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EFFECT OF A NANO-CERAMIC MOLD COATING ON THE FLUIDITY LENGTH OF THIN-WALL CASTINGS IN Al4-1 ALLOY GRAVITY SAND CASTING

VPLIV NANOKERAMIČNEGA PREMAZA PEŠČENE FORME NA TEKOČNOST V TANKOSTENSKIH ULITKIH IZ ZLITINE Al4-1 PRI GRAVITACIJSKEM ULIVANJU

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The thin-wall casting of aluminum alloys provides new opportunities for aerospace industries in producing lightmass structures with good mechanical properties. The fluidity of molten metal is very important in producing sound castings, particularly thin-wall castings. In the gravity casting of thin-wall castings of the Al4-1 alloy, the melt that fills the mold with the effect of self-weight, does not have sufficient fluidity, so causing defects such as cold shut, misrun and shrinkage defects during the solidification. These defects reduce the quality and mechanical properties of the cast parts. The casting fluidity depends on many factors, such as temperature, melt composition, casting part shape and mold coating. This study reports the influence of a nano-ceramics mold coating, a micro-ceramic mold coating, a graphite mold coating and the section thickness of the part on the fluidity length of Al4-1 alloy castings. The results showed that by applying nano-ceramic mold coatings on the surface of a sand mold, the fluidity length and the surface quality of the castings can be improved.

Keywords: Al4-1 alloy, nano ceramic coating, micro ceramic coating, fluidity length, thin wall castings

Tankostenski ulitki iz aluminijevih zlitin so nova priložnost za letalsko industrijo pri proizvodnji lahkih ulitkov z dobrimi mehanskimi lastnostmi. Tekočnost staljene kovine je pomembna pri proizvodnji ulitkov brez napak, posebno še tankostenskih. Pri gravitacijskem ulivanju tankostenskih ulitkov iz zlitine Al4-1 talina zapolni formo zaradi lastne teže, če pa nima dovolj tekočnosti, to povzroči nastanek napak, kot so hladni zvari, slabo tečenje, napake zaradi krčenja pri strjevanju. Omenjene napake zmanjšujejo kvaliteto in mehanske lastnosti ulitkov. Livnost zlitine je odvisna od mnogih dejavnikov, kot so temperatura, sestava taline, oblika ulitka in prevleka forme. Predstavljen je vpliv nanokeramičnega premaza, mikrokeramičnega premaza, grafitnega keramičnega premaza in lokalne debeline na tekočnost v ulitkih iz zlitine Al4-1. Rezultati so pokazali, da je mogoče z uporabo nanokeramičnega premaza na peščeni formi izboljšati tekočnost in kvaliteto površine ulitka.

Ključne besede: zlitina Al4-1, nanokeramični premaz, mikrokeramični premaz, tekočnost, tankostenski ulitki

1 INTRODUCTION

Aluminum is one of the most important non-ferrous metals. Al–Si alloys are the most widely used aluminum alloys due to their castability, high strength-to-mass ratio, corrosion resistance, etc.[1] The industrial demand for thin-wall castings in aluminum alloys is of great importance in order to produce light components, which enable an increased payload and reduced energy consumption in aerospace applications. The Al4-1(Ak9pch) alloy is an aluminum-silicon alloy with 9–10.5 % silicon, 0.25–0.35 % manganese and 0.23–0.3 % magnesium. This alloy is used for reducing mass and good mechanical properties, and is employed for manufacturing many airplane and aerospace parts with complicated shapes and thin-wall castings.[2–6]

However, thin-wall castings of Al4-1 alloy can pose manufacturing problems associated with mold filling. The rapid cooling of thin-wall sections of the casting reduces the fluidity of the molten metal, which could cause the molten metal to prematurely freeze before it can completely fill the mold cavity, resulting in an incomplete fill or cold shuts. Hence, the fluidity of the melt is an important concern in the foundry for thin-wall castings and the production of thin-wall castings is limited by the fluidity of the molten metal. The fluidity of aluminum alloys has a direct influence, not only on the material's castability, but also on the casting mechanical properties of the casting part. The fluidity of molten metals, in the foundry environment, is defined as the length the metal flows before it is stopped due to solidification. This is because the fluidity limits the geometry of a casting that can be successfully filled. The study of fluidity is particularly important for the aerospace and automotive industries in order to produce thinner and lighter products. Therefore, in recent years, many foundries and metal suppliers have invested time and money in studying the fluidity of their foundry alloys. Fluidity is a complex parameter that is affected by the properties of the molten metal and mold (such as the mold coating), the pouring conditions and the solidification mechanism.[4,7–9] The mold coating significantly improves the fluidity. It also improves, indirectly, the mechanical properties of the cast products because the mold coating significantly increases the fluidity and, hence, a lower casting temperature can be used.[8] The surface roughness with the production of frictional forces reduces the flow of the melt, and consequently reduces the fluidity of the melt. In addition, various experiments show that the mold-coating materials will produce smooth surfaces and reduce the wetting characteristics of the mold at the metal-mold interface and reduce the friction and the melt-mold contact, therefore reducing the heat-transfer coefficient (HTC) at the metal-mold interface, and so the fluidity is substantially increased.[8,10]

The most common application of nano-materials is nano-ceramic particles. Nano-ceramics are ceramic particles with dimensions in the nanometer rang.[11] The nano-mold coating has a proper surface, anti-sticking and a low coefficient of friction. The roughness is related to the grain size of the mold coating. The apparent fluidity is represented by the flow distance in the test mold and was found to be increased significantly by the mold coating.[6,12]

In this paper we investigate the effect of nano- and micro-ceramics and graphite mold coating on the fluidity length and the soundness of thin-wall castings of the aluminum alloy Al4-1 by gravity casting in a sand mold.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

The standard as well as the actual chemical composition of the Al4-1 alloy are shown in **Table 1**. A 180 kg crucible resistance furnace was used to melt the alloy. At first, 170 kg of Al4-1 alloy was put into the furnace. Then, additions of 0.05 % of melt-mass beryllium to aluminium-5 % beryllium master alloy in the ingot form at the start of the melting treatment. Then the alloy was melted and heated to 740 °C and kept for 10 min, and a mobile rotary degassing system was used. The impeller, made of a graphite pipe, was immersed into the melt and argon was injected into the melt for 20 min through the pipe. Then a RE- containing flux was injected into the melt for 10 min through the pipe. The rotating speed of the impeller was maintained at 350 r/min. The main composition of the flux used in this experiment can be seen in **Table 2**. For melting qualification treatment, the addition of 0.05 % of melt mass strontium in rod form, to the aluminum-10 % strontium master alloy. The strontium master alloy was added to the melt approximately 3 min before the end of the fluxing, because it has the best effect and fewest losses.

The addition of 0.2 % of melt mass, titanium with Al-5Ti-1B master alloy in rod form, simultaneously with strontium master alloy 3 min before the end of the fluxing treatment. The titanium master alloy was added at the end stage of fluxing, because without the loss of grain refiner, refinement of the structure.[5,13,14]

The sand molds were made from sodium-silicate bonded, CO_2-cured sand. After the preparation of the mold, a nano-ceramic (MM12), graphite or micron (ZR1) mold coating was applied to the sand mold surface using the spray gun and the mold surface was heated with a natural gas torch to harden the mold coating. The nano-ceramic mold coating MM12 was product by ltN Nanovation AG (Germany) in order to study the effects of mold coating and casting section thickness on the fluidity. The mold cavity was designed with four straight channels, 250 mm long, with rectangular cross-sections of (2, 4, 6, 8) mm thickness and 30 mm across. A mechanical drawing sample for fluidity test, a 3D model and one cast sample are shown in **Figure 1.**

The pouring basin that is shown in **Figure 2** was used for reducing the turbulence of the melt and to unify the velocity of the melt pouring. This basin was made using AFS (American foundry men society) supervision.[15]

Table 1: Chemical composition of the Al4-1alloy in mass fractions (*w*/%)
Tabela 1: Kemijska sestava zlitine Al4-1 v masnih deležih (*w*/%)

Elements	Standard	Actual
Si	9–10.5	10
Mn	0.25–0.35	0.3
Mg	0.23–0.3	0.3
Ti	0.08–0.15	0.1
Others	0.6	0.6
Al	Bal.	Bal.

Table 2: Composition of flux used in this research
Tabela 2: Sestava talil, uporabljenih pri tej raziskavi

Composition	Content (*w*/%)
NaCl	45
KCl	45
LaF3	5
Other composition	5

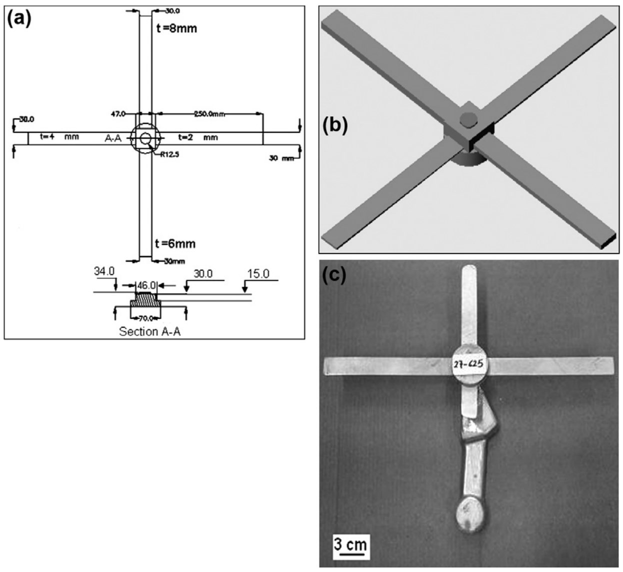

Figure 1: a) Mechanical drawing of sample for fluidity test, b) 3D model for fluidity test and c) one cast sample
Slika 1: a) Risba vzorca za preizkus tekočnosti, b) 3D-model za preizkus tekočnosti in c) ulit vzorec

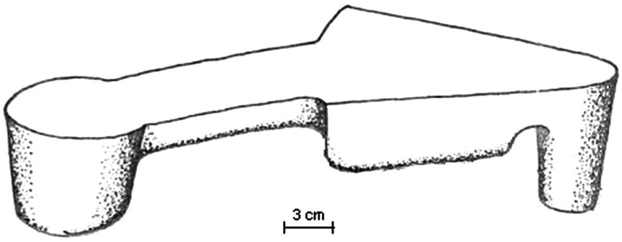

Figure 2: Pouring basin shape[15]
Slika 2: Oblika livne čaše[15]

2.2 Fluidity evaluation

In order to identify the effect of the mold coating and casting cross-sections on the fluidity, 12 samples were cast. The molten metal was poured manually from the furnace into the pouring basin with a ladle. The temperature of the metal was measured by the operator with a calibrated thermocouple (±1 °C accuracy) in the ladle, before pouring into the basin. The aim was to pour the molten metal into the basin as fast as possible and to fill up the basin completely, in order to have the same initial metallostatic pressure head on the flowing metal.

Table 3 shows the casting conditions of the samples. In this study, a temperature of 625 °C was selected for pouring the melt after some preliminary tests, because at the mentioned temperature all of the channels have misrun. Therefore, trying with a change of the coating type, improves the fluidity length and the castability, for better filling of the channels. For a phase analysis of the MM12 coating, the amount of coating drying and powdered then carry out X-ray diffraction (XRD) using a Philips Xpert-MPD model on a coating and show that the mentioned coating contains ZrO_2, SiO_2 and Al_2O_3 phases.

Table 3: Casting condition of various samples (for each condition, 3 samples were cast in a sand mold and 625 °C pouring temperature)
Tabela 3: Razmere pri ulivanju različnih vzorcev (za vsako stanje so bili uliti 3 vzorci v peščeno formo pri temperaturi ulivanja 625 °C)

Mold coating type	Sample
Without coating	1
Graphite coating	2
Micro-ceramic coating (ZR1)	3
Nano-ceramic coating (MM12)	4

3 RESULTS AND DISCUSSION

The beryllium element protects the melt from oxidation and burning of the active element such as magnesium.[2] The strontium element modifies the eutectic silicon phase morphology and changes the needle-like to a fine fibrous morphology, consequently the mechanical properties and, especially, the elongation was improved. The fine fibrous eutectic modifies the hypoeutectic Al–Si alloys that occur when elements such as strontium and sodium are added, and this has been explained based on observations of increased twinning. The increased density of twinning is believed to result from an impurity-induced twinning (IIT) mechanism that promotes further growth by encouraging the formation of a perpetuating twin plane re-entrant edge (TPRE).[16–18]

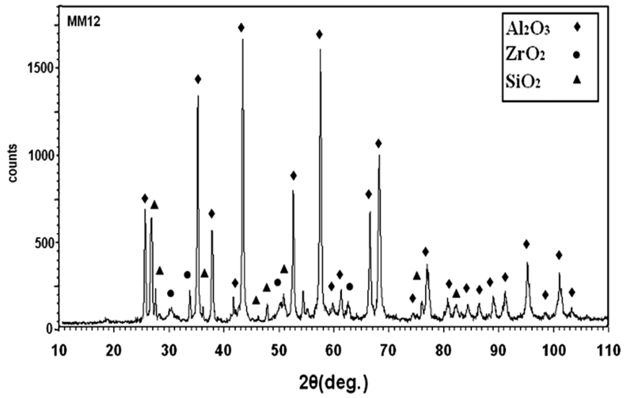

Figure 3: XRD pattern of nano-ceramic coating (MM12) used in this study
Slika 3: XRD-posnetek nanokeramičnega premaza (MM12), uporabljenega v tej študiji

The chemical compositions of the nano-ceramic coating (MM12) and micro-ceramic coating (ZR1) are shown in **Table 4**. The XRD patterns of the nano-ceramic coating (MM12) and the micro-ceramic coating (ZR1) powders are shown in **Figures 3** and **4**.

Table 4: Chemical composition of MM12 and ZR1 coatings used in this study
Tabela 4: Kemijska sestava premazov MM12 in ZR1, uporabljenih v tej študiji

Composition	Al_2O_3	ZrO_2	SiO_2	H_2O	Others
Content (*w*/%)	30	7	1	60	2

With reference to the XRD analysis shown in **Figure 3**, the nano-ceramic coating used in this research particularly contains Al_2O_3, ZrO_2 and SiO_2. Based on the broadening of the most prominent peak in the XRD profile, a

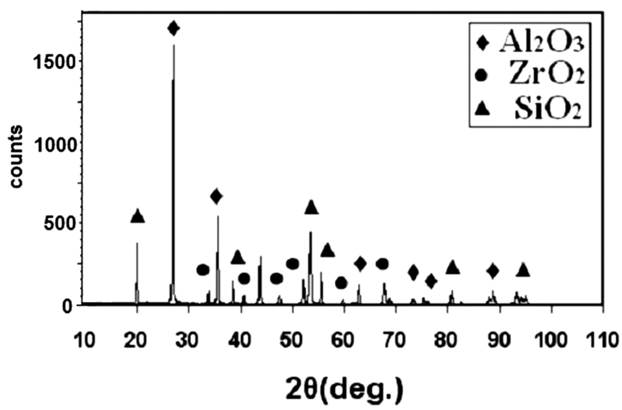

Figure 4: XRD pattern of micro-ceramic coating (ZR1) used in this study
Slika 4: XRD-posnetek mikrokeramičnega premaza (ZR1), uporabljenega v tej študiji

mean crystallite dimension D was calculated using Scherer's formula:[19]

$$D=\frac{0.9\lambda}{\beta\cdot\cos\theta} \quad (1)$$

where λ stands for the X-ray radiation wavelength (here 0.15406 nm), β stands for the line broadening at half the maximum intensity in radians. β calculated by equation (2):[20]

$$\beta^2=\beta_M^2-\beta_S^2 \quad (2)$$

$\beta_M = \beta$ in nano-ceramic coating pattern XRD (MM12)
$\beta_S = \beta$ in micro-ceramic coating pattern XRD (ZR1).

Here, $\beta_{Al_2O_3} = 0.0053$, $\beta_{ZrO_2} = 0.0012$, $\beta_{SiO_2} = 0.0058$, K is a shape factor, for the case of a sphere $K = 0.9$, and θ is the Bragg angle.[19] $\theta_{Al_2O_3} = 28.78°$, $\theta_{ZrO_2} = 16.91°$ and $\theta_{SiO_2} = 13.38°$, therefore, $D_{Al_2O_3} = 30$ nm, $D_{ZrO_2} = 120$ nm and $D_{SiO_2} = 25$ nm.

The melting temperature of bulk Al_2O_3 is 2015 °C. The melting temperature of the Al_2O_3 nano-particles (25 nm) should be similar to the bulk counterparts, because the size effect becomes significant only when the particle size is less than 10 nm.[21] Therefore, no sintering of the nano-coating occurs.

Figure 5 shows a SEM micrograph of the micro-ceramic coating ZR1 and the nano-ceramic coating MM12. The phase particles of the ZR1 coating have an average size of approximately 2–20 μm. The ZR1 and MM12 coatings have nearly similar compositions, but different particle sizes. The micro-ceramic coating with a similar composition to the nano-ceramic coating was used to study the influence of the particle size coating on the surface quality of the cast parts and the fluidity length.

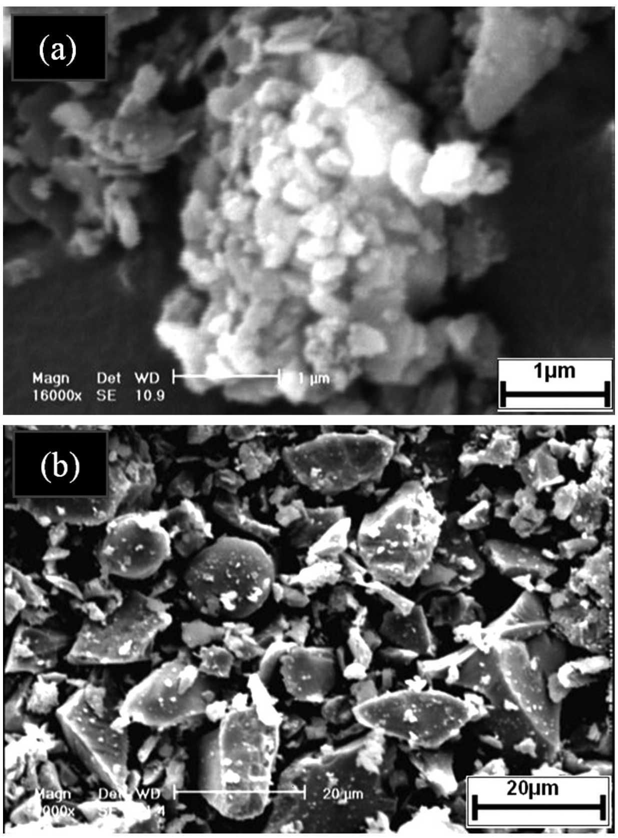

Figure 5: SEM micrographs of: a) micro-ceramic coating ZR1 and b) nano-ceramic coating MM12 used in this study
Slika 5: SEM-posnetka: a) mikrokeramičnega premaza ZR1 in b) nanokeramičnega premaza MM12, uporabljena v tej študiji

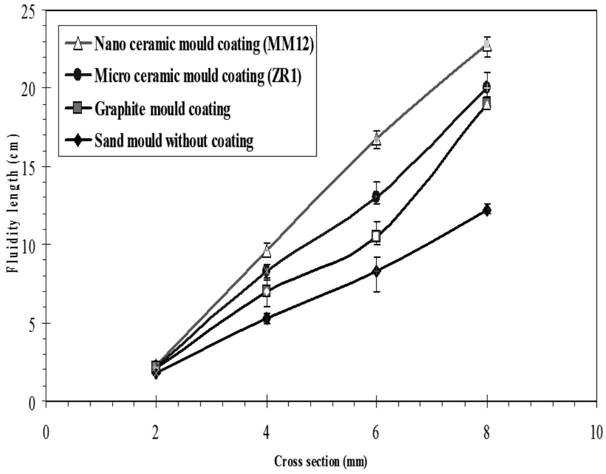

Figure 6: Fluidity length versus cross-section channel
Slika 6: Tekočnost v odvisnosti od prereza kanala

Figure 6 shows the effect of the cross-section and the mold coating type on the fluidity length of the melt. With an increasing cross-section of the channel, the fluidity of melt was improved. The fluidity in the mold with the nano-ceramic mold coating was a maximum and the fluidity in the mold with the micro-ceramic coating and graphite coating was better than in sand mold without coating.

The surface roughness was measured using a Mahr-Perthometer M2 roughness tester device. The nano-mold coating had a very smooth surface, hence it reduced the friction forces and the fluidity was improved. **Figure 7** shows the relationship between the mold coating and the surface roughness. This figure show that the nano-ceramic mold coating (MM12) has a minimum roughness, and hence the fluidity length in the mold with this

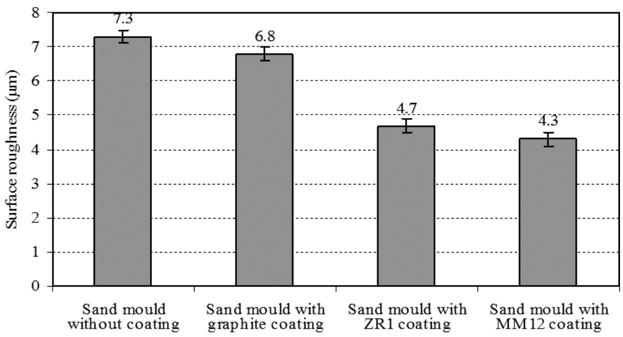

Figure 7: Surface roughness versus mold coating
Slika 7: Hrapavost površine pri različnih premazih forme

coating is better than the mold with micro-coating, graphite coating and a mold without coating.

Research has shown that the wetting angle between the Al melt and ZrO_2 and Al_2O_3 is 70° and 152°, respectively.[12] Thus, the wetting angles are large, and consequently the wettability of the mold when using molten aluminum is very low and the fluidity in the thin section can be improved.[12] The completely proper characteristics of the mold with nano-ceramic coatings can be for the following reasons:[12,22,23]

1. Thermal and chemical stability, because of ionic and covalent bonds of the ceramics. After the experiment, the composition analysis performed on the inner surface of the coating mold and in the alloy samples achieved, indicated that no chemical reaction occurred between the alloy melt and the mold materials, and therefore no gas is produced and this increases the fluidity.
2. Best flow of melt into mold, because this reduces the coefficient friction and the surface roughness of the mold by smooth and clean surfaces with the nano-mold coating, consequently the melt easily fills the mold and improves the fluidity.
3. Large wetting angle between the aluminum melt and the particles of the coating, which reduces the wettability of the mold coating with the aluminum melt, and consequently it easily fills the mold.
4. Crystal lattice misfit between the melt and the coating materials that inhibits the nucleation of the aluminum melt on a nano-mold coating and consequently there is easy melt flow and an enhancement of the fluidity.

4 CONCLUSIONS

1. By applying a graphite mold coating, a micro-ceramic mold coating and a nano-ceramic mold coating on a sand mold surface, because the coat operates the insulation role and reduces the roughness of the mold surface, this increases the fluidity and castability of melt.
2. The melt fluidity and the castability in the sand mold with a nano-ceramic coating has the best result in comparison with the sand mold with a micro-ceramic mold coating, a graphite mold coating and a sand mold without coating.
3. By increasing the cross-section of the channel, because it reduces the cooling rate and the surface tension, this improves the fluidity length and the castability.
4. Mold coating significantly improves the fluidity, and hence a lower casting temperature can be used. Therefore, casting defects were reduced and indirectly mechanical properties could be improved.

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