The development of a counter-gravity casting process for industrial gas turbine engine components

P. A. McQuay, A. Price, W. Roosa, R. Ruffini

A new casting process, Counter-gravity Low-pressure Inert-atmosphere (CLI) casting, has been developed for the production of integral turbine wheels and closed-face nozzle components for small power-generation turbine engines, also known as micro-turbines. Benefits of this casting process include improved cleanliness, improved fill of thin walls, and lower cost. In order to validate the ability of the CLI cast components to meet product and property requirements for micro-turbine engine applications, the components were characterized via X-ray radiography, metallography and mechanical testing. These were compared with components produced by conventional vacuum gravity casting. Comparisons between the two processes have also been made to compare the component quality, and production cost. In general, the mechanical properties of CLI cast IN713 LC and MAR-M247 alloy components compared favorably with conventional gravity castings. Additionally, a reduction in FPI indications has been documented, which should lead to lower rework and scrap costs. Overall, CLI casting has been demonstrated to offer advantages over conventional gravity casting for several applications and alloy types.

Parole chiave: impieghi in temperatura, superleghe

INTRODUCTION

The Howmet Corp. has teamed with the Hitchiner Manufacturing Corp. to develop and apply a new casting process, Counter-gravity Low-pressure Inert-atmosphere (CLI) casting, for the production of nickel-based superalloy components for Industrial Gas Turbine (IGT) engine applications. In particular, this program has focused on components for small power-generation turbine engines, also known as micro-turbines.
Micro-turbines are generally considered power generation turbines that produce less than 1 megawatt of power. They are generally simple in design, with a single moving part, the rotor assembly, that is comprised of a radial compressor wheel, shaft and a radial turbine wheel. The micro-turbine market, although still in it's infancy, is forecast to achieve very high volumes, and requires low cost components, relative to traditional aerospace and industrial gas turbine engines. This requires an investment casting process with a focus on rapid cycle times, high first-time quality (minimal rework and scrap), and high efficiency and productivity.
The Howmet Corporation is studying the use of the CLI casting process for several key components for micro-turbine engines, such as radial turbine wheels (Figure 1), and closed-face nozzles (Figure 2). The turbine wheel can be a challenge to cast due to microstructure and property requirements, coupled with a combination of very thin airfoils, and thick hub sections. Process changes made to improve the casting fill, such as increases in metal and mold temperatures, often have the deleterious effects of coarsening the grain size, and reducing tensile and fatigue strength. The nozzle, on the other hand, is cast in a non-weldable, Hf containing alloy, Mar-M 247, that is prone to surface indications in conventional casting.

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THE CLI PROCESS

The Hitchiner Manufacturing Co. has developed several different versions of counter-gravity casting to meet different alloy and product requirements [1, 2]. The CLI process was developed as a method to produce vacuum-cast quality components,

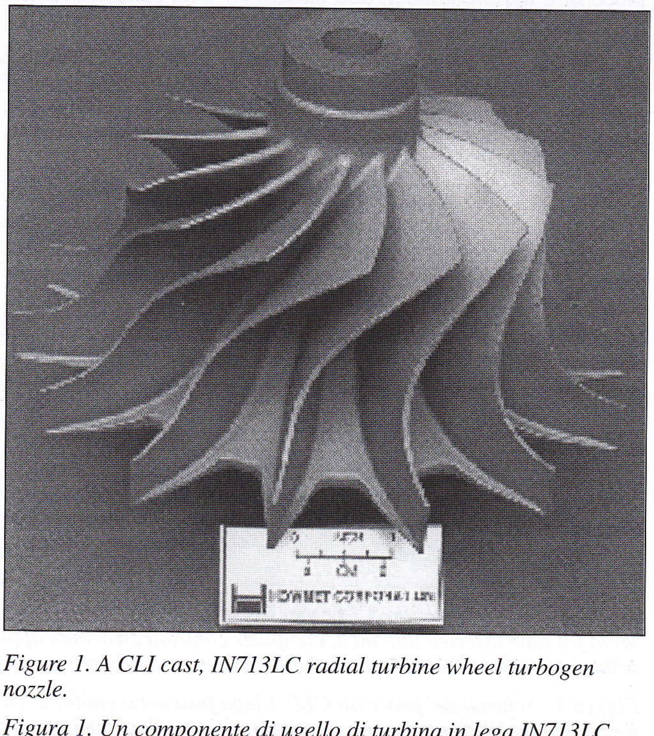


Figure 1. A CLI cast, IN713LC radial turbine wheel turbogen nozzle.

Figura 1. Un componente di ugello di turbina in lega IN713LC colata mediante processo CLI.

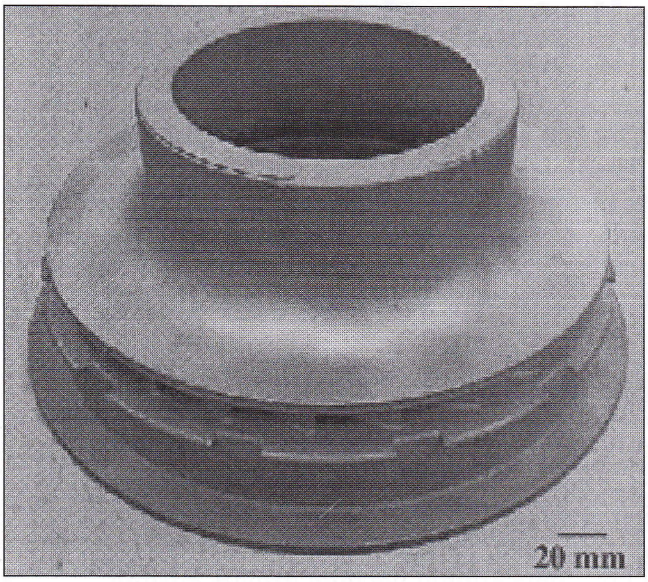


Figure 2. A CLI cast, Mar-M 247 closed-face.

Figura 2. Un pezzo di piccole dimensioni colato mediante processo CLI.

such as superalloys and titanium base alloys, at higher volumes and lower costs compared with what can usually be accomplished with traditional vacuum gravity casting processes [1, 2]. The Howmet Corporation has licensed the CLI casting process for several markets, including micro-turbine engine components.

A variant of the CLI process is the sand supported CLI process (ssCLI), where refractory sand is used to back up the mold during the casting process [1,2]. The ssCLI process allows for the use of thinner ceramic molds, which can reduce mold cost and cycle-time. Producing an invested ceramic mold is often one of the most expensive and time consuming steps in the investment casting process. Typical investment mold build times can be from 3-5 days for aqueous shell based molding systems.

A schematic of the ssCLI process is shown in Figure 3. While the melt is being prepared, a ceramic fill tube and mold are place in a mold chamber, and backfilled with sand and argon gas. When the melt is ready, the melt chamber is backfilled with argon gas slightly above atmospheric pressure, and the melt chamber cover is removed. The mold chamber is then brought in position over the melt chamber, and lowered so that the fill tube is inserted into the center of the melt. Vacuum is then applied to the mold chamber, creating a pressure difference between the melt and the mold, which draws the alloy up into the mold. The application of vacuum is computer controlled, which allows for control over the rate of fill or velocity of the molten alloy.

Because the mold is bottom filled, many of the problems associated with gravity casting can be mitigated or avoided, including turbulence, mold erosion, cold shuts or laps, etc. [3]. Additionally, gravity casting relies on the development of metallostatic head in order to fill the mold cavity. In counter-gravity casting the filling of mold cavities is accomplished by the pressure difference between the melt and the mold cavity, which allows for more even filling of components, one level at a time in a controlled manner, which can improve fill of thin sections [1, 2]. Computational modeling of the casting process was conducted using UES ProCast™ software, as a process tool in order to better understand the fill and thermal characteristics of ssCLI casting. A schematic of two simulations, utilizing two different vacuum profiles is shown in Figures 4 and 5. A fairly simple component, the micro-turbine heat shield was used for the simulation. You can see from the two time steps displayed in each figure that there is a dramatically different fill rate and fill behavior as a function of vacuum profile. The slow fill profile shown in Figure 4 shows a quiescent, even filling of the mold, one component layer at a time. Conversely, the rapid fill rate illustrated in Figure 5 results in high velocity metal rising up through the center sprue, impacting the top of the sprue, and then back-filling the part cavities in a chaotic, uneven manner, which may result in some casting defects. It is interesting to note that the chaotic filling behavior illustrated in Figure 5 is similar to the behavior seen in conventional gravity casting of a similar mold setup.

The ssCLI process also can make use of automated mold handling and casting equipment, dramatically reducing the casting cycle-time and increase productivity of the casting furnace. When coupled with a large alloy crucible, multiple molds can be cast off of a single melt, and casting cycle times of less than 2 minutes per mold are achievable [2]. Additionally, the CLI process has the potential to improve the quality and cleanliness of investment cast components. In the CLI process the molten metal is extracted from near the center of the melt crucible and introduced to the mold via bottom filling through a fill tube. Hence, high and low density inclusions in the melt are not introduced to the mold [1, 2].

In the casting of thin wall parts, where the thickest section is generally less than 25 mm, following the solidification of the gate the vacuum on the mold chamber is released, and the majority of the alloy in the center sprue returns to the melt.

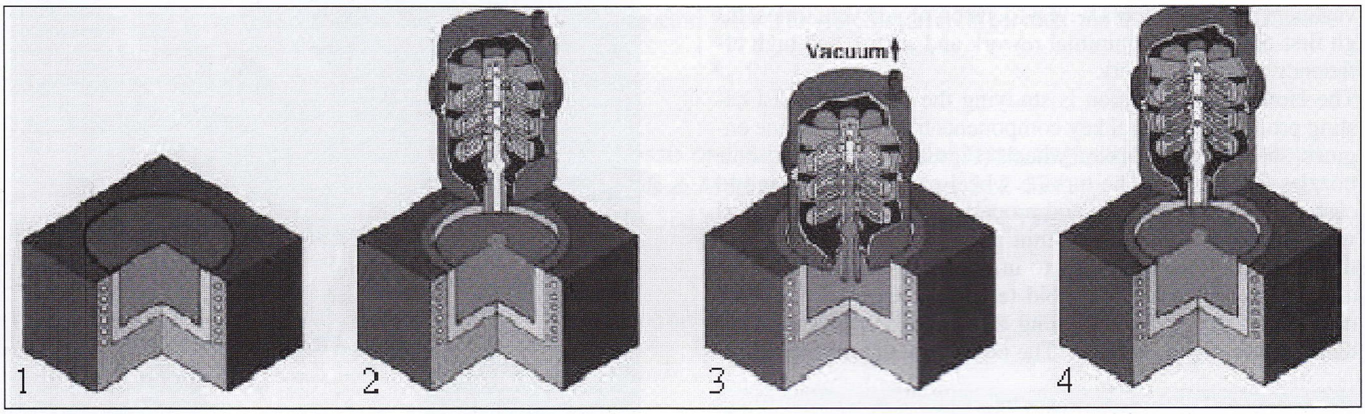


Figure 3. Schematic of the CLI process: 1. Alloy melted under vacuum; 2. Alloy chamber and melt chamber back-filled with argon gas; 3. Mold fill tube inserted into melt, computer controlled vacuum applied to mold chamber drawing alloy into the mold; 4. After the part or gate solidifies, vacuum is released, and alloy in the center sprue returns to the melt.

Figura 3. Schema del processo CLI: 1.lega fusa sotto vuoto; 2. riempimento della camera di fusione con argon; 3. inserimento del tubo di riempimento dello stampo con aspirazione controllata mediante computer; 4. dopo la solidificazione, l'aspirazione viene cessata e il metallo nel canale di colata torna nella fusione.

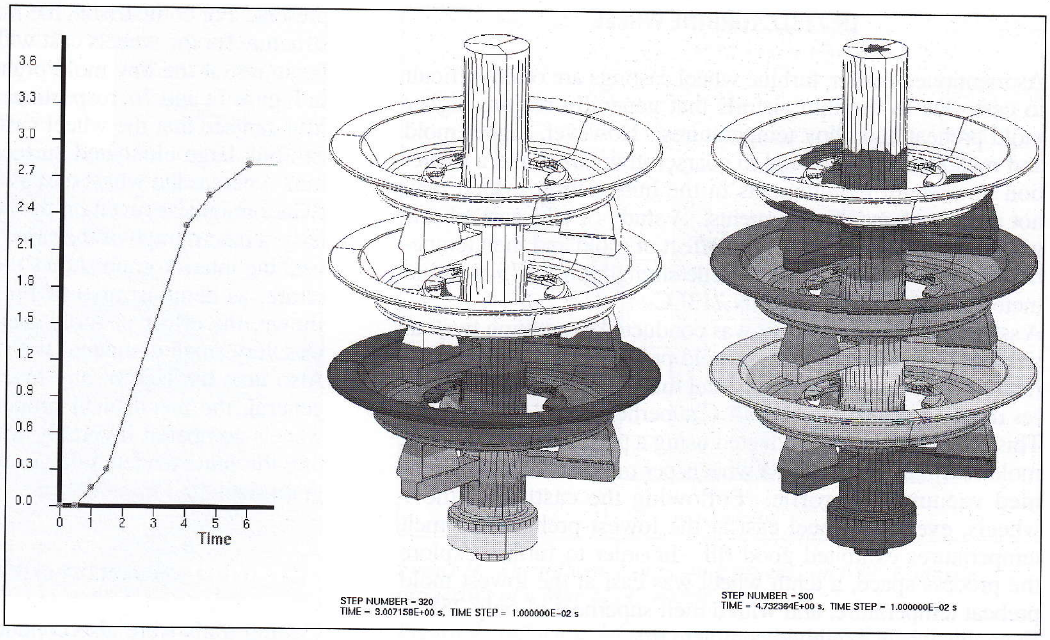


Figure 4. Computational model of the filling behavior of a heat shield in ssCLI casting process utilizing a gradual multi-step vacuum profile (left), resulting in quiescent, even filling of the mold. The time steps are taken at 3.01 (center), and 4.73 seconds (right).

Figura 4. Modello a computer del comportamento a riempimento di uno schermo termico colato mediante processo ssCLI usando un profilo di vuoto a più passi (a sinistra) che dà luogo a un riempimento uniforme, inattivo dello stampo. I passaggi sono rilevati dopo 3.01 secondi (centro) e dopo 4.73 secondi (destra).

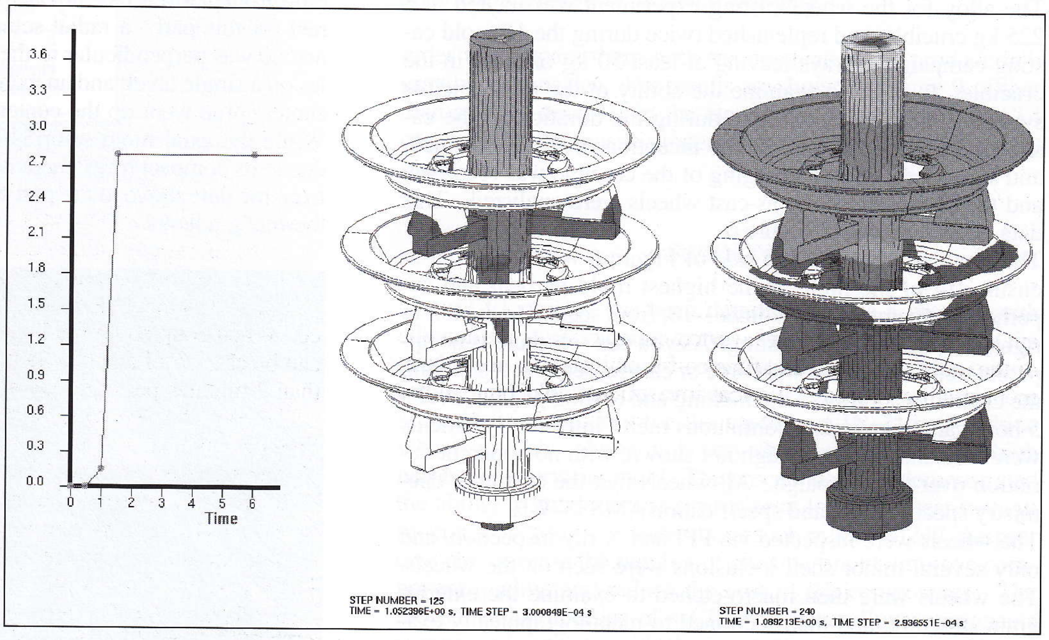


Figure 5. Computational model of the filling behavior of a heat shield in ssCLI casting process utilizing a rapid, single step vacuum profile (left), resulting in non-quiescent, uneven filling of the mold. The time steps are taken at 1.05 (center) and 1.09 seconds (right).

Figura 5. Modello a computer del comportamento a riempimento di uno schermo termico colato mediante processo ssCLI con un solo passaggio di vuoto (a sinistra) che dà luogo a un riempimento dello stampo non uniforme e non inattivo. I passaggi sono rilevati dopo 1.05 secondi (centro) e 1.09 secondi (destra).

This can lead to dramatic improvements in metal efficiency, and can eliminate the need to cut the parts off of the mold cluster [1, 2]. In gravity casting the number of parts per mold is often restricted by the need to leave room for cutting the parts off of the mold cluster. This is not necessary in the CLI casting of thin-wall parts, which can lead to more than doubling the part density on the mold.
A summary of the benefits of the CLI process is given in Table 1, for typical thin-wall and thick-wall components.

CASTING PROCESS EVALUATIONS

An evaluation was conducted in order to validate the ability of the CLI process to produce micro-turbine turbine wheels and nozzles that meet product and property requirements. The components were characterized via chemical analysis, metallography, fluorescent penetrant inspection (FPI), X-ray radiographic inspection and mechanical testing. These results were compared with the same components produced by conventional vacuum gravity casting. Comparisons between the two processes have also been made to compare the suitability of the process for high volume production and cost.

Benefit	Thin-wall	Thick-wall
Lower Cost	Yes	Yes
Control Over Mold Rate of Fill	Yes	Yes
Reduction in Turbulence	Yes	Yes
Reduced Melt Inclusions	Yes	Yes
Lower Casting Temperatures	Yes	Yes
Improved Ability to Fill Thin Walls	Yes	NA
Increased Number of Parts per Mold	Yes	No
Elimination of Rough Cut Operation	Yes	No
Reduced Metal Usage per Part	Yes	No
Rapid Turn Times - Can be Highly Automated	Yes	Yes

Table 1. Advantages of the CLI process for thin- and thick-wall castings.

Tabella 1. Vantaggi dell'utilizzo del processo CLI in pezzi fusi con pareti sottili e spesse.

IN 713LC TURBINE WHEEL

As mentioned earlier, turbine wheel castings are often difficult to cast, due to the thin airfoils that generally require higher mold preheat and alloy temperatures. However, higher mold and melt temperatures lead to coarser grain sizes and a reduction in strength requirements in the hub section, which may not meet customer requirements. A study of CLI cast wheels was undertaken to examine the effect of mold and melt temperature on the grain size and tensile strength on a 175 mm diameter turbine wheel cast in IN 713LC.
A ssCLI casting experiment was conducted examining two variables at three levels each: 3 mold preheat and 3 melt temperatures. In the initial experimental matrix, the melt temperatures ranged from a high of 150° C superheat, to a low of 55° C. This experiment was conducted using a previously established mold setup that simulated 4 wheels per mold, at a set programmed vacuum fill profile. Following the casting of the 9 wheels, even the wheel cast at the lowest preheat and melt temperatures exhibited good fill. In order to further explore the process space, a tenth wheel was cast at the lowest mold preheat temperature, and with a melt superheat of only 25° C. Even this wheel exhibited complete fill.
The alloy for the wheel casting experiment was melted in a 225 kg crucible, and replenished twice during the 10 mold casting campaign, always leaving at least 50 kg of alloy in the crucible. In order to examine the ability of the melt crucible system to maintain chemistry during the duration of the casting campaign, the time of the inception of the initial melt, and subsequent alloy recharging of the crucible was recorded, and the chemistry of the as-cast wheels were analyzed. This data is summarized in Figure 6.
The first data from the left side of Figure 6 was a test trial to ensure fill of the mold at the highest mold preheat and superheat temperatures. Castings 1-10, from second to the left to right, followed this test casting. As you can see, there is no apparent trend in the data with time or casting sequence, showing the chemical stability of the melting and casting process over a 5 hour campaign with a continuous melt. Interstitial elements were also analyzed, although not shown, with no apparent variation over the campaign. All wheels met the customer chemistry specification, and specification AMS5377-E.
The wheels were inspected via FPI and X-ray inspection, and only several minor shell inclusions were seen on the wheels. The wheels were then macro-etched to examine the exterior grain structure, and then sectioned to metallographically examine the internal grain structure and to quantify any porosity present. For comparison, the macrograph of the exterior grain structure for the wheels cast with highest and lowest melt temperatures, at the low mold preheat temperature, are presented in Figure 7a and 7b, respectively.
You can see that the wheel cast with a high melt temperature exhibits large elongated surface grains, some as large as 10 mm, whereas the wheel cast at the lower melt temperature has a finer grain size, even on the hub section of the wheel. Similarly, a macrograph of the same wheels, sectioned in half to reveal the interior grain shows the same trend with melt temperature, as demonstrated in Figures 8a and 8b. Although not shown, the effect of mold preheat temperature on grain size was very small compared with the effect of melt temperature. Also note the lack of any macro-porosity in either wheel. In general, the mechanical properties of ssCLI cast IN713 LC wheels compared favorably with gravity cast wheels, exhibiting the same tendency for increased strength with decreasing grain size.

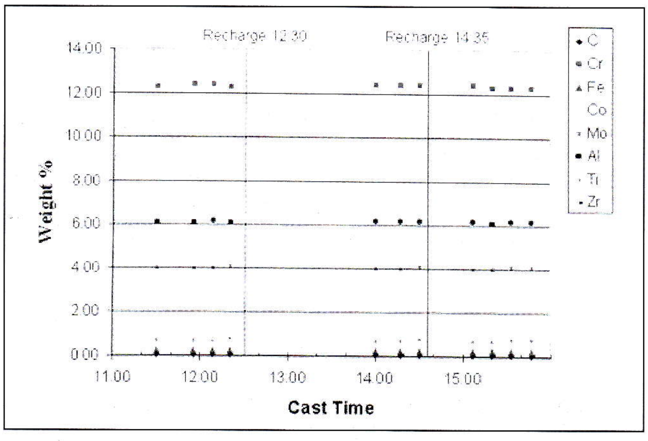
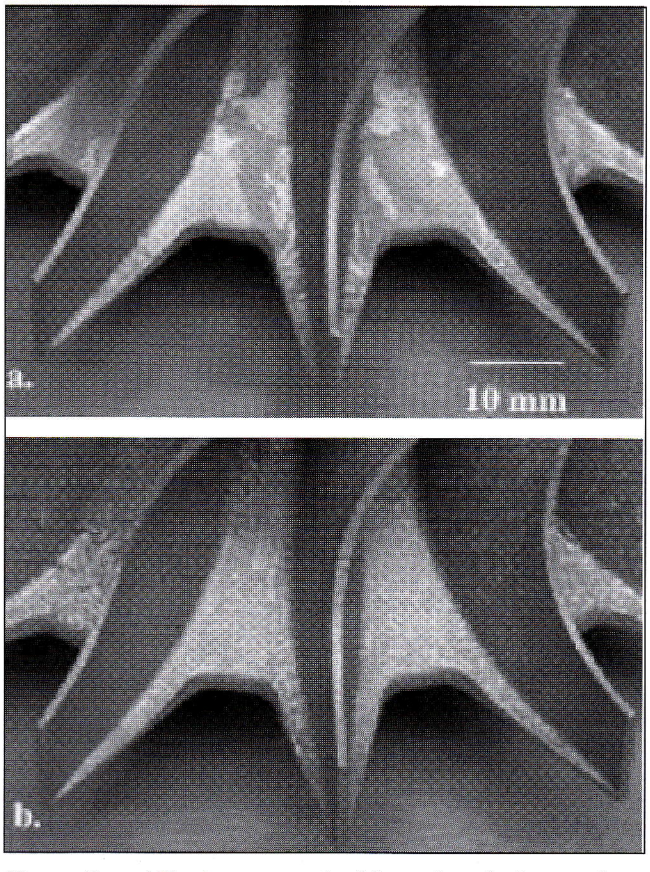


Figure 6. IN 713LC as-cast wheel analyzed chemistry of major elements as a function of casting time, with casting ingot recharges also shown. Results are given in weight percent.

Figura 6. Ruota in lega IN713LC as-casterdizzata in termini di chimica dei maggiori elementi in funzione dei tempi di fusione. I risultati sono riportati in percentuali di peso.

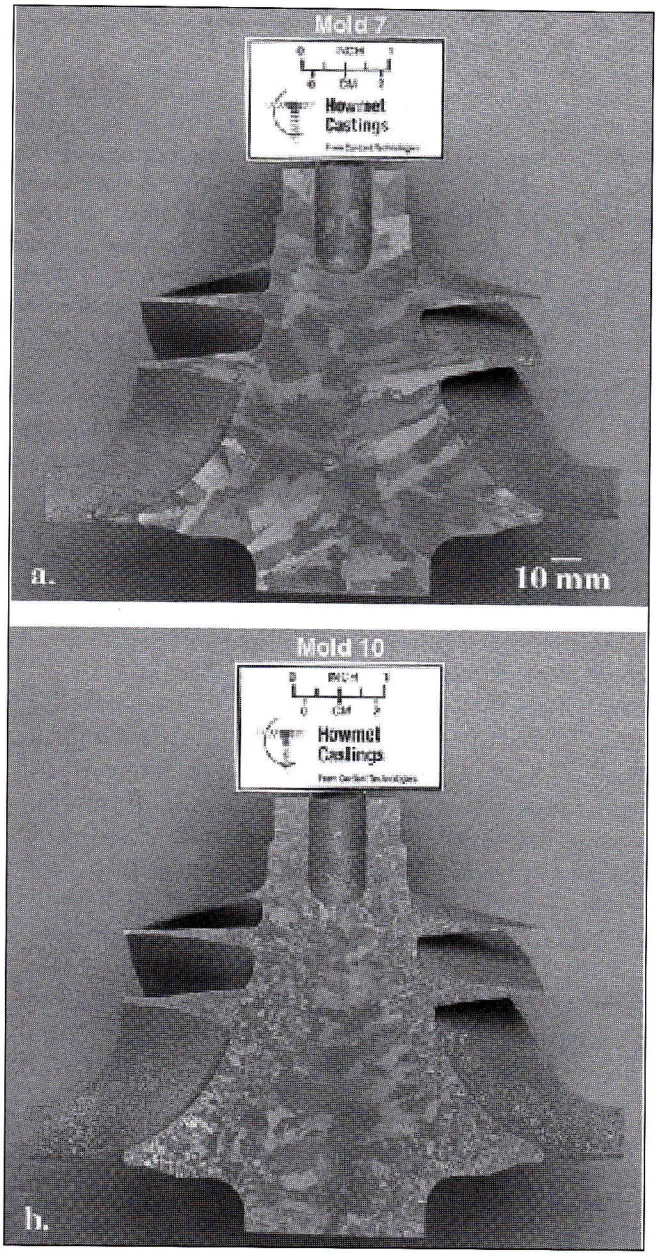
MAR-M247 CLOSED-FACE NOZZLE

Casting trials were also conducted on a Mar-M247 alloy micro-turbine closed-face nozzle. Two mold setups were examined for this part: a radial setup where the center-line of the nozzle was perpendicular to the center sprue, with three nozzles on a single level; and an axial or "stacked" setup, where the center sprue went up the center line of three stacked nozzles. While the axial mold setup is easier to handle and assemble due to its compact form, there is some influence of radiant heat from the part above to the part below, which leads to non-ideal thermal gradients.



Figures 7a and 7b. A macrograph of the grain etched external structure of an IN 713LC turbine wheel cast with a melt superheat of 150° C and 25° C, respectively.

Figure 7a and 7b. Macrografia della struttura esterna del grano sottoposto ad attacco chimico di una turbina in lega IN713LC colata con un surriscaldamento rispettivamente di 150 e 25°C.



Figures 8a and 8b. A macrograph of the grain etched internal structure of a sectioned IN 713LC turbine wheel cast with a melt superheat of 150° C and 25° C, respectively.

Figure 8a and 8b. Macrografia della struttura interna del grano sottoposto ad attacco chimico di una turbina in lega IN713LC colata con un surriscaldamento rispettivamente di 150 e 25 °C.

Both mold setups exhibited complete fill. However, X-ray and metallographic inspection of the nozzles indicated higher porosity in the outer flange of the axially oriented nozzles, while the radially oriented nozzles met the customer requirements. Mar-M 247 alloy, which contains Hf, is prone to dross-related FPI defects in conventional vacuum gravity cast components. One goal of these trials was to determine if there was an effect of casting method on FPI defects, because the alloy in CLI casting is drawn from near the center of the melt, as described earlier. Comparison of the FPI results for the axially and radially cast nozzles versus conventional gravity cast nozzles indicated that there was at least a 50% reduction in FPI related defects, with some CLI cast nozzles requiring no FPI related rework, a first for this component. Additionally, utilizing the ssCLI process, the number of nozzles per mold was increased from one to three, which represents additional cost savings over the conventional process.

Tensile specimens were excised from the ssCLI cast nozzles in order to compare them with the conventional ("production") gravity cast nozzles. The results are shown in Figure 9. Other than a slight decrease in the elongation in the "stacked" CLI cast nozzles, the tensile properties for the processes are nearly identical.

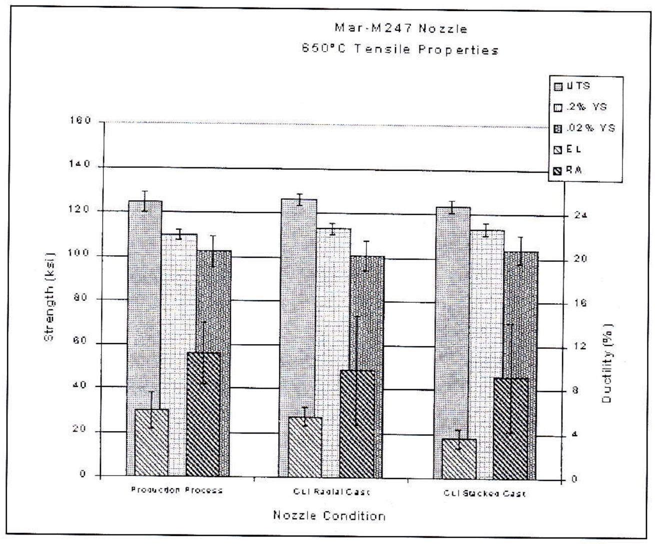


Figure 9. The influence of casting process on 650° C tensile properties of a Mar-M247 nozzle.

Figura 9. Influenza del processo di colata a 650° C sulle preprietà di tensione di un ugello Mar-M247.

SUMMARY

The ssCLI process has been demonstrated as a process with advantages over vacuum gravity investment casting for the production of nickel-based superalloy components for microturbine applications. The process has been demonstrated to be a competitive process for the casting of IN 713LC turbine wheels in high volume with very short cycle times, and high numbers of parts per mold. The process has also demonstrated the ability to produce fine grain size at low superheat without misrun. For "reactive" superalloys such as Mar-M247, the process can increase the number of parts per mold, improve component quality, and reduce the cost of the components. The mechanical properties of ssCLI cast superalloy components compares favorably with the properties of conventional gravity cast components.

REFERENCES

1. G.D. Chandley, Material Research Innovations, Vol. 3, Issue 1, Springer-Verlag, Heidelberg, Germany (1999), p. 14.
2. Alfred T. Spada, Modern Casting, American Foundrymen's Society, Inc., Des Plaines, IL, (July 1998).
3. J. Cambell, Castings, Butterworth-Heinemann Ltd., Oxford, UK (1991), pp. 31, 71.

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ABSTRACT

SVILUPPO D'UN PROCESSO DI COLATA ANTIGRAVITAZIONALE PER COMPONENTI DI TURBINE A GAS INDUSTRIALI

E' stato sviluppato un nuovo processo di colata, antigravitazionale a bassa pressione in atmosfera inerte CLI (Countergravity Low-pressure Inert-atmosphere), per la produzione di dischi di turbine integrali e di componenti di ugelli destinati a turbine per la produzione di energia, conosciute anche come micro-turbine.

I vantaggi di questo processo di colata comprendono una migliore pulizia metallurgica, una migliore qualità delle pareti sottili e costi più bassi. Per validare la capacità dei componenti colati mediante CLI di soddisfare i requisiti, sia in termini di prodotto che di proprietà, per applicazioni a micro-turbine, i componenti sono stati caratterizzati mediante radiografia ai raggi X, metallografia e prove meccaniche.

Questi sono stati confrontati con componenti prodotti mediante fusione sotto vuoto convenzionale.

I due processi sono stati inoltre raffrontati al fine di valutare sia la qualità del componente ed il costo di produzione. In generale, le proprietà meccaniche dei prodotti colati mediante il processo CLI (in lega IN713 LC ed in lega MAR-M247) si sono dimostrati favorevolmente paragonabili a quelli colati in modo convenzionale. Inoltre, è stata documentata una riduzione delle indicazioni rilevabili con ispezione FPI, che dovrebbero portare ad un abbassamento dei costi per rilavorazione e smaltimento. In generale, la fusione mediante processo CLI si è dimostrata vantaggiosa rispetto ai metodi convenzionali sotto vuoto per parecchie applicazioni e tipi di lega.

Una variante del processo CLI (ssCLI - sand supported CLI) si è rivelato particolarmente competitivo per la fusione di componenti per micro-turbine in lega 713LC con tempi di ciclo molto brevi ed un elevato numero di parti per stampo.

Il processo inoltre si è mostrato in grado di produrre dimensioni fini del grano a basso surriscaldamento senza rischi di fusione incompleta. Per le superleghe "reattive", come ad esempio Mar-M247, il processo può consentire ancora di aumentare il numero di parti per stampo, di migliorare la qualità dei componenti e di ridurne il costo.