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Vplivi na kristalizacijo rotorjev turbo polnilnika iz zlitin na osnovi niklja

Influencing the crystallization of nickel-based turbocharger rotors

1. Uvod

Ulitki rotorjev turbopolnilnika v energetiki, pri letalskih in avtomobilskih motorjih so izdelani predvsem iz superzlitin na osnovi niklja. Te zlitine s trgovskim imenom Inconel so legirane s karbidotvornimi elementi in drugimi elementi, ki utrjujejo osnovo in povečujejo dimenzijsko stabilnost pri visokih temperaturah. Pogosto je uporabljena zlitina npr. IN713LC, v kateri so zlitinski elementi predvsem Cr, Mo, W, Ta in Ti. Nikljeve superzlitine imajo osnovo iz substitucijske nikljeve trdne raztopine in karbidnih izločkov. Po toplotni obdelavi se faza pretvori v intermetalno fazo, sestavljeno iz Ni3Al ali $Ni_3(Al,Ti)$.

Pri strjevanju ogljik iz nikljevih superzlitin tvori z W, Ti, Mo, Hf, Ta in Nb primarne karbide. Primarni karbidi tipa MC imajo kubično morfologijo in se pojavljajo predvsem na mejah kristalnih zrn, kjer tvorijo mreže (slika 1). Pri mehanskih in toplotnih obremenitvah začno karbidi pokati in se lomiti (slika 2).

Slika 1 Mikrostruktura zlitine IN 713 LC s karbidno mrežo in razpokami. Makrostruktura ulitkov v vzdolžni smeri je navadno sestavljena iz treh morfoloških območij slika 2.4:

- območje drobnih globulitnih zrn v tankih stenah, pri veliki hitrosti strjevanja – **A**
- območje stebričastih zrn pri usmerjenem toplotnem toku - **B**
- območje grobih globulitnih ali deloma stebričastih zrn na mestih počasnega

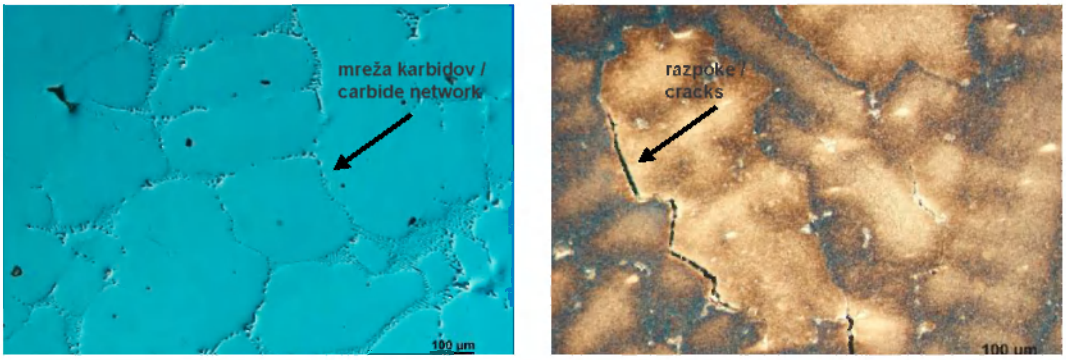
1. Introduction

Castings of turbocharger rotors for power engineering, aircraft and automobile engines are made of nickel-based superalloys in particular. These alloys, referred to as Inconel, are alloyed with carbide-forming and other elements which reinforce the matrix and increase dimensional stability under high temperatures. A frequently used alloy is, for example, the IN 713LC alloy, in which the alloying elements are mainly Cr, Mo, W, Ta, and Ti. Nickel superalloys are generally formed by a matrix of substitutional nickel solid solution and carbide precipitates. After heat treatment, the phase is transformed into the intermetallic phase' formed by Ni_3Al or $Ni_3(Al, Ti)$ components.

In the course of solidification, carbon in nickel superalloys forms primary carbides with the elements W, Ti, Mo, Hf, Ta, and Nb. Primary carbides of type MC are of cubic morphology and they occur in particular on grain boundaries, where they form a network -Fig.1. Under mechanical or thermal stress, the carbides can initiate cracks and fractures-Fig.2.

The macrostructure of castings in longitudinal section usually forms 3 morphological regions – Fig. 2:

- region of fine equiaxed grains in thin walls, with a high solidification rate – **A** - region of columnar grains in the direction of heat flow – **B**
- region of rough equiaxed or partially



Slika 1. Mikrostruktura zlitine IN 713 LC s karbidno mrežo in razpokami

Figure 1. Microstructure of IN 713 LC alloy with carbide network and cracks

strjevanja, brez izrazitega usmerjenega toplotnega toka – posebno pri pestih koles – **C.**

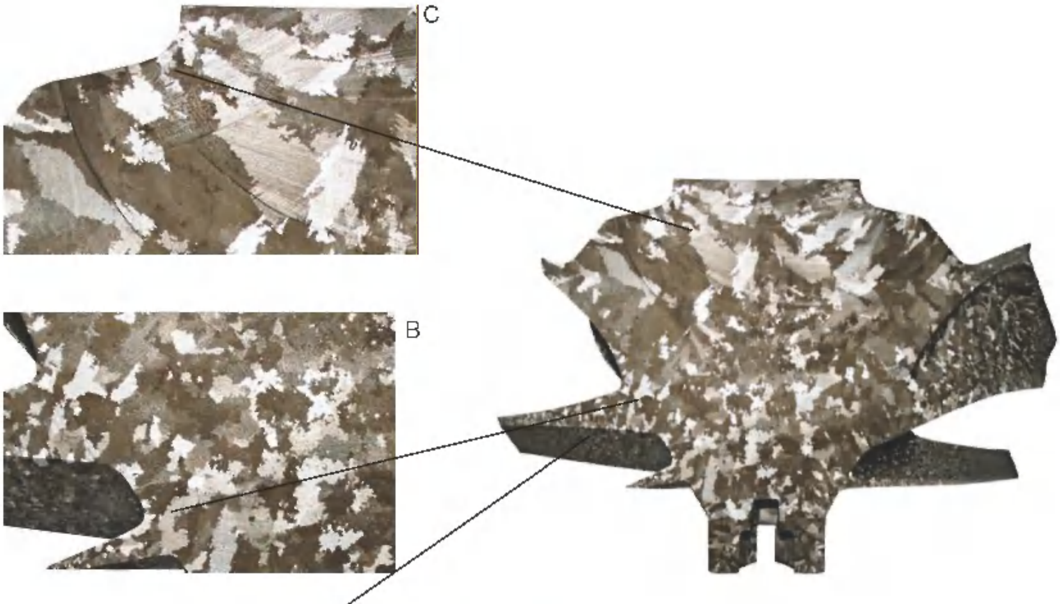
Zahteve posameznih kupcev po drobni mikrostrukturi so zato popolnoma razumljive. Omejitve se navadno zahtevajo za največje velikosti dendritnih in globulitnih zrn, toda možne so še druge zahteve. V ulitkih se ne smejo pojavljati razpoke.

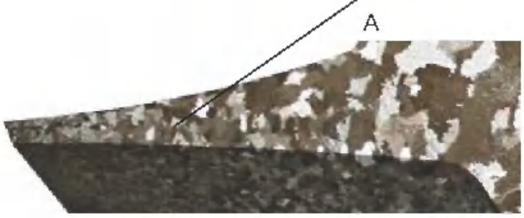
V mikrostrukturi ulitkov iz nikljevih zlitih se navadno v določenem obsegu pojavljajo mikropore. Pojavljajo se tako v notranjosti zrn, kjer so navadno kroglaste oblike, kot na mejah zrn – sliki 3a in b. Pore na mejah kristalnih zrn so kopija mreže izločenih karbidov in predstavljajo začetek pojavljanja interdendritnih razpok. Poroznost se pojavlja predvsem v tankostenskih predelih pri majhnih hitrostih strjevanja. Obseg poroznosti se zmanjšuje s povečanjem temperaturnega gradienta v sistemu forma – napajalnik, s povečanjem hitrosti strjevanja v določenem predelu in z velikostjo zrn. Poroznost je eden od glavnih kazalnikov kakovosti teh ulitkov, ki ga kupci natančno ocenjujejo. Ulitki turbo polnilnikov se ulivajo v vakuumskih indukcijskih pečeh v maske, izdelane po metodi iztaljivih modelov. Kolesa večjih dimenzij se ulivajo posamezno z napajalnikom, ki je blizu pesta

columnar grains at points of slow solidification, without any pronounced directional orientation of heat flow – in particular in wheel hubs – **C.**

Individual customers' requirements for structure dispersity are not exactly unambiguous. Limitations are usually required for the maximum size of dendritic and equiaxed grains but other requirements are also possible. Occurrence of cracks in the castings is not admissible.

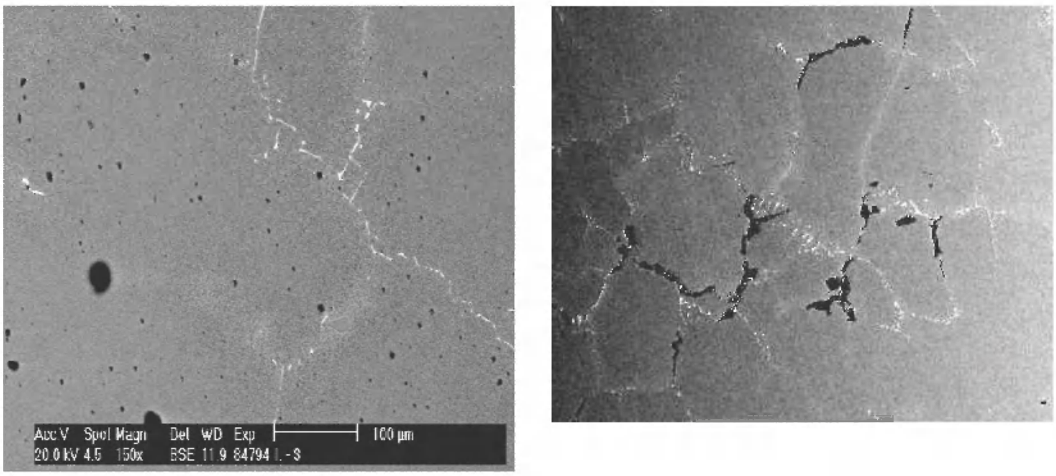
In the structure of nickel-alloy castings, microshrinkages usually occur to a considerable degree. They form both inside the grains, where they are usually of spherical shape, and on grain boundaries – Fig. 3a,b. Pores on the boundaries copy the precipitated carbide network and initiate the appearance of interdendritic cracks. Porosity occurs in particular in thin-walled cross sections with a low solidification rate. The porosity extent decreases with increasing temperature gradient in the mould-riser system, with increasing solidification rate in the given cross section, and with the grain size. Porosity is one of the main qualitative parameters for these castings and is usually strictly assessed by the customers.





Slika 2. Značilna mikrostruktura ulitka turbo polnilnika

Figure 2. Typical structure of turbocharger castings



Slika 3. Poroznost v ulitku turbo polnilnika, a) znotraj zrn, b) na mejah zrn

Figure 3: Porosity in turbocharger castings: a) inside grains, b) on grain boundaries

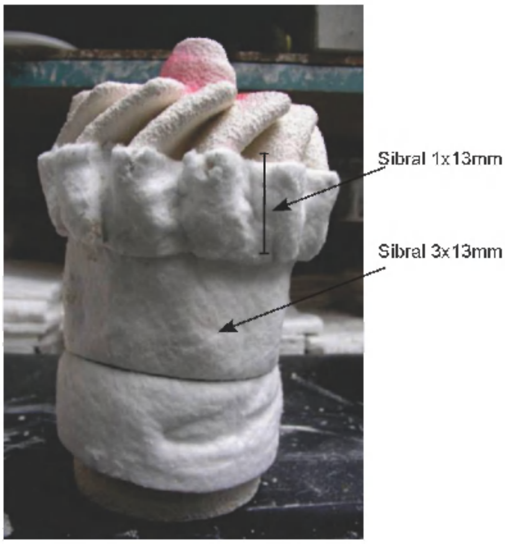
(slika 4). Manjša kolesa so razporejena v »grozd« in imajo skupen ulivni sistem. Pri velikih kolesih se na proces strjevanja vpliva predvsem s povečanjem temperaturnega gradienta med ulitkom in napajalnikom s toplotno izolacijo napajalnika ali tudi dela ulitka. Uporablja se bazaltna izolacijska tkanina, katere debelina se veča v smeri napajalnika (slika 5).

Slika 4. Voščeni grozd koles

Figure 4. Wax tree for wheels

Učinek toplotne izolacije je sorazmerno velik in se kaže v boljšem usmerjanju strjevanja in zmanjševanju obsega krčilnih mikropor. Mikrostruktura v toplotno izoliranih delih je bolj groba. Vpliv livne temperature kovine in temperature maske smo eksperimentalno preverjali. Oba parametra delno vplivata na drobnost mikrostrukture, toda ta vpliv ni bistven.

Turbocharger castings are cast in vacuum induction furnaces into shell moulds produced by the method of lost wax model. Wheels of larger dimensions are cast individually, with the riser located on the hub – see Fig. **4**. Smaller wheels are arranged into a "tree" on a common ingate. With large wheels, the solidification process is influenced mainly by increasing the temperature gradient between the casting and the riser, via thermal insulation of the riser or also a part of the casting. Insulation matting of basalt insulation fabric is employed, with the thickness of insulation layer increasing in the direction of the riser – see Fig. 5.



Slika 5. Toplotna izolacija grozda

Figure 5. Thermal insulation of tree

The effect of thermal insulation is relatively strong and it manifests itself by better solidification directionality and limitation of the extent of microshrinkages. In thermally insulated parts the structure becomes rougher. The effect of the pouring temperature of the metal and that

Za udrobnjenje mikrostrukture nikljevih zlitin se navadno uporabljajo kristalizacijske kali. V praksi se pogosto uporablja kobaltov(II) aluminate, $CoAl_2O_4$, v čelni plasti mask. Na ta način se lahko doseže občutna udrobnitev mikrostrukture v tankih stenah, ne pa v masivnih pestih turbinskih koles.

2. Vplivanje na mikrostrukturo z delovanjem fizikalnih sil

Ena od možnosti, kako vplivati na obliko in drobnost mikrostrukture, je delovanje fizikalnih sil na talino, ki se strjuje. Taka je npr. metoda Grainex, ki je sestavljena iz cikličnih sprememb hitrosti in smeri vrtenja forme z ulito kovino. Zaradi vztrajnostnih sil se deli strjenih dendritov zdrobijo, kar vodi do tvorbe novih kristalizacijskih kali. Rezultat je močno udrobnjena mikrostruktura z globulitnimi zrni. Negativni faktor te metode je endogena gobasta morfologija strjevanja, kar je povezano s trendom pojavljanja razpršenih krčilnih mikropor.

Učinek fizikalnega vplivanja na kristalizacijo smo v livarni PBS Velká Bíteš preverili z različnimi vrstami koles. Poskuse smo delali v vakuumski indukcijski peči VIM-IC 5E/II s talilno zmogljivostjo približno 50 kg nikljeve zlitine. Na peč smo instalirali dodatno pripravo, ki omogoča vrtenje ali vibriranje livne klopi med ulivanjem in kristalizacijo (slika 6). Pri vrtenju se je lahko spreminjalo smer in število vrtljajev, medtem ko je bilo vibriranje sestavljeno iz ciklično spreminjajoče se smeri vrtenja in nastavljive frekvence.

Poskuse smo delali z različnimi vrstami koles, narejenih iz zlitine IN 713LC, podrobneje smo se ukvarjali s kolesom, katerega masa v ulitem stanju je bila 32 kg. Maska in toplotna izolacija sta bili standardni, kot je prikazano na sliki 5. (Trenutno poteka preskušanje te metode z

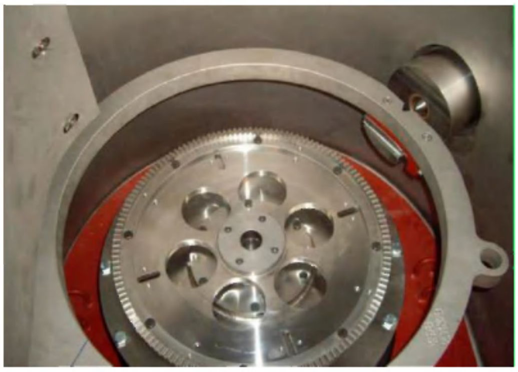
of the initial temperature of the shell were also experimentally verified. Both these parameters have a partial effect on structure dispersity, but this effect is not fundamental.

To refine the structure of nickel alloys, the nucleation effect of substances is commonly used that support the formation of crystallization nuclei. In practise, cobalt (II) aluminate, $CoAl_2O_4$, is frequently used in the face layer of shells. In this way, significant refinement of structure can be achieved in thin walls but not in bulky hubs of axial turbine wheels.

2. Influencing the structure by action of physical forces

One of the possibilities how to influence the type and dispersity of the structure is the action of physical forces on the solidifying melt. This is, for example, the case of the Grainex method, which consists in applying cyclic changes in the rate and sense of rotation to the mould with cast metal. Due to inertia forces, parts of solidifying dendrites break off, leading to the formation of new crystallization nuclei. The result is a markedly refined structure with equiaxed grains. A negative factor in this method is the endogenous mushy morphology of solidification and the associated tendency to form scattered microshrinkages.

The effect of physically influencing the crystallization was verified on several wheel types in the PBS Velka Bíteš foundry. The experiments were carried out in a VIM-IC 5E/II vacuum induction furnace with a melting capacity of ca. 50 kg nickel alloy. Installed on the furnace is an additional facility that enables rotating or oscillating the casting bench during pouring and in the course of crystallization. – see Fig. 6. In the case of rotation, the sense of rotation an the



Slika 6. Vakuumska talilna peč in priprava za vrtenje ter vibriranje klopi

Figure 6. Vacuum melting furnace and facility for bench rotation and oscillation

drugimi vrstami koles). V tej fazi smo ulili tri kolesa in sicer:

1. z mirnim ulivanjem,
2. z 1-minutnim vrtenjem med litjem in po njem (hitrost vrtenja se je spreminjala 50/100/50 vrt/s v intervalih po 10 s,
3. z vibriranjem med strjevanjem – 3 min s frekvenco 1/s.

Pri ulitkih se je ocenila mikrostruktura in mehanske lastnosti. Makrostruktura v osni smeri je prikazana na sliki 7.

Tanke stene lopatic, ko je bilo kolo 1 ulito z mirnim ulivanjem, imajo mikrostrukturo iz stebričastih zrn z vzdolžno osjo v smeri odvajanja toplote. Mikrostruktura spodnjega dela pesta (pri sorazmerno veliki hitrosti ohlajanja) je bila iz sorazmerno drobnih globulitov, katerih velikost se je občutno večala v smeri proti napajalniku.

Z vrtenjem med ulivanjem (kolo 2) se je doseglo delno udrobnjenje dendritne mikrostrukture v lopaticah. To je verjetno

number of revolutions can be chosen while oscillation consists in cyclically changing the sense of rotation with adjustable frequency.

Tests were performed on several types of wheel made of the IN 713LC alloy, in greater detail on a wheel of 32 kg in pouring mass. The shell and its thermal insulation were of standard execution, as indicated in Fig. 5. (The testing currently continues on other types of wheel.)

At this stage, three wheels have been cast, namely with

1. stationary pouring
2. rotation during and after pouring – for a period of 1 min, the rate of rotation change 50/100/50 rev/s for 10 s
3. oscillation during solidification – oscillation frequency 1/s for 3 min.

The castings were evaluated for structure and mechanical properties. Macrostructure in an axial section can be seen in Fig. 7.

1 – mirno ulivanje / stationary pouring

2 – ob vrtenju / rotation

3 – ob vibriranju / oscillation

Slika 7. Makrostruktura dela kolesa

Figure 7. Macrostructure in wheel section

In thin blade walls, the wheel 1 produced by stationary pouring exhibits columnar crystals with the longitudinal axis oriented in the direction of heat removal. The lower part of the hub (with a relatively high cooling rate) is formed by comparatively fine equiaxed crystals, the size of which increases considerably towards the riser.

Rotation during pouring (wheel 2) leads to a partial refinement of the dendritic structure in the blades. This is probably the result of a better contact between the metal and the mould due to the acting inertia force, and thus a more intensive heat removal. In the hub region, no detectable effect of rotation on grain dispersity can be established. This kind of pouring contributes to the metal running perfectly into thin walls but has no fundamental effect on structure changes.

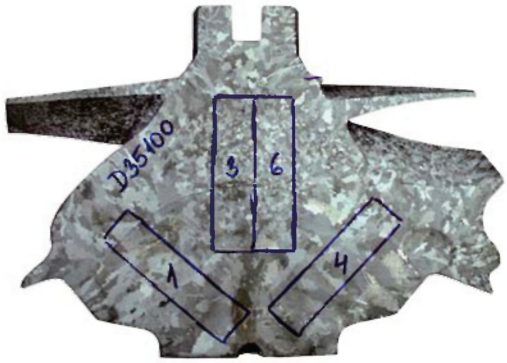
Oscillation gives rise to a provable and marked change in the nature and dispersity of the structure. The structure is fine and equiaxed over the whole volume; also in the blades the dendritic nature of grains changes to equiaxed grains. This effect was confirmed in all the subsequent experiments.

3. Effect of rotation and oscillation on mechanical properties

Samples for mechanical testing were taken from the wheels as indicated in Fig. 8. Samples marked 1 and 3 were used in cold testing while samples 4 and 6 were used in tests at a temperature of 600 °C; the results are given in Table 1:

rezultat boljšega stika med kovino in formo zaradi delovanja vztrajnostnih sil in s tem intenzivnejšega odvajanja toplote. V območju pest ni bilo zaznati občutnejšega učinka vrtenja na drobnejšo mikrostrukturo. Ta način ulivanja prispeva, da kovina bolj popolno steče v tanke stene, nima pa bistvenega vpliva na spremembo mikrostrukture.

Vibriranje je povzročilo večje, dokazljive in pomembne spremembe oblike in drobnosti mikrostrukture. Mikrostruktura je bila iz drobnih, globulitnih zrn po vsej prostornini, tudi v lopaticah se je dendritna mikrostruktura spremenila iz dendritne v globulitno. Ta učinek je bil potrjen pri vseh nadaljnjih poskusih.



Slika 8. Mesta vzorčevanja za mehanske preskuse

Figure 8. Sites of sample removal for mechanical tests

Razpredelnica 1. Mehanske lastnosti koles pri različnih strjevalnih razmerah

Table 1. Mechanical properties of wheels, for different solidification conditions

Vzorec / Sample	Rp0,2 (MPa)	Rm (MPa)	Z (%)	A5 (%)
Preskušanje v hladnem / Cold testing (20 °C)				
1 -1	625	636		5,8
1 -3	682	736		3,1
2 -1	650	706		7,6
2 -3	695	731		1,7
3 -1	731	807		3,5
3 -3	745	803		2,5
Najmanjše vrednosti / min. values	≥ 620	priporočene / recommended > 740		≥ 3,0
Hot testing / Preskušanje v vročem (600 °C)				
1-4	593,5	664,6	9,7	6,7
1-6	653,6	763,9	9,7	-
2-4	637,3	749,8	12,9	7,7
2-6	641,9	750,5	12,9	6,7
3-4	710,2	828,7	9,7	5,0
3-6	693,2	801,8	9,7	4,0
Najmanjše vrednosti / min. values	> 620	priporočene / recommended > 720		> 4,0

3. Učinek vrtenja in vibriranja na mehanske lastnosti

Preizkušanci za mehanske preskuse so bili izrezani iz koles, kot kaže slika 8. Vzorca 1 in 3 sta se uporabila za preskušanje v hladnem, vzorca 4 in 6 pa za preskuse pri 600 °C. Rezultati so v razpredelnici 1.

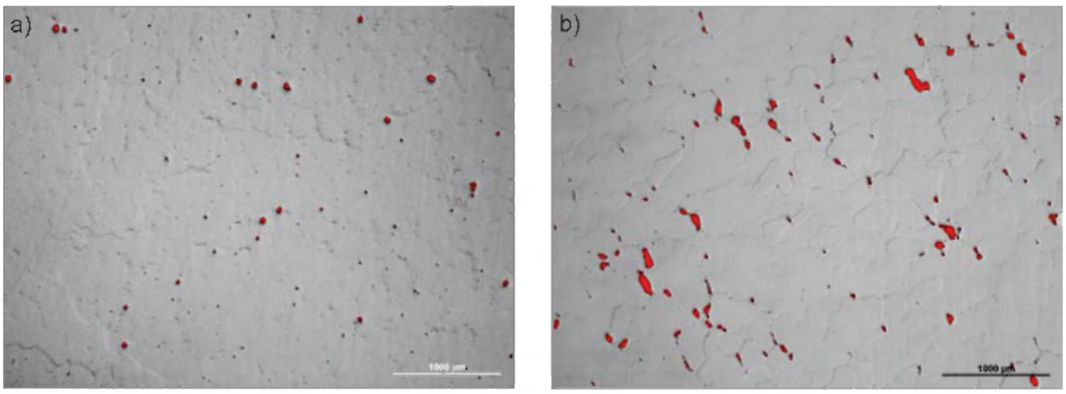
4. Makro- in mikostrukture ter delež krčilnih mikropor

Makro- in mikrostrukture smo ovrednotili v vzdolžnih prerezih koles ter ugotavljali površinske krčilne mikropore. Na mestih, kjer je bil pojav por merljiv, smo z analizo slike ovrednotili delež površine s porami. Lahko rečemo, da je bila v vseh preiskanih primerih pestov koles poroznost le lokalna. V lopaticah ali na prehodu lopatica pesto ni bilo zaznati merljivega deleža mikropor. Največja velikost mikropor je bila velikostnega reda 0,1 – 0,2 stotinke. Pore so se pojavljale tako v zrnih kot na mejah zrn. Največji delež porozne površine je bil pri mirnem litju kolesa 0,12 % in 0,76 %

4. Structure and content of microshrinkages

In axial sections of the wheels the macrostructure and microstructure were evaluated and the surface area of microshrinkages was determined. At points where the occurrence of pores was measurable, the content of pores was evaluated via image analysis as the proportion of pore area in the evaluated image. It can be said that in all the cases examined, porosity occurs only locally in parts of the wheel hubs. No measurable pore content can be found in the blades or in the hub/blade transition. The pore size is in the order of hundredths, 0.1 – 0.2 as a maximum. Pores appear both within the grains and on grain boundaries. The maximum porosity values are 0.12 % for the wheel with stationary pouring, and 0.76 % of the evaluated area for the wheel with oscillation; as expected, the effect of oscillation is negative from the porosity point of view – see Fig. 9.

The tests performed did not confirm any significant difference in the distribution



Slika 9. Poroznost na mestih največjega pojavljanja por: kolo pri a) mirnem ulivanju, b) pri ulivanju z vibriranjem

Figure 9. Porosity at points of maximum occurrence: a) wheel with stationary pouring, b) wheel with oscillation

pri vibriranju. Po pričakovanju je bil učinek vibriranja z vidika poroznosti negativen – slika 9.

Poskusi niso pokazali občutne razlike v porazdelitvi karbidnih mrež na kristalnih mejah. Uporabili smo kemično mikroanalizo za ugotavljanje kemične sestave posameznih mikrostrukturnih komponent. Ugotovljeno je bilo, da karbidne mreže oblikujejo izključno niobijevi in titanov karbidih.

5. Sklepi

Poskusi so potrdili izrazit učinek vztrajnostnih sil pri spreminjanju hitrosti in smeri vrtenja form na morfologijo in udrobnjenje mikrostrukture med ulivanjem in kristalizacijo toplotno odpornih nikljevih zlitin, v našem primeru vrste IN 713LC. Vibriranje forme, ki je bilo sestavljeno iz periodično spreminjajoče se smeri vrtenja livne klopi, se je pokazalo kot zelo učinkovito. Standardno mirno ulivanje, ki je značilno za območja velikih ohlajevalnih hitrosti, je povzročalo pojavljanje dendritne mikrostrukture, medtem ko se je groba globulitna mikrostruktura pojavljala v masivnih delih pest koles. Z vibriranjem se je mikrostruktura po vsej prostornini spremenila v globulitno z občutno manjšimi in zelo pravilnimi kristalnimi zrni. Učinek delovanja vztrajnostnih sil, povezan s spreminjanjem vrtenja forme, je bil občutno bolj izrazit kot učinek spremembe temperature kristalizacije zaradi sprememb temperatur kovine ali maske ali toplotne izolacije.

Pri statičnih mehanskih preskusih se je pokazalo, da vibriranje poveča trdnostne vrednosti Rm in Rp0.2 tako pri sobni temperaturi kot pri 600 °C. Duktilnost se je spreminjala zelo malo, z rahlim trendom zmanjševanja. Pokazalo se je, da ulivanje ob vrtenju forme nima občutnega vpliva na

of carbide network on grain boundaries. Chemical microanalysis was used to establish the chemical composition of individual structure components; it was established that the carbide network was formed almost exclusively by niobium and titanium carbides.

5. Conclusion

Experimental tests have confirmed a pronounced effect of inertia forces appearing in the course of changing the rate and sense of rotation of moulds during pouring and crystallization on the structure morphology and dispersity of heat-resistant nickel alloys, in our case of the IN 713LC type. Mould oscillation, consisting in changing periodically the sense of rotation of the casting bench, proved to be highly effective. The usual static mode of pouring, typically in regions of high cooling rates, leads to the appearance of dendritic structure while rough equiaxed structure appears in bulky hub regions. Due to oscillation, the structure in the whole volume of the casting changes to equiaxed structure with a substantially smaller and very regular grain size. The effect of the action of inertia forces appearing in connection with the change in mould rotation is considerably more pronounced than the effect of the change in the crystallization temperature due to changes in the metal and shell temperatures or in thermal insulation.

In static tests, oscillation was clearly responsible for increased R_m and $R_{p0\,2}$ strength values both at normal temperature and at a test temperature of 600 ºC. The ductility values change very slightly, with some tendency to decrease. It was found that pouring under rotation has in itself a certain but not significant effect on grain udrobnjenje zrn v območju lopatic, drugače je bilo v območju pesta. Poleg tega se mehanske lastnosti niso spreminjale v primerjavi z mirnim ulivanjem.

Preiskava vzorcev, ulitih ob vibriranju, je pokazala, da so bili posamezni deli pesta bolj porozni v primerjavi z mirnim litjem. Ta sklep potrebuje še nadaljnje preverjanje. Z vibriranjem se dobi enakomerno drobnozrnato mikrostrukturo, ki v celoti zadovoljuje navadne pogoje za preverjanje kakovosti. Primerno bi bilo optimirati način vibriranja z nadaljnjimi preskusi.

Prispevek je bil napisan na osnovi rezultatov projekta MPO CR-TIP FR-TI 2/104: »raziskave in razvoj tehnologij za precizijsko lije novih vrst ulitkov lopatic in turbinskih koles plinskih turbin«

refinement in the region of blades but not in the hub region. Also, the mechanical properties practically do not change in comparison with static casting.

On examination, the oscillated samples revealed in local parts of the hub a higher porosity content in comparison with static pouring. This conclusion needs checking in further tests.

The application of oscillation yields a fine-grain structure with a dispersity that fully satisfies the usual conditions of quality inspection. It would be appropriate to optimize the oscillation mode via further testing.

The paper has been written in connection with solving the MPO CR-TIP FR-TI 2/104 project "Research into and development of technologies for precision casting of novel types of castings of blades and turbine wheels of gas turbines.

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