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Clean metal nucleated casting

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Nucleated casting is a method of casting metal below its liquidus temperature, casting as a semisolid rather than as a liquid. In nucleated casting, a stream of liquid metal is directed into a gas atomizer, which converts it into a spray and accelerates the spray droplets from the atomization zone toward a collection mold. Because of the high surface-to-volume ratio, high relative velocity, and a large temperature difference between the gas and droplets, the droplets lose heat very efficiently to the surrounding gas.

Droplet diameter and process parameters such as gas-to-metal flow ratio, process rate, and spray distance have significant impact on the solid fraction of the metal at the collection zone. Small particles lose all of their heat of fusion and are fully solid when they strike; they will likely remelt in the semi-solid pool. Large particles are fully liquid when they strike. Medium-size particles are partially solid. When the particles strike the surface of the pool, a large number of nucleation sites are available for further solidification. Each nucleation site grows until it strikes an adjacent site and all local liquid is consumed and a fine-grained metallurgical structure results. When operated at high gas-to-metal ratio the semisolid will have small ($<30\%$) fraction liquid, and free-form casting is possible. This process is commonly called spray forming. When operated at low gas-to-metal ratio the semisolid will have a high ($>75\%$) fraction liquid, and a mold is required to contain the metal as it continues to solidify. This process is termed nucleated casting.

Alloy 718 metal has been cast in a prototype nucleated casting system for demonstrating the feasibility of the new process. Metallographic examination shows that the as-cast material possesses a uniform, equiaxed 0.075 mm (ASTM 4.5) grain structure. Macrosegregation-related defects were not found in the casting or in forgings that were obtained from the ingots.

1. Clean metal nucleated casting

Clean metal nucleated casting (CMNC) is a process that combines an oxide-free melting and pouring system that is based on electroslag remelting [1, 2] with the nucleated casting process [3, 4]. The process is shown schematically in Fig. 1. The raw material is a consumable electrode, which is cast from a vacuum induction melting system, and should be of the desired alloy chemistry. The goal of the CMNC process is to improve the quality of the metal by: (1) removing any harmful oxide inclusions; (2) removing any segregation defects or voids in the metal; and either (3a) Reducing the grain size to allow efficient subsequent thermomechanical processing of the metal; and/or (3b) increasing the diameter that can be cast in any particular alloy.

A description of the CMNC process sequence follows.

1.1. Melting system

A consumable electrode is fed into the furnace from above using a drive mechanism. The bottom face of the electrode is immersed in a hot liquid slag, which heats the bottom of the electrode causing it to melt. Metal droplets are formed on the face of the electrode and fall through the slag to form a liquid metal pool below the slag. Any oxide inclusions that are present in the electrode will be exposed to the slag and will be dissolved.

The slag is kept hot with alternating electric current, generally at low voltages and conventional frequencies, that is fed into the slag through the electrode. The required voltage is measured as a signal that is used to control the rate of advance of the electrode as the end is melted. Constant immersion depth is key for effective processing, and various schemes for control of the voltage or voltage swing are in commercial use.

Alternatives exist for feeding electric current to the slag. In addition to the consumable electrode, current may be fed through an unconsumed electrode for additional process capability. An unconsumed electrode may take any of several geometric configurations [5–7]. In Fig. 1 it is drawn as the top portion of the crucible. The unconsumed electrode must be made of a suitable

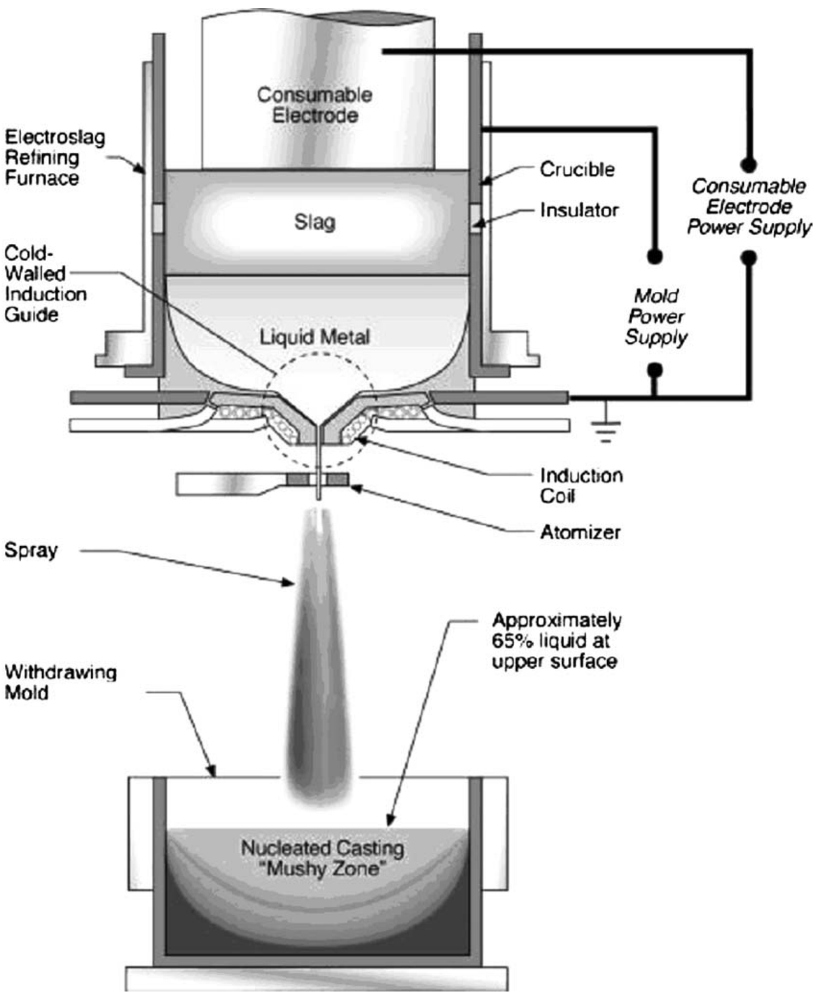

Figure 1 Clean metal nucleated casting process.

material, or coated with a suitable material, to avoid contamination of the melt. The use of an unconsumed electrode allows decoupling to the furnace temperature from the melt rate; this decoupling is key to successful CMNC operation.

1.2. Pouring system

The liquid metal is bottom-poured from the ESR furnace to form a liquid metal stream. To avoid contaminating the metal with oxide inclusions that may erode from a ceramic nozzle, a ceramic-free induction-heated copper funnel is used to form the stream. The copper nozzle is segmented radially and surrounded by an induction coil. Electric current is oscillated in the coil, inducing a current in each of the copper segments, subsequently inducing a heating current in the flowing liquid metal stream. Heat that is induced in the copper components is removed with cooling water. Experimentation with the copper nozzle, which has been termed a "Cold Induction Guide" (CIG), has shown the device to be approximately 10% efficient.

Significant effort is expended in conventional ESR processing to assure a constant melt rate because it assures a constant solidification rate, which has been shown to reduce the propensity to form segregation defects in ingots. In the CMNC process, the melting and the solidification processes are decoupled; it is the pour rate that must be held constant to assure a constant solidification rate. The pouring system relies on active pressure control above the melt to compensate for metal head changes that occur due to the integrated effect of any differences between melt rate and pour rate. Thus, a constant pour rate is maintained by measuring the melt level to control the pressure above the melt, requiring an enclosed melt chamber. The same signal is used to make adjustments to the furnace power, thereby influencing the melt rate to avoid over-filling or emptying the furnace.

1.3. Atomization and collection systems

After a short free-fall from the CIG, the stream is atomized using a conventional open atomizer. This atomizer is similar to those used for spray forming, except that the gas to metal ratio is relatively low. The atomizer directs a gas jet onto the metal stream and converts it into a spray, accelerating the spray droplets from the atomization zone toward a collection mold, cooling them in flight. Nitrogen or argon can be used as the atomizing gas.

The process is tuned by adjusting the superheat of the metal stream, the gas-to-metal ratio, and the spray distance so as to obtain a metal pool with a top surface at approximately 25–35% solid fraction. Thus, a semisolid metal is cast into the collection mold. When the particles strike the surface of the pool, large particles will be fully liquid, small particles will be fully solid, and medium sized particles will be semisolid. Many of the small solid particles will remelt after being deposited into the mold. However, when the system is tuned properly, a sufficient number of solid particles will remain to serve as nucleation site for further solidification. As these sites grow, they will eventually come into contact with adjacent growing zones, and solidification stops. If a sufficient number of nucleation sites are present, a fine-grained metallurgical structure results.

The water-cooled collection mold is key to the nucleated casting process. The CMNC process relies on a withdrawal mold with stationary sidewalls and a moveable bottom plate. As metal is deposited on the top of the ingot, the ingot is withdrawn through the stationary sidewalls so as to maintain a constant metal spray distance.

2. Preliminary CMNC results

Alloy 718 metal has been cast in a prototype system for demonstrating the feasibility of the proposed process. The collection mold for this prototype system was 406 mm (16 in.) in diameter and metal was cast to a depth of 200 mm (8 in.). Metallographic examination (Fig. 2) shows that the CMNC material possesses a uniform, equiaxed 0.075 mm (ASTM 4.5) grain structure with Laves phase present on the grain boundaries, rather than the typical primary/secondary dendritic arm structure. Delta phase decorates some grain boundaries, but it probably precipitated during annealing prior to machining. In a similar VAR ingot, greater Laves phase volume fraction and larger Laves particle size would be evident, indicating that this phase would be dissolved during conventional heat treatments. Macrosegregation-related defects such as white spots and freckles (casting segregation or other inhomogeneities) were not observed in this macro plate. To determine if freckles and white spots were present, a forging specimen of the CMNC-cast metal was upset from a height of 127 to 43.2 mm (5 to 1.7 in.) to enhance freckle detection ability. This forging did not reveal any macrosegregation defects.

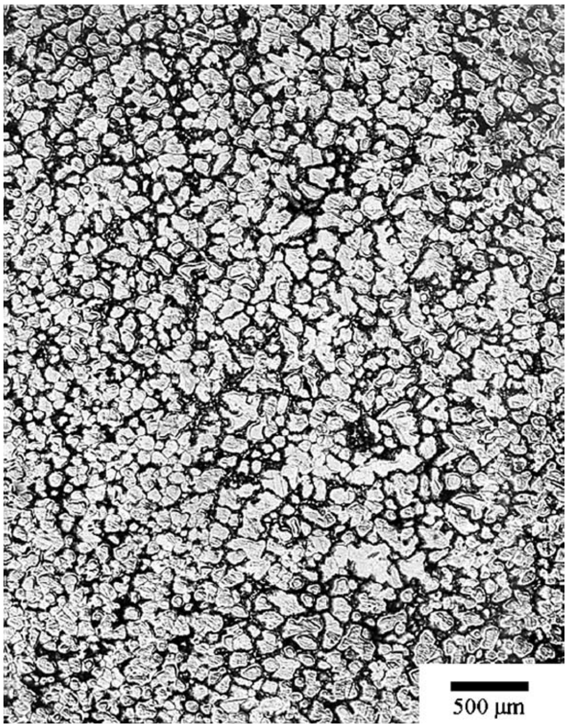

Figure 2 Alloy 718 as cast in a CMNC feasibility trial. The as-cast grain size is 0.075 mm (ASTM 4.5).

3. Conventional processing of gas turbine wheels

The need for a process such as CMNC is established through an evaluation of the current processing sequence for a gas turbine wheel. The turbine wheel is the rotating hub on which turbine blades are mounted. It is a highly stressed component that experiences large thermal cycles in service. Turbine efficiency is limited by the firing temperature, which is in turn limited by the properties of the materials used in the turbine. This drives the metals industry toward increasingly complex alloys that have progressively better high-temperature properties. Increased turbine power is achieved by increasing the size of the turbine, requiring ingots of increasing size. Unfortunately, as the complexity of alloys and/or the size of the required ingots is increased, the likelihood of casting inhomogeneities or segregation defects is increased.

The conventional processing sequence for producing a turbine wheel is shown across the bottom of Fig. 3. It starts with a triple-melt sequence, which includes vacuum induction melting (VIM), electroslag refining (ESR), and vacuum arc remelting (VAR). The resulting ingot is thermomechanically processed through repeated upset and draw operations to produce a billet. The billet is then forged to produce a wheel forging. Because of the required size and the strength of the material, forging of large-diameter turbine wheels requires the largest forge presses in the world (640 MN or 72,000 tons). After forging, the metal is heat-treated and machined to produce a turbine wheel. The goal of the triple melt process is to produce an ingot of the certified alloy chemistry that is free of oxide inclusions, voids, or other defects, and of homogeneous structure. These are essentially the goals of the CMNC process. However, triple melt has been in existence for many years, and the process has been extensively optimized to the point that it is reaching its intrinsic limits. However, as pointed out previously, the demand for higher efficiency and higher turbine output requires more complex larger ingots of increasingly complex alloys. This is a significant metallurgical problem and new processes such as CMNC must be developed to further the state of the art.

3.1. Melt-related defects

Components made from superalloys are generally subject to intense levels of cyclic stress at high temperature, and therefore a predominant mode of mechanical failure is low-cycle fatigue. Such failures occur in two phases: crack initiation followed by crack growth. The crack growth characteristics of nickel-based superalloys are intrinsic and measurable properties of the

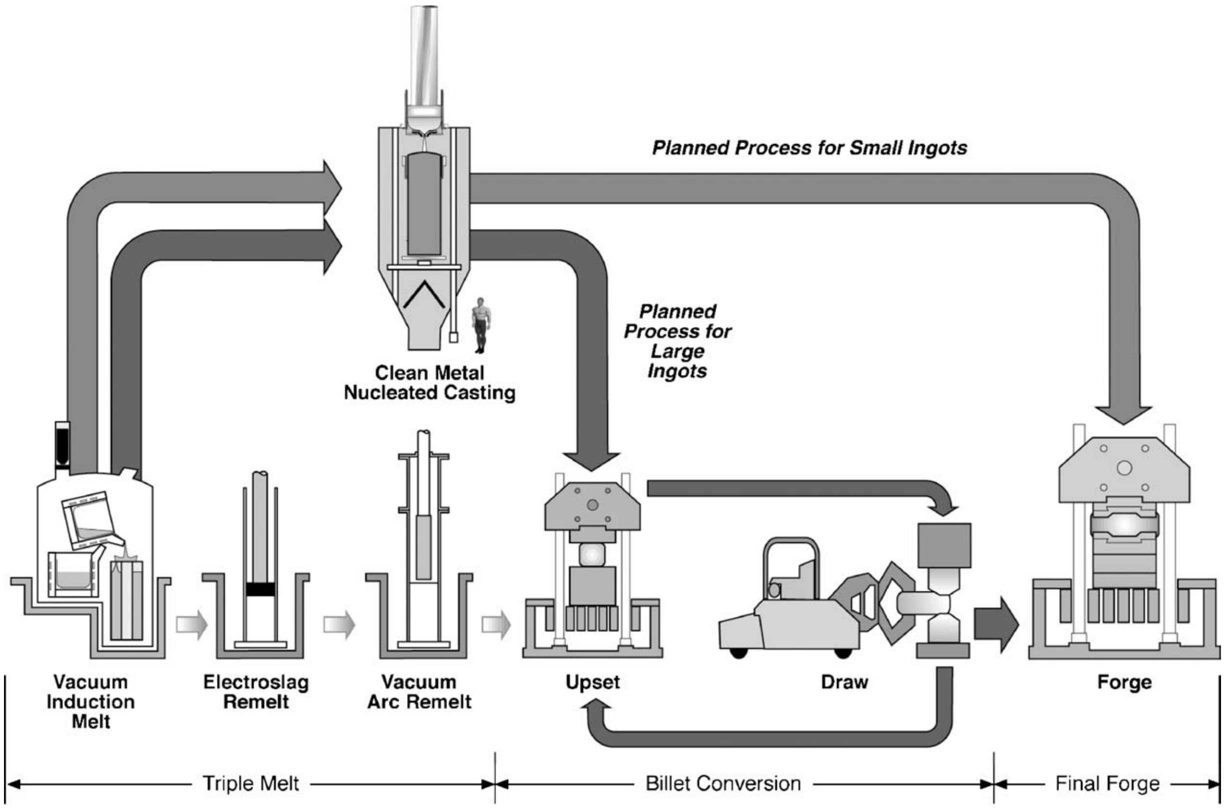

Figure 3 Processing sequence for gas turbine wheels.

alloy and are quite predictable. Long cracks grow faster than short ones; high stress and high temperature make them grow faster. Unlike crack growth, crack initiation is not an intrinsic property of the alloy because initiation most frequently occurs at a defect—a site that is different from the basic alloy. Possible initiation sites include brittle precipitates, inclusions, and voids. The larger the defect, the faster the cracks initiate, and the shorter the low-cycle fatigue life.

The industry relies on ultrasonic inspection for quality assurance. In the extremely large ingots required for today's gas turbines, ultrasonic inspection of the ingot or billet is not possible because of background noise associated with the large-grained structure of the ingot and billet. It is only after forging that the grain structure is fine enough that ultrasonic inspection is possible. This has significant economic impact because the cost of the thermomechanical process to generate the forging is very high. The types of defects that typically result in ultrasonic indications are termed in the trade as *ceramic inclusions*, *freckles*, *white spots*, and *large grain size*.

Ceramic inclusions play a significant role in the low-cycle fatigue life of components made from superalloys. The source of ceramic inclusions in ingots is usually a ceramic crucible liner, filter, or launder used in the vacuum induction melting process for achieving the basic alloy chemistry. Mechanistically, a ceramic inclusion is brittle compared to the surrounding metal and will crack early in life, possibly as early as the first loading cycle. The fractured inclusion acts as a crack starter for the surrounding metal. It is extremely important to eliminate ceramic inclusions or to limit their size to obtain high life. This requirement poses a metals-processing challenge that has been aggressively researched in the metals industry. Typically the elimination and/or reduction in size of oxides is achieved through Electro-Slag Remelting [8].

Freckles are regions of high Nb and Ta concentration formed by microconvection-induced segregation during solidification. Freckles typically contain Laves-phase regions that have low ductility. The presence of freckles frequently causes microcracks and voids to form during forging or hot forming, thus increasing the size of the fatigue crack initiation site [9–11]. Solidification time must be minimized in the final vacuum arc remelting operations to avoid freckle formation. This in turn imposes a limitation on the size of ingot that can be cast by processes such as ESR and VAR.

White spots can occur during vacuum arc remelting operations. In the vacuum, some species in the hot liquid metal pool (e.g., Cr, Al) can evaporate from the melt and subsequently condense on the crucible wall. This material will oxidize with the little oxygen left in the vacuum chamber. If the material falls into the melt pool and does not remelt or dissolve, a "white spot" defect is formed. White spots can also occur due to the fall-in of shelf, crown and electrode material [9].

Large grain size is an unavoidable consequence of the VAR casting process that necessitates the subsequent thermomechanical processes such as upset and draw to achieve the fine grain structure that is needed for both forging and ultrasonic inspection. Typical grain sizes at each phase of the manufacturing process are given in Table I. Occasionally, an unusually large grain may survive the thermomechanical processing with partial or no recrystallization, leading to ultrasonic indications.

TABLE I Typical grain sizes in conventional processing

	Grain size
Triple melt ingot	>20 mm
Billet	ASTM 00-2 (0.51–0.15 mm)
Forging	ASTM 8-10 (0.011–0.022 mm)

In conventional melting, limiting the maximum diameter of vacuum arc remelted ingots to less than 914 mm (36 in.), or limiting the process rate to a very low level has been required to reduce the occurrence of melt-related defects in superalloys. Control of processing rate variations has also been key. Unfortunately, these process controls cannot guarantee the absence of such defects. Therefore, ultrasonic inspection is currently used at the final component stage to find and discard components containing melt-related defects.

4. Processing turbine wheels using nucleated casting

Analysis of solidification during ingot casting shows that casting as a semi-solid, rather than as a liquid, represents a possible method of reducing melt-related defects. Fig. 4 is a composite of results from two separate computer simulations showing a vacuum arc remelting process and an alternative process in which the metal is deposited into a mold as a semisolid.

On the left (a) is the predicted steady state pool for a 0.508 m (20″) diameter VAR ingot of alloy 718 processed at nominal melt rate of 0.06 kg/s. The results were obtained using the Specialty Metals Processing Consortium (SMPC) proprietary code, BAR, which have been experimentally verified [12]. A considerable volume of liquid metal is present above a transitional region of semisolid. The results on the right (b) were generated using the general-purpose CFD code COMPACT® and represent an ingot of the same alloy cast as a semisolid at the same casting rate. Note the complete absence of a liquid metal head and the much shallower mushy zone in the case of the nucleated cast ingot. The shallow region suggests that higher processing rates are possible. The casting rate was doubled for another analysis (d) that shows an increase in the depth of the semisolid region, but still no liquid layer. The results (a) were duplicated in (c) for clarity in the figure.

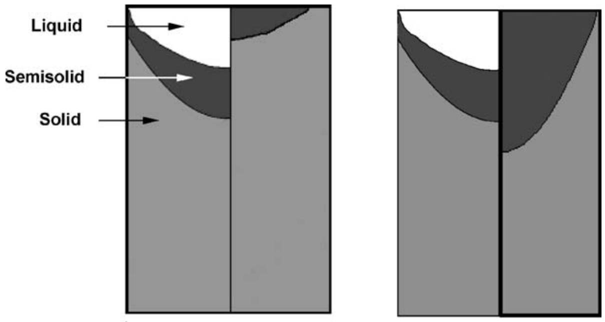

Figure 4 Modeling results indicating liquid, semisolid, and solid volumes in a casting. Results shown are (a) conventional VAR casting at 0.06 kg/s, (b) nucleated casting at 0.06 kg/s, (c) conventional VAR casting at 0.06 kg/s, repeated for clarity, and (d) nucleated casting at 0.12 kg/s.

It is apparent that a semisolid casting process has potential for achieving higher casting rates than are feasible with existing processes such as VAR. Nucleated casting, as discussed above, represents one possible method of depositing semisolid metal into a collection mold. One of the goals of the CMNC program is to replace electroslag refining and vacuum arc remelting with the single CMNC processing step as shown at the top of Fig. 3. Reducing the number of melting steps by one third reduces the energy required to produce the ingot. This energy savings represents a marginal benefit in CMNC processing over conventional triple melt, but it is not the most significant advantage of the process. The most significant advantage is a segregation-free ingot with a grain size of 0.075 mm (ASTM 4.5). This grain structure, shown in Fig. 2 was produced during feasibility trials and is substantially finer than that of the standard triple-melt ingot that has been further subjected to three subsequent upset-and-draw operations.

This fine as-cast grain size, achieved directly from clean metal nucleated casting, obviates the need for the upset and draw operations. Thus, it is possible that a CMNC ingot may be forged into a disk immediately after casting without any intermediate billet conversion. However, it is expected that as the CMNC ingot diameter is increased, the as-cast grain structure will become larger. This is a result of the longer heat path and consequent increase in solidification time. Therefore, some larger diameter ingots will still require some level of thermomechanical processing to develop a satisfactory billet structure. This is shown in Fig. 3 as the "planned process for large ingots."

The ingot diameter above which thermomechanical processing is required is not known at this time; one goal of the CMNC program is to determine this upper limit for clean metal nucleated casting. However, the lack of segregation in the feasibility study indicates that very large ingots are possible without segregation defects.

5. Conclusions

The Clean Metal Nucleated Casting (CMNC) program is a 4-year NIST-sponsored effort aimed at developing this new semisolid casting method for superalloy ingot casting. The goal of the project is to establish the process capability for Alloy 718 by the end of the year 2005. This will be accomplished through the construction of a $\frac{1}{2}$-ton capacity pilot plant, which will operate at production rates, to be used to cast ingots for evaluation and conduct experiments aimed at developing suitable sensors and optimizing process control. Simultaneously, process models for the process will be developed and validated against the experimental results of the program. The process will be scaled up to industrial scale for commercialization after the program.

CMNC processing has the potential to reduce or eliminate many of the melt-related defects currently limiting superalloy processing. Ceramic inclusions are virtually eliminated through the ESR melting system, which dissolves any that may be in the electrode. Macrosegregation and freckling was not seen in the feasibility trial and it is conjectured that casting as a semisolid reduces the possibility for microconvection-induced segregation. The grain size is significantly finer than conventional casting. Other feasible technical improvements of CMNC compared to conventional superalloy casting fall into several categories:

- New segregation-prone alloys can be cast.
- Finer grain size will lead to a reduction in the number of ingot conversion steps to a final forging.
- Larger ingots will provide the manufacturing capability for larger parts, and allow economies of scale in smaller parts.
- The number of melt-related defects will be reduced, leading to extended low-cycle fatigue life of components.
- The metal is cast into an ingot mold, resulting in high process yield.

The CMNC process shows great promise for reducing melt-related defects and achieving fine homogeneous superalloy structure in large-scale ingots. The unique melting and pouring system avoids the possibility of oxide inclusions. The first alloy of interest is Alloy 718, which is currently used for turbine wheels in land-based gas turbine engines for electric power production.

Acknowledgements

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