ R^2 = 0.99 \quad (10)$$

$$\text{BH: } y = 1.7834x - 3.0739;\ R^2 = 0.99 \quad (11)$$

$$\text{SH: } y = 1.6824x - 3.0568;\ R^2 = 0.99 \quad (12)$$

$$\text{BP: } y = 1.7327x - 3.143;\ R^2 = 0.98 \quad (13)$$

Mould permeability

The results of the mould gas permeability measurements are presented in Figure 6. Moulds modified with organic materials showed differences in permeability at ambient temperature; however, at the elevated temperature of 1050 °C, these differences became relatively minor. Only the mould modified with spelt husk (SH) exhibited a noticeable increase in permeability, reaching 21% higher values compared to the fused silica (FS) mould. At the same time, the SH-modified mould was characterized by the highest porosity among the modified moulds, amounting to 22.4%.

Table 2. Mechanical properties of shell moulds

Properties	Mould type							
	Foundry Mould 1	Foundry Mould 2	Fused Silica	OF modified	WP modified	BH modified	SH modified	BP modified
Flexural strength MPa	2.68 ± 1.05	3.03 ± 0.83	3.48 ± 0.61	1.32 ± 0.28	1.46 ± 0.31	1.45 ± 0.39	1.51 ± 0.76	1.22 ± 0.28
Young modulus GPa	2.77 ± 1.08	3.37 ± 1.44	4.41 ± 1.09	2.43 ± 1.11	3.44 ± 0.60	0.70 ± 0.15	1.18 ± 0.89	0.42 ± 0.24
Weibull modulus	3.14	4.25	6.68	1.79	1.60	1.60	1.73	1.78

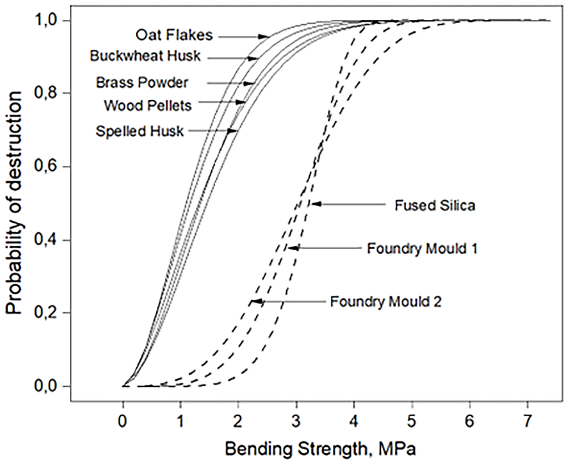


Figure 5. Probability of failure different shell moulds materials

For the remaining moulds, the differences in permeability were close to the measurement error. The exception was the mould modified with brass powder (BP), for which no permeability measurement was performed because the permeability was significantly reduced.

The results demonstrated that the distribution of modifier particles plays a crucial role. All organic modifiers formed layers composed of separated individual particles. As a result, the bulk mould material remained between the particles, containing microcracks originating from the polymer present in the binder. These microcracks determine the permeability of the moulds rather than the large isolated pores formed after burnout of the organic modifiers.

In contrast, the inorganic metal powder formed a continuous liquid film at 1050 °C, which acted as a barrier to gas flow and effectively sealed the mould. This is an unfavorable phenomenon, as it may promote defects such as misruns in thin-walled castings.

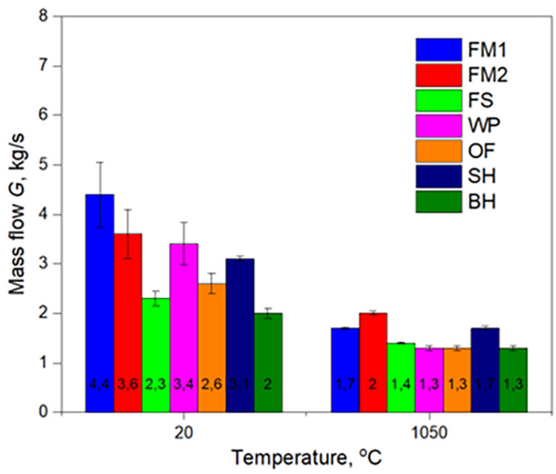


Figure 6. Permeability of different shell moulds materials

Thin-walled demonstration casting

To confirm the validity of the assumptions made, namely that a weaker mould would enable the production of castings free from defects such as hot tears, demonstration castings were produced (Figures 7a and 7b). A specially designed thin-walled sample casting was manufactured for the study in order to promote constrained contraction and generate tensile stresses within the casting.

The thin section of the casting had a thickness ranging from 1.0 mm at the first edge to 2.0 mm at the second edge, with a cross-sectional area of 60 mm² (Figure 7c). Based on the testing results, the shell system modified with oat flakes (OF) was selected for the preparation of the demonstration castings. Three shell moulds containing thin-walled samples (12 samples in total) were cast using nano-bainitic steel. No defects such as hot tears or misrun cavities were observed.

DISSCUSION

This paper presents extended possibilities for controlling the relative pore volume in precision investment casting moulds in order to reduce their mechanical strength. The focus is placed primarily on readily available, renewable plant-based materials that enable the formation of different pore morphologies within the mould structure.

Comparative studies by other researchers have mainly concentrated on strengthening moulds using both organic and inorganic additives. Materials such as cattail fibres [20], short polypropylene fibres [23], needle coke [26], sawdust [36], hydroxypropyl methylcellulose (HPMC) fibres [38], and steel fibres [34] have been applied to increase bending strength and permeability. Fine polyethylene wax powder and betel nut fibres were also used to enhance mould properties [21]. In addition, metallic powders [28] and ground walnut shell chips were investigated in terms of their influence on permeability in both the green and fired states [30,32]. Other approaches focused on mould properties include pre-wetting techniques [27] and variations in mould thickness [31]. New powders were used in ecological technology of shell moulds fabrication also [39].

A key distinction in the present work lies in the method of introducing the modifier into the mould structure. Here, the modifier is applied as a stucco layer after the firth coat. In contrast, most previously reported studies incorporate modifiers as additives directly into the slurry. This difference results in a fundamentally different distribution of the modifier within the mould. When added to the slurry, the modifier is dispersed throughout the entire volume of the mould, which is formed by successive back-up slurry layers. In the present approach, however, the modifier is localized within a single layer as a stucco, which leads to a different balance between mechanical strength and permeability.

In studies where modifiers were introduced into the slurry, mould strength typically increased by several tens of percent. Reported flexural strength values range from 4.5 to 6.5 MPa [22, 33, 37], 7 to 9 MPa [35], and even up to 14 MPa [38]. In contrast, the objective of the present study was to achieve the opposite effect—namely, a reduction in mould strength. A decrease of approximately 60% was obtained, resulting in flexural strength values in the range of 1.2 to 1.5 MPa.

In all previously reported studies, permeability generally improved with the addition of modifiers to the slurry [30, 32, 33, 35, 36], including cases involving steel fibres [38]. In the present study, the effect of organic modifiers on high-temperature permeability was negligible, with results falling within the measurement error. In contrast, the modification using metallic micro-powder had a pronounced effect, reducing gas permeability to values below the measurable range. At 1050 °C, the metallic powder is in a liquid state and likely forms a continuous layer, which effectively blocks gas flow through the mould.

It is generally known that mechanical strength correlates with the relative volume of porosity. In the present work, this relationship is not observed. In this case, it is pore morphology, rather than the total porosity value, that determines the strength of the mould.

Hot tearing (hot cracking) develops during the final stage of solidification when the alloy is in a

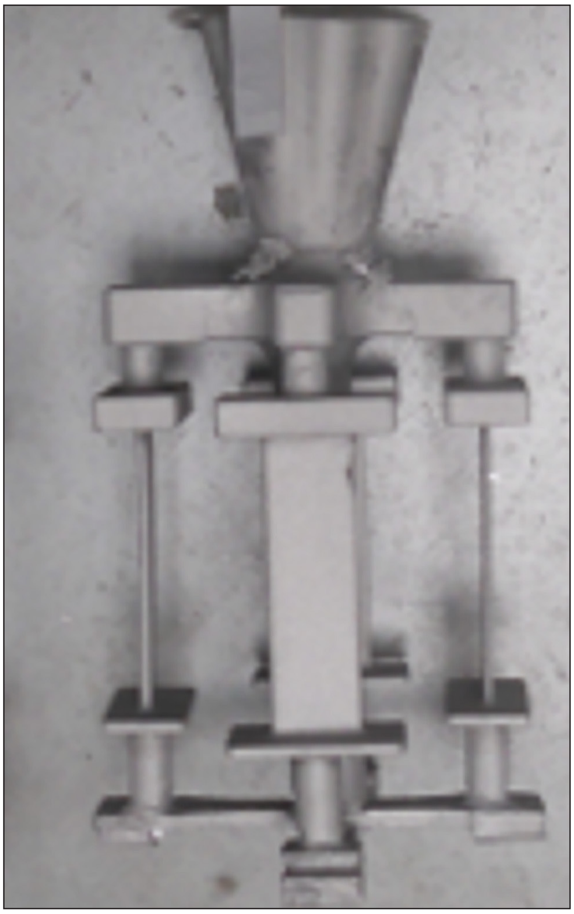
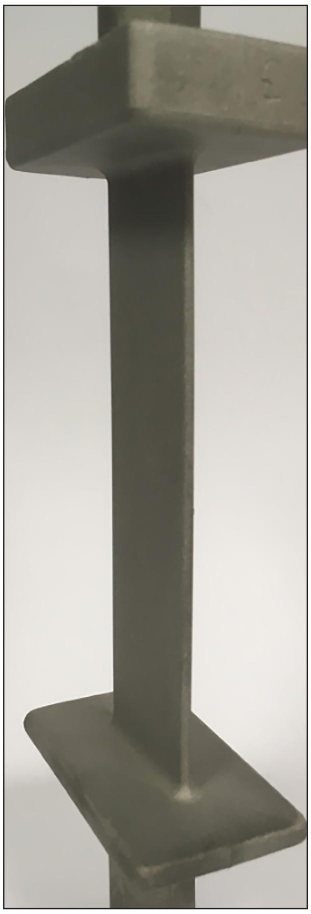
a)  b) 

Figure 7. Demonstration casting for hot-tears evaluation: (a) casted mould after cleaning, (b) casting sample

semi-solid (mushy) state and is unable to accommodate thermally and shrinkage-induced tensile strains [40]. The defect forms when interdendritic liquid films can no longer feed the shrinkage, while a coherent solid network is already able to transmit tensile stresses, leading to crack initiation and propagation along weak interdendritic regions [41].

In investment casting processes using ceramic moulds, the mould acts as a strong mechanical constraint that restricts the free contraction of the casting. This restraint increases the level of tensile stresses generated during solidification shrinkage. As a result, the susceptibility to hot tearing depends strongly on the balance between alloy feeding capability, thermal contraction, and the degree of mould restraint imposed by the ceramic shell.

Studies on ceramic shell moulds show that mould strength plays a dual role: insufficient strength may lead to deformation and non-uniform cooling, whereas excessive rigidity increases mechanical restraint and promotes tensile stress build-up in the mushy zone. Consequently, an optimal level of ceramic mould strength is required to minimise hot tearing susceptibility while maintaining dimensional stability of the casting [42].

A representative study on investment casting confirms that ceramic shell strength significantly affects hot tearing behaviour, as higher restraint conditions can either suppress or promote cracking depending on the solidification conditions and contraction behaviour of the alloy [43].

Therefore, achieving an optimal mould strength is crucial, as it provides a balance between dimensional stability and the ability to accommodate casting shrinkage. In this work, the obtained results ranging from 1.2 to 1.5 MPa indicate that this is indeed the optimal strength which allows the production of defect-free castings with respect to hot tearing.

CONCLUSIONS

1. The method of applying a mould modifier in the form of a stucco layer has been confirmed as effective for controlling both mould porosity and mechanical strength.
2. The use of organic, readily renewable materials as mould modifiers is feasible and effective.
3. The application of micro-sized metal powder with a sufficiently low liquidus temperature effectively reduces mould mechanical strength without significantly affecting its porosity.
4. The use of such micro-sized metal powder as a mould modifier results in a complete blockage of gas flow within the mould, reducing gas permeability to near zero. For this reason, metallic powder is not recommended as a modifier in practical production.
5. Moulds modified with oat flakes, wood pellets, and brass powder exhibit characteristics similar to standard sands that can be used in gravity sanders for mould production. In contrast, spelt husk and buckwheat husk, due to their lower density, may require the use of a fluidized-bed sander.
6. When using this mould modification method, no clear correlation between relative porosity and mechanical strength is observed. This relationship is significantly influenced by pore morphology, including pore shape and size, which disrupts the expected correlation.
7. An investment casting shell mould with a strength of 1.2 to 1.5 MPa enables the production of nano-bainitic steel castings free from hot tearing defects.

Acknowledgements

The work was financed from the public resources of the Polish National Centre for Research and Development. The project was realized within the frames of the Program POIR: 2/1.1.1/2017.

REFERENCES

1. Bhadeshia H. K. D. H., Edmonds D. V., The mechanism of bainite formation in steels. acta metallurgica. 1990; 28, 1265–1273. https://doi.org/10.1016/0001-6160(80)90082-6
2. Bhadeshia H. K. D. H. Nanostructured bainite. Proc. Royal Soc. A. Proc. R. Soc. A 2010; 466, 3–18. https://doi.org/10.1098/rspa.2009.0407
3. Caballero F.G., Bhadeshia H. K. D. Mawella H., K. J.A., Jones D.G., Brown P. Very strong low temperature bainite. Mater. Sci. Technol. 2002; 18, 279–84. https://doi.org/10.1179/026708301225000725
4. Garbień P., Kokosza A., Maj W., Rogal Ł., Chulist R., Janus K., A. Wójcik, Żółkiewicz Z., Maziarz W. Effect of heat treatment on microstructure and mechanical properties of high-carbon and high-manganese cast steel subjected to bainitic reaction. Arch. Metall. Mater. 2023; 68(4), 1667–1676 https://doi.org/10.24425/amm.2023.148335
5. Janus K., Rogal Ł., Dutkiewicz J. et- al. Effect of a novel controlled thermomechanical treatment on

the microstructure and mechanical properties of a high-carbon nanobainitic steel. Archiv. Civ. Mech. Eng. 2023; 252(23), 252. https://doi.org/10.1007/s43452-023-00791-8

6. Adamczyk-Cieslak B., Koralnik M., Kuziak R., Majchrowicz K., Zygmunt T., and Mizera J. The impact of retained austenite on the mechanical properties of bainitic and dual phase steels. J. of Mater. Eng. and Perfor. Online 04/01/2022. https://doi.org/10.1007/s11665-021-06547-w
7. Kumar A., Singh A. Mechanical properties of nanostructured bai-nitic steels. Materialia. 2021; 15, 101034. https://doi.org/10.1016/j.mtla.2021.101034
8. Ríos-Diez O., Aristizábal-Sierra R., Serna-Giraldo C., J. A. Jimenez, C. Garcia-Mateo. Development of nanobainitic microstructures in carbo-austempered cast steels: heat treatment, microstructure and properties. Metals. 2020; 10, 635. https://doi.org/10.3390/met10050635
9. Zhang F., Yang Z. Development of and perspective on high-performance nanostructured bainitic bearing steel. Engineering. 2018; 3, 29–43. https://doi.org/10.17729/ebis.2018.3/3
10. Raza M., Svenningsson R., Irwin M. Experimental study of the filling of thin-walled investment castings in 17-4ph stainless steel. Metallurgy and Foundry Engineering. 2015; 41, 85–98. https://doi.org/10.7494/mafe.2015.41.2.85
11. Raza M., Svenningsson R., Irwin M., Fagerström B., Jarfors A.E.W., Effect of process related variations on fillability simulation of thin-walled in718 structures. Int. J. of Metalcasting. 2018; 12, 543–53. https://doi.org/10.1007/s40962-017-0189-9
12. Sabau A. S. Mirmiran M. S., Glaspie C., Apelian S. Li, D., Shyam A., Haynes J. A. and Rodriguez A. F. Hot-tearing of multicomponent al-cu alloys based on casting load measurements in a constrained permanent mold. TMS 465–473, Oak Ridge 2017. https://doi.org/10.1007/978-3-319-51493-2_44
13. Heydari D., Shahkaram A. Fard, Bakhshi A., Drezet J.M. Hot tearing in polycrystalline Ni-based in-738LC superalloy: influence of Zr content. J. of Mater. Proc. Tech. 2014; 214, 681–687. https://doi.org/10.1016/j.jmatprotec.2013.10.001
14. Zhang J., Singer R.F. Hot tearing of nickel-based superalloys during directional solidification. Acta Materialia. 2002; 50, 1869–1879. https://doi.org/10.1016/S1359-6454(02)00042-3
15. Akhyar A. Hot tearing, parameters and mould types for observation. Rev. Arch. Of Foundry Eng. 2022; 22(2), 25–49. https://doi.org/10.24425/afe.2022.140223
16. Behera M. M., Pattnaik S., Sutar M K. Thermo-mechanical analysis of investment casting ceramic shell: a casestudy. Mesurement. 2019; 147, 2–11. https://doi.org/10.1016/j.measurement.2019.07.033
17. Nyichomba B. B., Cheya I. M., Campbell J. Linear contraction of ductile iron castings. Int. J. of Cast Metals Res. 1998; 11, 179–186. https://doi.org/10.1080/13640461.1998.11819272
18. Raza M., Irwin M. The effect of shell thickness on defect formation in investment cast Ni-base alloy. Proc. of ICI, Covington 2014. https://doi.org/10.1515/afe-2015-0090
19. Cho G.-H., Kim E.-H., and Jung Y.-G. Improving strength in casting mold by control of starting material and process. J. of the Korean Ceramic Soc. 2016; 53(5), 541–547. http://dx.doi.org/10.4191/kcers.2016.53.5.541
20. Lu K., Liu X.-d., Du Z.-x., and Li Y.-f. Bending strength and fracture surface topography of natural fiber-reinforced shell for investment casting process. R&D China Foundry. 2016; 13(3), 211–215. https://doi.org/10.1007/s41230-016-5100-4
21. Pattnaik S., Sutar M. K. Preparation and analysis of a hybrid ceramic shell for investment casting. Int. J. Adv. Manuf. Tech. 2017; 91, 3061–3078. https://doi.org/10.1007/s00170-022-10054-0
22. Li Y., Liu X., Lu Y. and Lu K. Research on the hot strength and retained strength of shells reinforced by dispersed fibers for investment casting. Inter. J. of Metalcasting. 2023; 17(2), 753–760. https://doi.org/10.1007/s40962-022-00805-w
23. Lu Y., Liu X., Lu K., and Li Y. Properties and fracture surface features af plaster mold reinforced with short polypropylene fibers for investment casting. Inter. J. of Metalcasting. 2021; 15(2), 700–709. https://doi.org/10.1007/s40962-020-00505-3
24. Bansode S. N., Phalle V. M., Mant S. S. Influence of slurry composition on mould properties and shrinkage of investment casting. Trans. Indian Inst. Met. 2020; 73(3), 763–773. https://doi.org/10.1007/s12666-020-01872-5
25. Rakoczy Ł., Grudzien-Rakoczy M. and Cygan R. The influence of shell mold composition on the as-cast macro- and micro-structure of thin-walled in713C superalloy castings. J. of Mater. Eng. and Perfor. 2019; 28(7), 3974–3985. https://doi.org/10.1007/s11665-019-04098-9
26. Wang F. et al. Microstructure and strength of needle coke modified ceramic casting molds. Ceram. Int. 2016; 40, 479–486. https://doi.org/10.1016/j.ceramint.2013.06.027
27. O' Sullivan N., Mooney J., Tanner D.A. Enhancing permeability and porosity of ceramic shells for investment casting through pre-wetting. J. of the European Ceramic Soc. 2021; 41(11), 411–422. https://doi.org/10.1016/j.jeurceramsoc.2021.09.022
28. Cygan R. Patent Application, Self-supporting multi-layered ceramic moulds with the addition of metals to production of precision castings. Number P.421560. Warsaw 2017.

29. Antoniak J. Underground transport equipment and systems in mines. Wydawnictwo Śląsk, Katowice 1990.
30. Małek M. et al. Thermal and structural behavior of investment casting molds modified with biodegradable walnut shell chips. Materials. 2025; (18), 4289. https://doi.org/10.3390/ma18184289
31. Sukhoiri et al. Study on the shrinkage porosity of automotive parts quality: the influence of reinforced shell mold thickness in investment casting. Int. J. of Mechanical Engineering Technologies & Apllications. 2025; 6(2), 236–248. https://doi.org/10.21776/MECHTA.2025.006.02.7
32. Wisniewski P. et al. Molding binder influence on the porosity and gas permeability of ceramic casting molds. Materials, 2020; 13(12), 2735. https://doi.org/10.3390/ma13122735
33. Kumar S., Karunakar D.B. Enhancing the permeability and properties of ceramic shell in investment casting process using ABS powder and needle coke. Inter Metalcast 2019; 13, 588–596. https://doi.org/10.1007/s40962-018-00297-7
34. Lü K., Shen S., Ma C. et al. Research on modification of steel fiber in inve.stment casting shell. Inter Metalcast 2022; 16, 1849–1857. https://doi.org/10.1007/s40962-021-00722-4
35. Wang F., Zhu G., Li F. et al. Effect of needle coke on gas permeability of ceramic casting molds. J. Shanghai Jiaotong Univ. (Sci.) 2018; 23 (Suppl 1), 124–131. https://doi.org/10.1007/s12204-018-2032-8
36. Pattnaik, S. An investigation on enhancing ceramic shell properties using naturally available additives. Int J Adv Manuf Technol 2017; 91, 3061–3078. https://doi.org/10.1007/s00170-016-9975-4
37. Li Y., Liu X., Lű K. et al. Exploration on preparation process of high-strength fiber-reinforced shell for investment casting. Inter Metalcast 2021; 15, 692–699. https://doi.org/10.1007/s40962-020-00494-3
38. Lü K., Duan Z., Liu X. et al. Effect of dispersant on fiber-reinforced shell for investment casting. Inter Metalcast 2020; 14, 1005–1012. https://doi.org/10.1007/s40962-020-00409-2
39. Małek M., Wachowski M., Kluczyński J., Wiśniewski P. Characterization of new powders used in ecological technology of shell moulds fabrication. Adv. Sci. Technol. Res. J. 2025; 19(7), 360–376. https://doi.org/10.12913/22998624/203702
40. Zhu J. Z., Guo J., Samonds M.T. Numerical modeling of hot tearing formation in metal casting and its validations. Int. J. Numer. Meth. Engng. 2011; 87, 289–308. https://doi.org/10.1002/nme.3054
41. Akhyar. Hot Tearing, Parameters, and Mould Types for Observation – Review. Archives of Foundry Engineering 2022; 22(2), 25–49. https://orcid.org/10.24425/afe.2022.140223
42. Suyitno W. Kool L. Katgerman. Integrated approach for prediction of hot tearing. Metall Mater Trans A 2009; 40, 2388–2400. https://doi.org/10.1007/s11661-009-9941-y
43. Norouzi S., Farhangi H. The impact of ceramic shell strength on hot tearing during investment casting. AIP Conf. Proc. 2011; 1315, 662–667. https://doi.org/10.1063/1.3552524