

DEVELOPMENT OF FOUNDRY CORES BASED ON INORGANIC SALTS

RAZVOJ LIVARSKIH JEDER NA PODLAGI ANORGANSKIH SOLI

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The aim of this study is to describe the possibilities of using salt cores for gravity, low-pressure or high-pressure die-casting technology. Determinations of the primary, secondary and final residual strengths were carried out in order to evaluate the possibilities of the salt-core utilization. Furthermore, this contribution is focused on developing composite salts with better mechanical properties. The solubility of these cores and a possibility of their reclamation in a closed cycle with positive impacts on the environment were also studied.

Keywords: salt cores, inorganic salts, die casting, PUR Cold-Box, Warm-Box, core solubility and stability

Namen te študije je opisati možnosti uporabe slanih jeder pri gravitacijski, nizkotlačni in visokotlačni livarski tehnologiji. Izvršeno je bilo določanje primarnih, sekundarnih in končnih zaostalih napetosti, da bi ocenili uporabnost slanih jeder. Poleg tega je prispevek usmerjen na razvoj kompozitnih soli z boljšimi mehanskimi lastnostmi. Preučevana je bila tudi topnost jeder in možnosti njihove predelave v zaprti zanki s pozitivnim učinkom na okolje.

Ključne besede: slana jedra, anorganske soli, tlačno litje, PUR Cold-Box, Warm-Box, topnost jeder in stabilnost

1 INTRODUCTION

The first salt cores appeared in the foundry industry in the 1970s. An extensive expansion took place in the 1990s in the mass production of Diesel engine pistons. The cores of simple forms (rings) are made from cooking salt (NaCl) by high-pressure compacting and they serve for blank casting of the holes (channels) hardly accessible to mechanical cleaning. They are dissolved in water, which is a precondition for the use in a technologically closed production cycle. Pistons are made by gravity or low-pressure casting in dies. The strength characteristics of the compacted cooking salt meet the requirements regarding the primary strength (the cold strength) and hot strength (650–700 °C) of the cores heated before they are inserted in the mould, which is also necessary for improving the fluidity of Al-alloys. The main advantages of this technology are as follows:

- dimensional accuracy and smoothness of the castings without the use of protective coats;
- solubility of the cores in water and possible recyclability of the salts and water;
- environmentally friendly core production;
- sufficient storage ability of the cores under common climatic conditions.

When changing to more complex and shape-demanding cores with a possibility of an additional functioning, using an increased press and dynamics of the metal injected into the mould (the high-pressure casting), the research focuses, above all, on improving the mechanical properties, not only the primary strengths under high

temperatures, but also the residual (secondary) strengths after a thermal exposure, which have recently drawn a lot of attention. More efficient ways of a core production, different from the compacting processes, are searched for.^{1,2}

For the blank casting of simple holes the high-pressure casting technology uses metal cores, in addition to the sand ones, made with the PUR COLD-BOX technology or the Combicore system,³ and the aluminium channels filled with a salt mixture (cleaned with water). Though sand cores (PUR COLD-BOX) allow blank casting of the holes with highly intricate shapes, low strengths and the possibilities of penetrating the base sand grains in the alloy and, above all, a bad collapsibility after the casting, are their disadvantages. Especially with the new applications of die-casting technologies (e.g., the master squeeze) lowering the temperature of the injected alloy, the perfect thermal destruction of the core polyurethane binder is not followed by difficult cleaning.

2 PRESENT TRENDS IN THE SALT-CORE MANUFACTURE

2.1 Cast cores from molten salts

The salt melt is cast in core boxes and to prevent the moistening, the crystallized cores are stored in an oven (a minimum of 200 °C). A contraction and volume shrinkage occur during solidification. High density (minimum porosity) prevents the dissolution in the water and, therefore, the cast cores are difficult to remove. To

eliminate the shrinkage, a mixture of salts and sand is recommended. Then the melt (820 °C) is cast in a core box under pressure.

2.2 High-pressure compacting of salts

A mildly moistened salt is compacted under high pressure. The cores are then strengthened by way of a mechanical deformation of the grains (conglomeration) and a recrystallization along the grain boundaries. Compacting takes place either under low pressures (30.0–50.0 MPa) and at the heating temperatures of 500–750 °C or under high compacting pressures (136.0–362.8 MPa) and lower sintering temperatures (180–300 °C), allowing a stress release.

2.3 Shooting in core boxes using the binders

After the core shooting (6 bars), the mixture with inorganic binders (alkali silicates) is hardened either with the aid of CO₂ or with thermal dehydration (180–210 °C). In the case of organic binders (synthetic resins) the cores are hardened with the core-box heat (Warm-Box, 150–300 °C). A possibility of applying common processes and equipment to the production of sand cores is an advantage. A higher porosity of salt cores (25–35 %) enables even dissolution in water though the bending strength is 2–3 times lower than that of the compacted cores.

All the mentioned processes, using cooking salt (NaCl), show a relatively low strength and they do not meet the requirements for the cores for high-pressure castings. The research was, therefore, aimed at applying the high-pressure compacting and improving the strength characteristics of the cores (the bending strength) by studying the compacting conditions, the choice of inorganic salts and their different mixtures, the influence of the salt-crystal shapes, granulometry and, above all, the composite salts with additives, as well as the hydration and kinetics during dissolution of the cores in water.

3 INFLUENCING THE STRENGTHS OF THE SALT CORES COMPACTED UNDER HIGH PRESSURES

The main criterion was the bending strength measured with an adapted universal apparatus LRu-2e (MULTISERVIS MOREK, PL). We measured both primary strengths, the cold strength and the strength under high temperatures (650 °C), and the residual (secondary) cold strength after the thermal exposure (650 °C, 1 h). Primary strengths were evaluated after 48 h, after the compacting had been completed and the second phase of hardening – recrystallization of salt-grain boundaries – began (Figure 1).

The moisture content of the salts plays a role in the initial phases of the strengthening (a lower moisture provides for a higher primary strength) but after a longer

storing time the influence of different moisture contents is balanced (Figure 2).

The basic tests were done on the chemically pure salts of KCl and NaCl with the granulometry as follows: D10 = 72.6–73.4 μm, D50 = 188–189 μm, D90 = 367–370 μm, using a FRITSCH-ANALYSETTE 22 MICRO Tcplus – isopropanol medium.

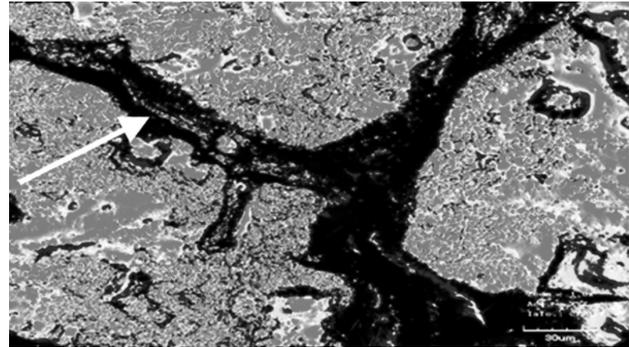


Figure 1: Grain boundaries after the KCl squeezing ($\rho = 1.85 \text{ g cm}^{-3}$, bending strength = 8.8 MPa)

Slika 1: Meje zrn po stiskanju KCl ($\rho = 1,85 \text{ g cm}^{-3}$, upogibna trdnost = 8,8 MPa)

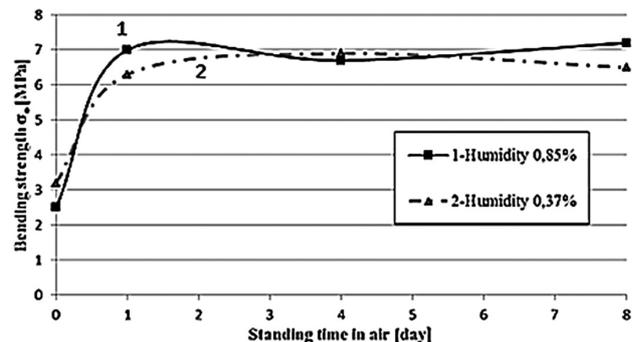


Figure 2: Course of the KCl compacting with different moisture contents after squeezing with a compression power of $100 \cdot 10^3 \text{ N}$ (23 °C, RV 65 %)

Slika 2: Potek kompaktiranja KCl z različno vsebnostjo vlage, po stiskanju s silo $100 \cdot 10^3 \text{ N}$ (23 °C, RV 65 %)

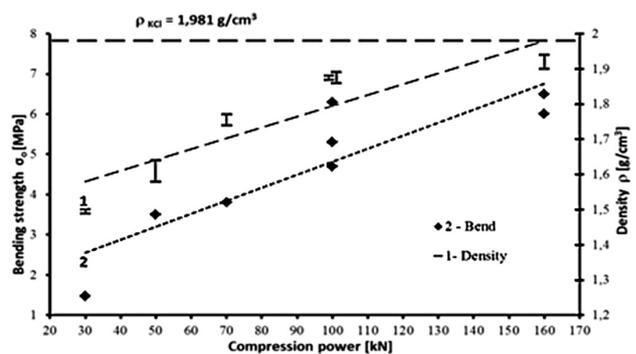


Figure 3: Influence of compression power on density and bending strength of KCl samples ($d_{50} = 190 \mu\text{m}$; humidity of 0.87 %)

Slika 3: Vpliv sile stiskanja na gostoto in upogibno trdnost vzorcev iz KCl ($d_{50} = 190 \mu\text{m}$; vlaga 0,87 %)

The influence of the compacting force ($30 \cdot 10^3$ – $160 \cdot 10^3$ N) on the bending strength and density of the cores were evaluated, too (**Figure 3**).

The bending strength grows with the compacting force up to the value of 6.5 MPa, with a simultaneous growth of density (**Table 1**). If the density of the crystalline KCl salt (1.981 g cm^{-3}) is taken as the base, then the so-called seeming porosity m can be determined as follows:

$$m = \frac{\rho_{\text{KCl}} - \rho_{\text{core}}}{\rho_{\text{KCl}}} \cdot 100\% \quad (1)$$

where:

m – porosity (%)

ρ_{KCl} – density of KCl (g cm^{-3})

ρ_{core} – density of the core (g cm^{-3})

Table 1: Comparison of the primary strengths of KCl after squeezing with different compression tensions

Tabela 1: Primerjava primarne trdnosti KCl po stiskanju z različnimi tlačnimi napetostmi

Compression power	$50 \cdot 10^3$ N		$100 \cdot 10^3$ N		$160 \cdot 10^3$ N	
Compression tension	28 MPa		56 MPa		87 MPa	
Salt	<i>BS</i>	<i>D</i>	<i>BS</i>	<i>D</i>	<i>BS</i>	<i>D</i>
KCl	4.65	1.68	5.53	1.90	6.5	1.94

Note: *BS* – bending strength (N mm^{-2}); *D* – density (g cm^{-3})

or the compacting force of $160 \cdot 10^3$ N $m = 2.06$ %. The growth from $100 \cdot 10^3$ N up to $160 \cdot 10^3$ N does not significantly reflect on the primary strength nor on the density. A decrease in the seeming porosity from 4 % to 2 % is not significant either. The achieved strengths exceed multiple times the strength of the sand cores made with the PUR COLD-BOX technology.

4 HOT STRENGTH AND THE RESIDUAL STRENGTH

The chosen temperature ($650 \text{ }^\circ\text{C}$, 0.5 h and 1 h) corresponded to the temperatures of heating the cores when inserting them in the dies for gravity casting of the

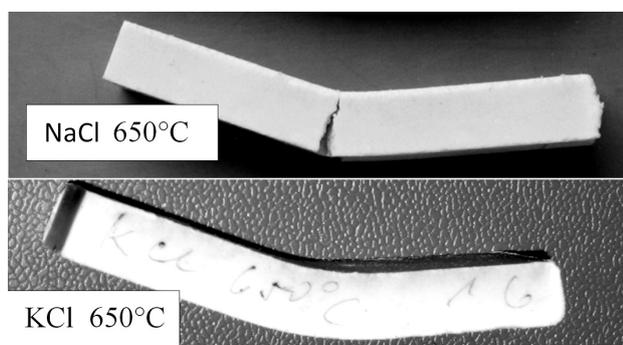


Figure 4: Plastic deformation of salt samples

Slika 4: Plastična deformacija slanih vzorcev

pistons. It is also the temperature that strengthens the cores for possible mechanical work. A comparison of the results of primary and residual strengths of the cores compacted with different forces is given in **Table 2**. The cores from NaCl, under the same compacting conditions, always had substantially lower primary strengths than the KCl cores (**Table 3**), even with the same densities.

Table 2: Comparison of primary strengths of KCl after squeezing with different compression tensions

Tabela 2: Primerjava primarne trdnosti KCl po stiskanju z različnimi tlačnimi napetostmi

Salt	<i>M</i>	<i>A</i>	<i>ST</i>	<i>CP</i>	<i>BS</i>	<i>D</i>
	%	h	h	10^3 N	MPa	g cm^{-3}
KCl	1.2	0.5	24	50	3.53	1.58–1.64
					3.44*	1.72
	0.87	1.0	72	100	5.41	1.71–1.75
					4.73*	1.71
					6.35	1.83–1.86
					6.34*	1.86–1.89

Note: *M* – moisture; *A* – annealing at $650 \text{ }^\circ\text{C}$; *ST* – storage time; *BS* – bending strength,* – primary *BS*; *D* – density

Table 3: Comparison of the primary strengths of KCl and NaCl cores made at a constant compression power

Tabela 3: Primerjava primarne trdnosti KCl in NaCl s konstantno tlačno silo

Salt	<i>M</i>	<i>A</i>	<i>ST</i>	<i>CP</i>	<i>PBS</i>	<i>D</i>
	%	h	h	10^3 N	MPa	g cm^{-3}
KCl	0.87	1	72	100	6.77	1.86–1.88
NaCl	0.83	1	72	100	3.69	1.87–1.89

Note: *M* – moisture; *A* – annealing at $650 \text{ }^\circ\text{C}$; *ST* – storage time; *PBS* – primary bending strength; *D* – density

Different behaviour was especially evident during the evaluation of hot strengths. While the cores from KCl showed a plastic state at $650 \text{ }^\circ\text{C}$, cracks were formed in the cores from NaCl (**Figure 4**).

The reason for different behaviours of the cores from KCl and NaCl was not found in the physical or chemical properties of both salts (**Table 4**).

Table 4: General properties of used salts

Tabela 4: Splošne lastnosti uporabljenih soli

Properties of salts	KCl	NaCl	
Molar mass	g mol^{-1}	74.551	58.443
Melting point	$^\circ\text{C}$	770.3	801
Boiling point	$^\circ\text{C}$	1411	1413
Density	g cm^{-3}	1.981	2.163
Water solubility	$20 \text{ }^\circ\text{C}$, $\text{g}/100 \text{ ml}$	34.19	35.86
Crystal lattice edge	pm	$a = 693$	$a = 562.7$
Crystal structure	–	cubic	cubic

The principal difference is found between the crystal shapes of both salts. While KCl had a homogeneous granularity of a regular cubic form (**Figure 5**), NaCl typically consisted of oval crystals (**Figure 6**).

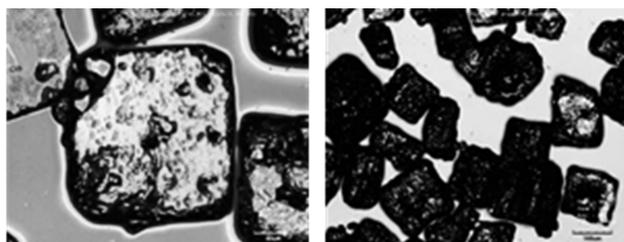


Figure 5: KCl crystals
Slika 5: Kristali KCl

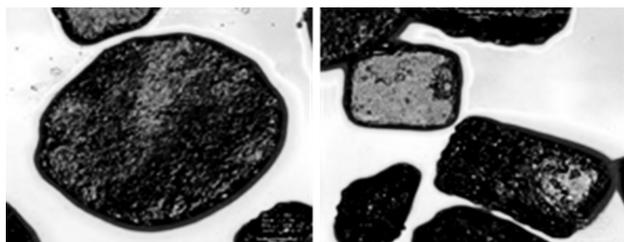


Figure 6: NaCl crystals
Slika 6: Kristali NaCl

Differences in the salt-grain shape were also confirmed with the measurement of the mean roundness related to the volume of the particles, for NaCl: SPHT3 = 0.906; for KCl: SPHT3 = 0.778. A similar dependence of the salt-core strengths on the crystal shape was confirmed by C. R. Loper.⁴

The integrity failure (the crack) in the NaCl sample runs through the salt crystals under the influence of a high grain equivalent (Figure 7). Different properties of both samples can also be identified with the aid of morphology of the fracture surfaces. The surface of KCl is compact without any pores or cracks (Figure 8).

5 COMPOSITE SALTS

Up to this time we worked with pure salts (KCl, NaCl) and the mixtures with other inorganic salts (K_2CO_3 , Na_2CO_3 , $MgSO_3$, Na_2SO_4). However, even with the highest compacting forces ($160 \cdot 10^3$ N) we could not obtain the cores with the mechanical properties that would meet the requirements for the applications of high-pressure casting.

For this reason we proceeded to develop composite salts. Very fine particles with defined granulometry of

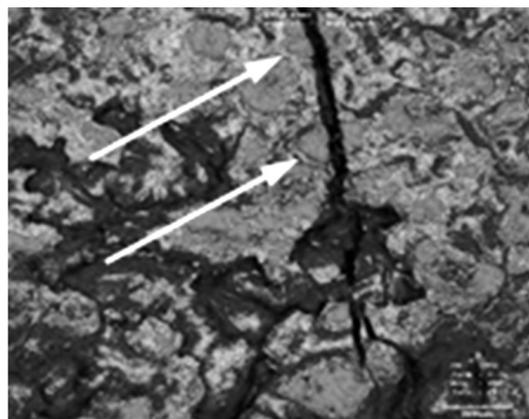


Figure 7: Crack in the NaCl structure
Slika 7: Razpoka v strukturi NaCl

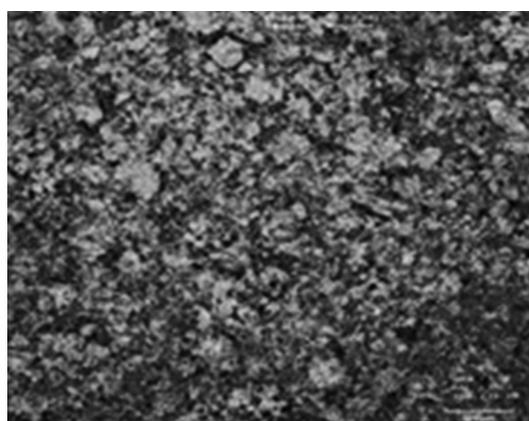


Figure 8: Compact structure of KCl
Slika 8: Zgoščena struktura KCl

different quartz- and non-quartz-based sands were dispersed in pure salts (KCl, NaCl), with the aim of failing the long dislocation lines present in the salt matrix. Three types of additives (marked as A, B, C) in the amounts of up to 30 % of the weight of a salt base were tested. Some partial results are summarized in Table 5.

The results show that with the aid of the composite salts and some additives (base sands) the core strengths can be considerably improved, especially the hot strength (650 °C) – the amounts of the A and B additives were up to 10 %. The composites with the NaCl matrix again show considerably lower strengths than those of KCl. The achieved residual bending strengths in the range of 8–9 MPa also make it possible to use the me-

Table 5: Strengths of composite salts
Tabela 5: Trdnost kompozitnih soli

KCl 100 · 10 ³ N	A/%			B/%			C/%			NaCl 100 · 10 ³ N	C/%		
	0	10	30	0	10	30	0	10	30		0	10	30
after 48 h (MPa)	7.53	7.93	3.72	7.63	8.11	1.93	6.47	7.21	6.79	after 48 h (MPa)	3.63	4.26	3.77
Hot strength 650 °C, 1 h (MPa)	>8.9	13.16	4.44	8.89	10.14	1.62	8.05	8.92	9.01	Hot strength 650 °C, 1h (MPa)	5.33	2.89	1.35
Residual strength 650 °C, 1 h (MPa)	8.49	8.66	3.91	6.84	9.94	6.02	7.88	7.78	8.06	Residual strength 650 °C, 1h (MPa)	2.55	6.80	1.15

chanical working of the cores, while the hot strengths of 10–13 MPa give hopes that these cores can be used for high-pressure castings.⁵

6 CONCLUSION

In the technology of salt-water soluble cores both new salt mixtures and their manufacturing processes meeting highly demanding conditions of high-pressure casting, especially of the automotive castings, are searched for. High primary strengths and the strengths under high temperatures (substantially higher than that of PUR COLD-BOX) give possibilities of treating the cores by mechanical working. It turns out that utilization under high pressure, especially when using composite salt mixtures, can be taken into account, too.

Shooting the salt cores with inorganic or organic binders in hot-core boxes (WARM-BOX) is a topic for the next research that could contribute to more extensive applications of wasteless foundry technology.

Acknowledgement

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