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Karakterizacija napak v ulitkih iz aluminija, proizvedenih z nagibnim gravitacijskim litjem, v povezavi s procesnimi parametri

Characterization of Defects in Aluminum Castings Produced by Tilt Gravity Casting in Relation to Process Parameters

Povzetek

V procesu proizvodnje ulitkov iz aluminija se velikokrat soočimo z napakami, ki jih zaznamo, ko so ulitki že sestavljeni oziroma tik pred uporabo. Med napake sodi tudi netesnost. Ta napaka plinu ali tekočini omogoča, da preide skozi stene ulitkov, zato je za nekatere ulitke ključna karakteristika tesnost. Med takšne ulitke sodijo ohišja, pokrovi itd. Za doseganje stabilnega proizvodnega procesa in razumevanje osnovnega vzroka napak je treba izvesti raziskave oziroma karakterizacijo napak z računalniško tomografijo, optično mikroskopijo in vrstično elektronsko mikroskopijo. V članku je predstavljena sistematična raziskava netesnih kosov, ulitih s postopkom nagibnega gravitacijskega litja, za določitev vzroka za netesnost. Vzrok za netesnost smo želeli povezati s procesnimi parametri, ki povzročijo napako, ki vodi do netesnosti. V raziskavi smo ugotovili, da sta glavna vzroka za netesnost kosov, ulitih z nagibnim gravitacijskim litjem, vključki oziroma oksidne kožice in krčilna poroznost. Pri nastanku krčilne poroznosti smo se osredotočili na vpliv temperature orodja. Meritve temperature orodja smo opravili s termično kamero. Za določitev vpliva temperature orodja na strjevanje ulitka smo izvedli simulacijo litja.
Ključne besede: nagibno gravitacijsko litje, napake v ulitkih, procesni parametri

Abstract

In the production process of aluminum castings, we often face defects that are detected when castings have already been assembled or just before final use. These defects include leaks that allow gas or liquid to pass through the walls of castings. Thus, for some castings tightness represents the key feature. Such castings include housings, covers, etc. To achieve a stable production process and to understand the root cause, it is necessary to perform research or characterization of defects with computer tomography, optical microscope, and scanning electron microscopy. In this paper, we performed systematical research of leaking parts cast with tilt gravity casting to determine the cause for the leakage. We wanted to relate the causes of leakage to process parameters affecting defects that lead to leakage. In the study, we found that the main reason for leakage of cast parts cast by tilt gravity casting are inclusions or oxide film and shrinkage porosity. For the formation of shrinkage porosity, we focused on the influence of mold temperature. For the measurement of mold temperature, we used a thermal imaging camera. To determine the impact of mold temperature on the solidification of cast parts we used a casting simulation.
Keywords: tilt gravity casting, casting defects, process parameters

1 Uvod

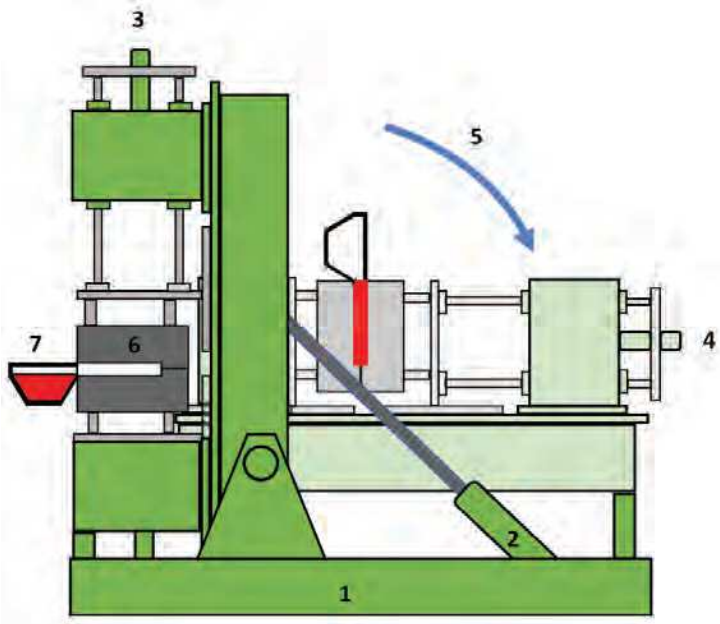
V industrijskih panogah, kot so sektor mobilnosti, vesoljske tehnologije, toplotna industrija in druge, je aluminij zelo uporaben material. Z različnimi aplikacijami in povečano uporabo aluminija se povečujejo tudi zahteve za aluminijaste ulitke. V proizvodnji ulitkov smo pogosto soočeni z napakami, ki vplivajo na njihove lastnosti in funkcijo. Cilj proizvodnje ulitkov je doseganje stabilnega procesa in kakovosti [1].

Tehnologije litja omogočajo proizvodnjo ulitih kosov kompleksnih oblik. Ena takšnih tehnologij je nagibno gravitacijsko litje. Načelo nagibnega gravitacijskega litja je predstavljeno na Sliki 1. Talina se iz vzdrževalne peči najprej nalije v čašo na livnem orodju oziroma kokili. Z nagibanjem stroja teče talina v livno orodje. V končnem položaju je livno orodje napolnjeno s talino in začne se strjevanje. Po končanem strjevanju se stroj vrne v začetni položaj,

1 Introduction

Aluminum is a very useful and important material for industrial applications such as the mobility sector, aerospace, heating industry, and many more. With different applications and increasing use of aluminum, requirements for aluminum castings increase as well. In the production of castings, we are often faced with defects affecting the properties and function of the casting. The goal of casting production is to achieve a stable process and quality [1].

Casting technology enables the production of cast parts of complex shapes. One of such casting technologies is tilt gravity casting. The principle of tilt gravity casting is presented in Figure 1. The melt is first poured from a holding furnace to a ladle (basin) on the casting tool or mold. By tilting the machine, the melt flows into the casting tool. At the end position, the casting tool is filled with the melt and solidification begins. After completed solidification, the machine returns to the start position and the casting



Slika 1. Načelo nagibnega gravitacijskega litja: 1. nagibni gravitacijski stroj, 2. hidravlika za nagibanje, 3. začetni položaj stroja, 4. končni položaj stroja, 5. smer nagibanja, 6. livno orodje (kokila), 7. čaša na livnem orodju za tekoči aluminij

Figure 1: Principle of tilt casting process: 1. tilt casting machine; 2. tilting hydraulic; 3. start position of the machine; 4. end position of the machine; 5. tilting direction; 6. casting tool (mold); 7. ladle on the casting tool for the molten aluminum

kjer se livno orodje odpre. Proizvedeni ulitek se nato vzame iz stroja [1, 2].

V proizvodnem procesu gravitacijskega litja lahko nastanejo različne napake. Na to vpliva veliko parametrov, kot so aluminijeva zlitina, geometrija ulitka, orodje itd. Nekatere napake vplivajo na videz ulitka, druge pa povzročijo poslabšanje njegovih lastnosti [3, 4].

Namen članka je raziskati nastanek netesnosti ulitka, proizvedenega z nagibnim gravitacijskim litjem. Netesnost pri nagibnem gravitacijskem litju ni pogost pojav. Ulitki, liti s to tehnologijo, imajo debelejše stene v primerjavi z ulitki, izdelanimi z visokotlačnim litjem, pri katerem je netesnost pogostejša. Ta napaka se zaznava s preskusom netesnosti, točna lokacija pa se določi s preskusom z mehurčki. Netesnost v ulitkih pomeni, da pride do nastanka poti, ki notranjo steno ulitka povežejo z zunanjo. V članku so predstavljeni trije različni pojavi netesnosti v ulitkih.

2 Eksperimentalno delo

V raziskavi smo uporabili ulitke, pri katerih smo netesnost poiskali s preskusom. Ulitki so bili izdelani iz livne zlitine AlSi8Cu3. Za določitev natančne lokacije netesne poti v ulitku je bila uporabljena računalniška tomografija (CT). Lokacijo netesnosti smo analizirali z optično mikroskopijo (OM) in vrstično elektronsko mikroskopijo (SEM in EDX).

S simulacijo litja s programom Magmasoft smo raziskali osnovni vzrok za krčilno poroznost. Za meritve dejanske temperature smo uporabili termično kamero za spremljanje površinske temperature orodja, in sicer Chem-Trend ter Inprotect IRT.

tool is opened. The produced cast part is then removed [1, 2].

In the production process of gravity casting, various defects can occur. There are many parameters with possible influence such as aluminum alloy, the geometry of casting, die, etc. While some defects affect the appearance of the casting there are defects that can cause deterioration of the product properties [3,4].

This paper aimed to study the formation of leakage of cast parts produced by tilt gravity casting. Leakage defect is not a common defect for the tilt gravity casting procedure. Castings cast by this technology have thicker walls compared to castings cast by high-pressure die casting, where leaks are more common. This defect is detected by the leakage test while the exact location is detected by the bubble test. Leakage of casting means there is a leakage path provided connecting the inner wall to the outer wall. This paper presents three different leakage occurrences of the castings.

2 Experimental Work

In our research, we used cast parts where a leak was found with a leakage test inspection. Cast parts were produced with cast alloy AlSi8Cu3. Computed tomography (CT) was used to determine the exact position of the leakage path within the cast part. The leak location was analysed with an optical microscope (OM) and a Scanning Electron Microscope (SEM) EDX.

We used a casting simulation with the Magmasoft program to investigate the root cause for the shrinkage porosity. To measure the actual temperatures, we used a thermal imaging camera to monitor the surface temperature of the tool. Specifically, we used Chem-Trend & inprotec IRT thermal imaging camera.

3 Rezultati

3.1 Računalniška tomografija (CT)

V industrijskem okolju se rentgensko slikanje pogosto uporablja za pregledovanje ulitkov, saj omogoča hitro izvedbo analize, vendar pa s to analizo ni mogoče pridobiti zahtevane informacije o vzroku netesnosti. Zato smo uporabili 3D-računalniško tomografijo, s katero je mogoče pridobiti informacije o velikosti por in razdaljah med njimi.

Analiza CT, ki smo jo izvedli na več vzorcih, je pokazala, da netesnost povzročijo vključki in krčilna poroznost. Na Sliki 2 so prikazani trije različni vzroki za netesnost, ki so bili zaznani pri analizi CT. Na Sliki 2a je prikazano, da poroznost ni bila zaznana kot napaka, vidna pa je napaka, ki je videti kot vključek. Na Sliki 2b je prikazana kombinacija vključka in poroznosti. V tretjem primeru smo zaznali netesnost zaradi velike pore (Slika 2c).

3.2 Preiskava z optičnim mikroskopom (OM)

Na področju, na katerem smo z uporabo analize CT zaznali napake, smo izvedli metalografsko preiskavo. Rezultati so prikazani na Sliki 3. Na Sliki 3a je prikazana razpoka (pot za netesnost – rdeča puščica) oziroma oksidna kožica. Podobna situacija je predstavljena na Sliki 3b, vendar z zaznano poroznostjo. Kombinacija teh dveh pojavov na ulitku povzroči netesnost. Na Sliki 3c je prikazana potrjena prisotnost velike pore, ki je bila vidna z analizo CT. Netesnost povzroči velika krčilna poroznost na steni ulitka.

3 Results

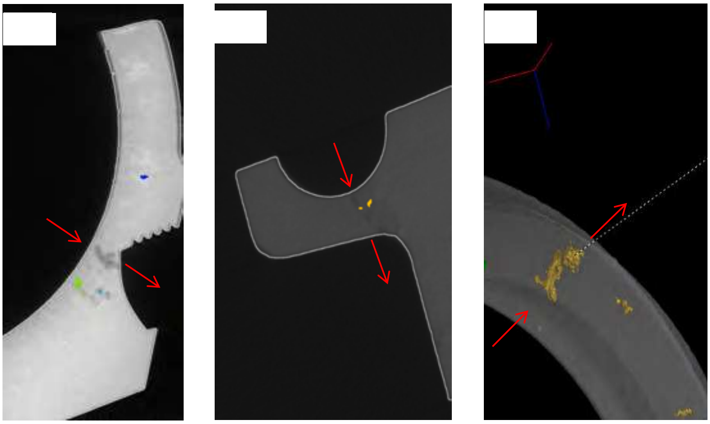
3.1 Computed Tomography (CT) Scan

In an industrial environment, the 2D radiographic method (x-ray) is commonly used to inspect cast parts since the analysis can be performed quickly. However, with this analysis, we cannot obtain the required data for the cause of the leakage. For these reasons, we use 3D computed tomography scans which can provide information on pore sizes and interpore distances.

CT analysis was performed on several samples, which showed that leakage occurs due to inclusions and shrinkage porosity. Figure 2 shows three different occurrences of leakage which we detected on CT. In Figure 2a the CT does not recognize the defect as porosity. However, there is a visible defect that looks like inclusion. Figure 2b shows a combination of inclusion and porosity. In the third case, we detected a leak due to a large pore (Figure 2c).

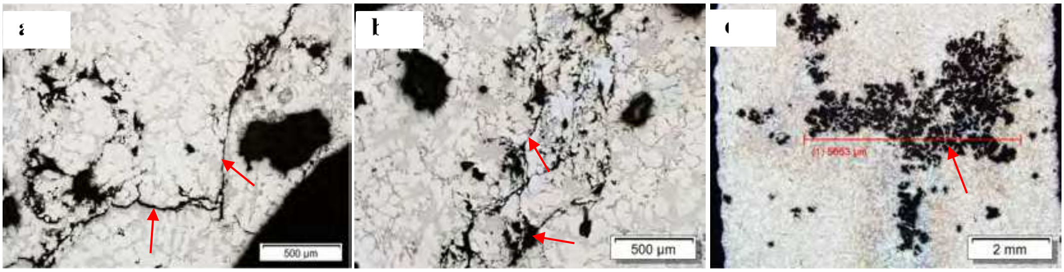
3.2 Optical Microscope Examination

On locations where we detected defects using CT analysis, we performed a metallographic examination. Results are presented in Figure 3. Figure 3a shows a crack (leakage path - red arrow) or oxide skin. A similar situation is presented in Figure 3b, however, there is also a noticeable porosity. A combination of the two effects causes leakage of the cast part. Figure 3c confirms the large pore which has been seen on the CT scan. A large shrinkage porosity in the wall of the casting causes the leakage of the cast part.



Slika 2. Slike prečnih presekov, izvedene z računalniško tomografijo, s prikazanim področjem netesnosti:
a) vključek v vzorcu,
b) poroznost + vključek,
c) krčilna poroznost

Figure 2. Images of Computed Tomography cross-section of samples displaying the leak location,
a) inclusion in samples;
b) porosity + inclusion;
c) shrinkage porosity



Slika 3. Rezultati metalografske preiskave področij na ulitku z računalniško tomografijo: a) oksidne razpoke oziroma kožice, b) oksidna kožica + krčilna poroznost, c) velika poroznost

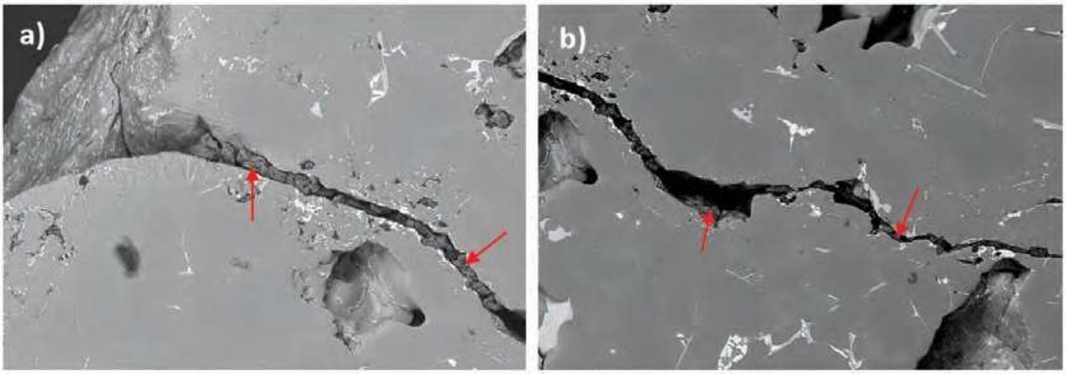
Figure 3. Results of the metallographic examination of the cast parts by the tomographic scan; a) oxide crack or skin; b) oxide skin + shrinkage porosity; c) large porosity

3.3 Vrstična elektronska mikroskopija (SEM)

Glavni namen karakterizacije z vrstičnim elektronskim mikroskopom (SEM) je bila analiza morfologije razpok in poroznosti ter opredelitev vrste vključka. Na razpoki smo izvedli analizo EDX. Na Sliki 4 so prikazana področja, na katerih smo izmerili kemično sestavo napak. Meritev EDX (Slika 5) je razkrila kemično sestavo vključka, ki vsebuje ogljik (C) in kisik (O). Rezultati potrjujejo naše domneve iz preiskave z OM, da so v ulitku prisotne oksidne kožice.

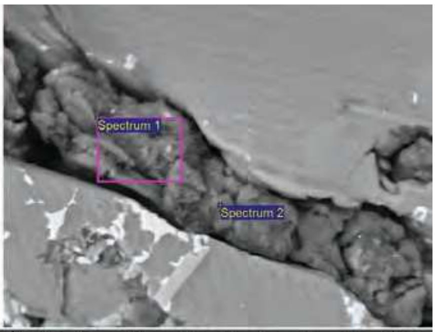
3.3 Scanning Electron Microscopy (SEM)

The main goal of the characterization technique with Scanning Electron Microscopy (SEM) was to analyse the morphology of cracks and porosity and define the type of inclusions. We performed EDX analysis on the cracks. Figure 4 presents locations where we measured the chemical composition of defects. EDX measurement (Figure 5) revealed the chemical composition of inclusion consists of carbon (C) and oxygen (O). This result confirms our assumptions from OM



Slika 4. Mikrostruktura napak s SEM: a) razpoke z vključki, b) razpoka + krčilna poroznost

Figure 4. SEM microstructure of defect: a) crack with inclusions; b) crack + shrinkage porosity



Spectrum	In stats.	C	O	Mg	Al	Si	Ca	Fe	Total
Spectrum 1	Yes	39.47	39.18	0.83	7.91	0.37	7.14	5.09	100.00
Spectrum 2	Yes	37.24	44.17	0.91	7.16	1.00	6.52	3.00	100.00

Slika 5. Kemijska analiza s SEM in EDX

Figure 5. Chemical analysis with SEM EDX of the inclusion

3.4 Termična kamera

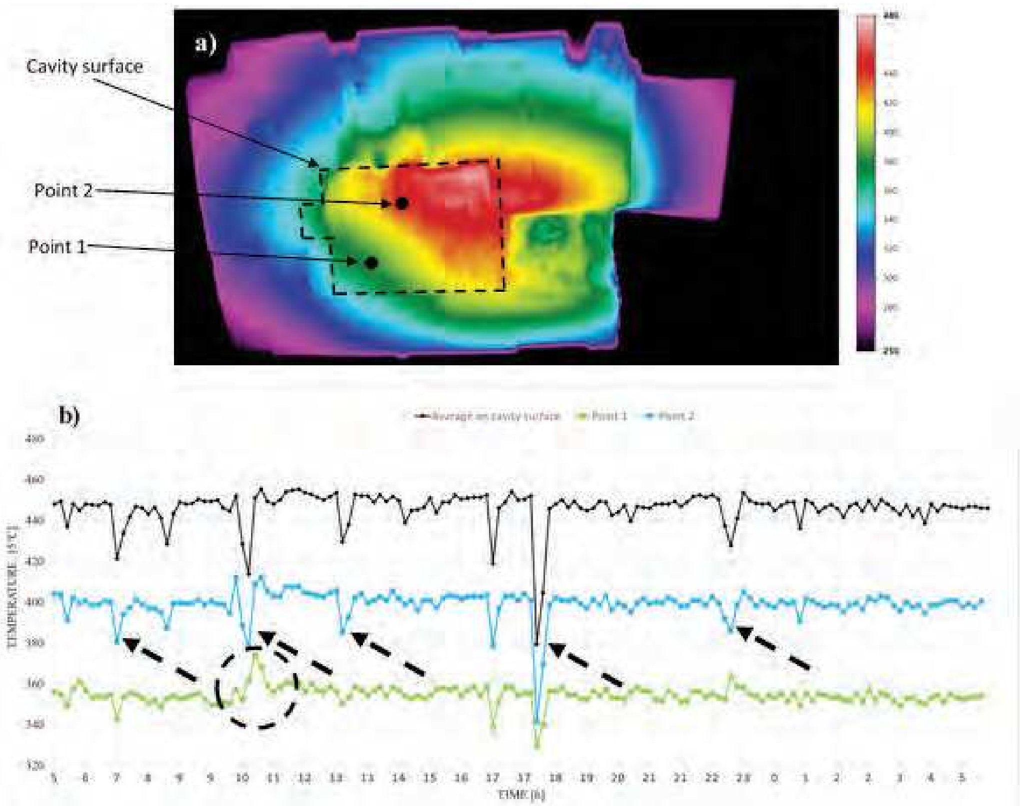
Za zaznavanje temperature smo uporabili termično kamero. Na Sliki 6a je posnetek s termično kamero oziroma temperaturna distribucija na odprtem livnem orodju po končanem ciklu. Spremljali smo temperature na karakterističnih lokacijah. Na sliki 6b je prikazan graf posameznih temperaturnih ciklov za en livni dan z navedbo povprečne temperature na površini orodja in s po dvema točkama, na katerih je bilo zaznano tveganje za poroznost na ulitku. S črtkano

examination there is oxide film or oxide skin in the cast part.

3.4 Thermal Imaging Camera

For temperature detection, we used a thermal imaging camera. Figure 6a shows the thermal image or temperature distribution of the opened casting tool after the finished cycle. We monitored temperatures on characteristic locations. Figure 6b is a graph of temperatures over puščico so na Sliki 6b označeni vrhovi (odstopanja) in označujejo čas, ko so bila na livnem orodju opravljena velika vzdrževalna dela. To so bili tudi razlogi za padec temperature na livnem orodju. Med posameznimi cikli, prikazanimi na grafu, smo opazili relativno stabilno temperaturo. V stabilnem ciklu je bilo moč opaziti, da se temperature na točkah 1 in 2 spreminjajo povprečno za 5 do 10 °C. Na grafu je razvidno, da je v nekaterih primerih po velikih vzdrževalnih delih temperatura na karakterističnih lokacijah (točka 1) narasla

a single casting day showing average temperature on cavity surface and two points with a risk of leakage of the cast part. Dashed arrows in Figure 6b mark peaks where major maintenance interventions were performed on the casting tool. These were the reason for the drop in temperature of the casting tool. We observed relatively stable temperatures during separate cycles in the graph. In stable cycles, it was observed that the temperature at points 1 and 2 varied by an average of 5 to 10 °C. The graph indicates that in some cases,



Slika 6. a) Temperaturna razporeditev na livnem orodju z označenimi karakterističnimi področji za spremljanje temperature, b) graf temperature na karakterističnih področjih za posamezni cikel (en dan litja)

Figure 6. a) Surface temperature distribution of the casting tool with marked characteristic locations for monitoring of temperatures; b) Graph of temperatures on the characteristic locations for separate cycles (single casting day)

(črtkani krog). Termična analiza prikazuje nestabilno temperaturo na karakterističnih področjih, ko je operater izvedel vzdrževalne posege.

3.5 Simulacije litja

Eden pomembnejših procesnih parametrov, ki vplivajo na krčilno poroznost, je temperatura orodja oziroma kokile. Študije in reference [5] kažejo, da temperatura orodja vpliva na nastanek krčilne poroznosti, ki se veča z naraščanjem temperature orodja. Krčilna poroznost je napaka, ki nastane zaradi pomanjkljivega napajanja.

Velike pore, prikazane na Slikah 2c in 3c, zelo redko nastanejo v stabilnem procesu, vendar se pojavljajo in želeli smo ugotoviti njihov vzrok. Pri preiskavi s termično kamero smo opazili, da se v stabilnem ciklu pojavijo spremembe v temperaturi orodja na karakterističnih lokacijah, in to do 20 °C (črtkani krog na sliki 6b). To je bil razlog, da smo raziskali mogoče spremembe strjevalne fronte in potencialno tveganje za nastanek krčilne poroznosti s simulacijo litja.

Simulacijo smo izvedli z običajno temperaturo orodja 380 °C in s temperaturo nad običajno. Na Sliki 7b je prikazana strjevalna fronta na karakterističnem področju (točka 1 na Sliki 6a) s temperaturo 361 °C (Slika 7a). Zaznali smo (Slika 6b, graf), da pride do odstopanj, saj se temperatura lahko poviša do 380 °C. Zato smo simulirali temperaturo orodja 400 °C, pri čemer smo na karakterističnem področju dosegli temperaturo približno 380 °C (Slika 7c). Na Sliki 7d je prikazana strjevalna fronta, ki se je v primerjavi z običajnim ciklom spremenila. Višja temperatura povzroči počasnejše strjevanje v ulitku. Ta sprememba v strjevalni fronti lahko vodi do nastanka krčilne poroznosti na karakterističnem področju.

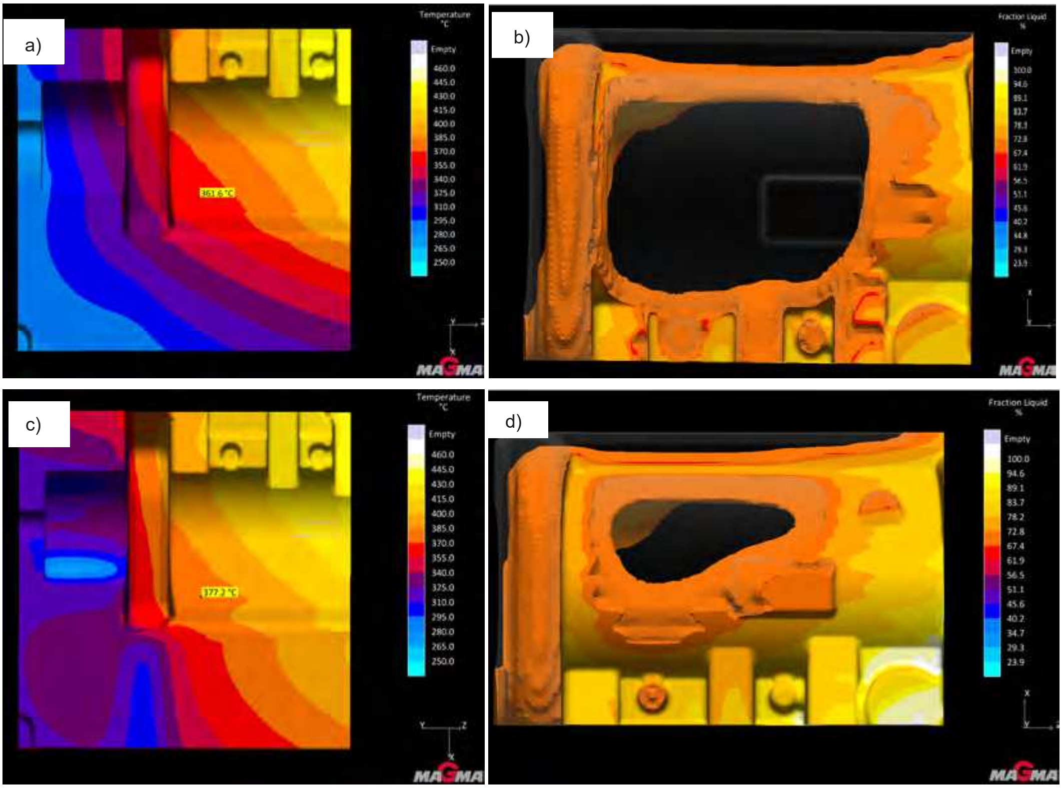
after major maintenance work, temperature rises (dashed circle) at a characteristic location (point 1). Thermal analysis showed the unstable temperature at characteristic locations when the casting operator performed maintenance interventions.

3.5 Casting simulation

One of the process parameters influencing shrinkage porosity is the casting tool or mold temperature. A study in reference [5] shows that mold temperature influences formation of shrinkage porosity which increases with increasing mold temperatures. Shrinkage porosity is a defect that occurs due to a failure in effective feeding.

Large pores as shown in Figures 2c and 3c are a very rare occurrence in a stable process. However, they do turn up and we wanted to identify the root cause. Examining the thermal images, we observed that in stable cycles the change in tool temperature can reach up to 20 °C at a characteristic location (dashed circle in Figure 6b). For this reason, we examined the possible change of solidification front and potential risk of shrinkage porosity formation with the casting simulation.

We performed casting simulations with normal mold temperature at 380 °C and with a temperature above normal. Figure 7b shows solidification fronts on the characteristic location (Point 1 in Figure 6a) with a temperature at 361 °C (Figure 7a). Figure 6b (graph) indicates a deviation at other locations where the temperature increases up to 380 °C. For this reason, we simulated mold temperature at 400 °C whereby we achieved a temperature near 380 °C at the characteristic location (Figure 7c). Figure 7d shows solidification fronts that are changed compared to the normal cycle. Higher mold temperature influences slower solidification of the cast part. This



Slika 7. Simulacija litja ulitka: a) temperatura orodja 380 °C s temperaturo 361 °C na karakterističnem področju, b) strjevanje pri temperaturi orodja 380 °C, c) temperatura orodja 400 °C s temperaturo 377 °C na karakterističnem področju, (d) strjevanje pri temperaturi orodja 400 °C

Figure 7. Casting simulation of casting part; a) mold temperature 380 °C with temperature 361 °C on the characteristic location; b) solidifications for mold temperature 380 °C; c) mold temperature 400 °C with temperature 377 °C on the characteristic location; d) solidification for mold temperature 400 °C

4 Zaključki

V raziskavi so bile raziskane napake za netesnost ulitkov, proizvedenih z nagibnim gravitacijskim litjem. Čeprav so v proizvodnjo ulitkov uvedeni ukrepi za preprečitev vključkov, je pojav oksidnih vključkov v ulitkih vedno mogoč. Debelejše oksidne kožice lahko v procesu nagibnega gravitacijskega litja preprečimo z uporabo keramičnega filtra, ki ga vstavimo v orodje pred začetkom cikla. S spremljanjem uporabe keramičnega filtra za vsak cikel je change in the solidification front can lead to the formation of shrinkage porosity at the characteristic location.

4 Conclusions

This study investigated leakage defects in cast parts produced by tilt gravity casting. Although casting production involves measures to prevent inclusions there is always a possibility for an oxide inclusion occurrence in the casting. A thicker oxide mogoče zmanjšati tveganje za debelejše oksidne kožice v ulitku in potencialno netesnost.

Velika krčilna poroznost lahko nastane zaradi različnih procesnih parametrov. V članku smo se osredotočili samo na temperaturo orodja. S termično kamero smo na karakterističnih področjih opazili spremembe v temperaturi orodja, in to do 20 °C. S simulacijo litja smo simulirali spremembe temperature orodja za določitev vpliva na strjevanje. Spremembe, ki lahko vplivajo na nastanek krčilne poroznosti, smo opazili na poteku strjevalne fronte. Prav zato je pri nagibnem gravitacijskem litju pomembno nadzorovati temperature orodja, čeprav je to v industrijskem okolju velik izziv.

skin in the tilt gravity casting process can be prevented with a ceramic filter which is put on the mold before the start of a cycle. By monitoring the utilization of the ceramic filter for each cycle, it is possible to reduce the risk of a thick oxide skin in the cast part and its potential leakage.

Large shrinkage pores which can be formed due to many process parameters are a different issue. In the present paper, we focused only on the mold temperature. By the thermovision camera, we observed there are changes in mold temperatures up to 20 °C at characteristic locations. With a casting simulation, we simulated a change in mold temperature to examine the influence on solidification. We observed a change in the solidification front that can have an impact on the formation of shrinkage porosity. For this reason, it is important to control the mold temperature at tilt gravity casting although this represents a major challenge in an industrial environment.

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