PROCEEDINGS OF THE
10TH INTERNATIONAL SYMPOSIUM ON

# SUPERALLOY 718 and Derivatives

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# Proceedings of the 10th International Symposium on Superalloy 718 and Derivatives

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# Preface

Following with tradition since 1989, this edition of the International Symposium on Superalloy 718 and Derivatives continues the legacy of journal-quality, peer-reviewed, technical papers published concurrently with oral presentations at the in-person conference in Pittsburgh, Pennsylvania, USA. As the editorial team and conference organizers, we are proud to continue to offer a forum where the most relevant research, development, and application of superalloy materials of the family including alloy 718 can be shared with the technical community and can be archived for perpetuity in the form of this published electronic proceedings. The 2023 session is the 10th symposium in the series, and this proceedings volume provides 50 new papers representing the most recent advances of technical efforts in the field of superalloys adding to the more than 650 published papers in this overall series covering over 30 years.

While our experiences as a community over the last several years have led to strengthened electronic communication ties and channels, we look forward to this symposium's in-person gathering offering the opportunity to bring researchers and users together in one forum to discuss technical learnings, define new relationships, and renew and build peer networks. With the pace of progress in the technical field moving more and more quickly, we have chosen to expand access to the latest work by soliciting "late news abstracts" as part of the in-person conference. Although we are not able to publish detailed papers tied to these added topics due to timing, we expect that these poster presentations along with the core group of papers in these proceedings will help to add to and promote more collaboration and spirited technical debate in the field on high temperature superalloy materials. As a celebration of the long legacy created by our predecessors in the field, we also have added a special historical look at the progress of technology in the field in this proceeding's introduction from the perspective of one of our Keynote speakers from ATI. A look back through time helps us to appreciate where we've come from technically and helps to plot the future trajectory of the technology.

This proceedings volume represents contributions from all corners of the world. Author affiliations include participation from eight countries across three continents, and the demographics further underline the breadth of the perspectives that have historically made up these proceedings with academia, laboratories, and companies representing 40%, 15%, and 45% of the papers, respectively. We would like to thank our editorial and organizing committees for their investment in continuing this symposium series and would like to extend a special thanks to all of the paper, presentation, and poster authors for sharing their experiences and technical findings with us and the community. Finally to our symposium attendees, we want to extend our deepest gratitude for making the 718 Conference series a success for the tenth time.

Eric A. Ott
Lead Editor

Joel Andersson
Organizer

# Historical Introduction: Meeting the Challenges of the Future by Understanding Our Past

## Introduction

Understanding a material and its future performance in a potential application often begins by studying its history. If known, a detailed review of the processing it has undergone is most helpful, and if not available, an examination of its microstructure. While the correlation of structure, properties, and performance is not quite as connected in the evolution of an industry, understanding the past often provides significant insights to the potential of the future. It's important to review this history through a lens of understanding of what has been done, what was the outcome, and most importantly, why was it done. The "why" is critical to understanding the past limitations in the drive for continued advancement. This reflection brings an appreciation of how far the superalloys' history has come along with a humble realization of how far there is yet to go.

ATI's history is intertwined in the industrial advancement of superalloys to the ubiquitous applications powerhouse they are today. ATI was formed by merging Teledyne and Allegheny Ludlum in 1996. Teledyne owned two of the business units still part of ATI: Specialty Alloys and Components, then Wah Chang, and Specialty Materials, then Allvac. Teledyne also owned a slew of other companies, most of which were spun-off or sold.

Allegheny Ludlum was created in a 1938 merger between Allegheny Steel and Ludlum Steel. Both companies were pioneers in the steel industry with vestiges going back to the production of cannon balls for both the British and Continental Army in the Revolutionary War. Allegheny Steel primarily made flat products, was the first to use an electric arc furnace and supplied stainless steel for the Chrysler Building. Ludlum Steel produced steels primarily in bar, rod, and wire form and supplied for the construction of the Empire State building. The merged Allegheny Ludlum company initially focused primarily on specialty stainless steel products. However, they were active in the growing aerospace industry and had engineers focused on developing heat resistant alloys for jet engines, and methods to make them in production quantities. They ventured into numerous other alloys, including titanium (a joint venture with National Lead), Uranium (to support the US government) and Nickel. In 1950 they produced the first large (10 ton) heat of an aluminium and titanium strengthened superalloy in Watervliet, NY. This was followed three years later with the first production scale vacuum arc remelting. Allegheny Ludlum's remaining facilities operate under the name ATI Specialty Rolled Products.

Allvac was formed in 1957 as an "All-Vacuum" melting company by Jim Nesbit, a former General Electric engineer who believed that vacuum melting was critical to the continued advancement of nickel melting. The very first heat in tank 1 was Waspaloy for Pratt and Whitney blade bar. From the very beginning, Allvac's focus was clearly on clean melting for the aerospace and defense markets. By 1962 they had installed what was then the world's largest vacuum induction melting (VIM) tank at 12,000 lbs. capacity, a bet that the future of superalloys would require the cleanliness vacuum melting delivered. Allvac was sold to Vasco in 1965. Vasco Metals Corporation was acquired by Teledyne in 1966 and this unit now operates as ATI Specialty Materials.

The fourth current business unit of ATI, Forged Products, was an acquisition of the Ladish Company in 2010. Ladish began in 1905 when a supervisor for American Malting Company, Herman Ladish, started looking around for someone to make more reliable machine components. He partnered with John Obenberger, who ran a local forge shop, purchased a steam powered hammer forge, and began making axles and other forgings. While initially focused on small parts, by the 1930's they were making larger parts for industrial and farming applications as well as serving the burgeoning aerospace industry. They were making parts for jet engines by the mid-1940s.

## Melting

The initial large melts of alloy 718 were air melted, including at Allegheny Ludlum. With this process melting is done with Argon Oxygen Decarburization (AOD) and may be followed by Electro Slag Remelting (ESR). The air melting process of the era lacked the chemistry control to handle the higher levels of titanium and aluminium additions. While there are much tighter controls in air melt today, the use is largely restricted to applications outside of the aerospace and aeroderivative industries. The introduction of vacuum melting provided both chemistry control and an increased cleanliness in the ingot to drive improved mechanical properties. Initial Vacuum Induction Melting (VIM) tanks did not have the ability to make additions during the melt process, Fig. 1. Ingots were static cast without remelting. As a result, the chemistry was far less controllable overall, and the chemical segregation was substantial. The shrink pipes were enormous (potentially dominating the length of the ingot), Fig. 2.

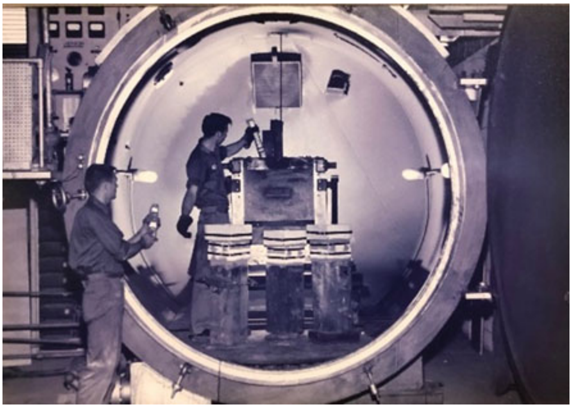

**Fig. 1** Initial charging of a VIM tank in 1958

**Fig. 2** Shrink pipe from a statically cast VIM electrode

Later VIM furnace designs included the ability to make chemistry additions. During melting, Nickel alloys are best thought of as a soup versus a cake. It's important to "taste" via in-process dip sampling to test the chemistry and make the appropriate modifications. This allows the chemistry to be dialed in prior to casting the liquid into a mold. Further improvements include using a hot topping procedure to insulate the upper portion of the electrode and slow down solidification, resulting in a smaller pipe cavity, thus a more solid electrode for further processing.

Remelting is critical whether via ESR, Vacuum Arc Remelting (VAR) or both. A schematic of the remelting processes can be seen in Fig. 3. An ESR remelt offers additional cleaning of the melt as the molten droplets go through a slag. During the exposure to the slag impurities can be removed via reaction, floatation, or dissolution.

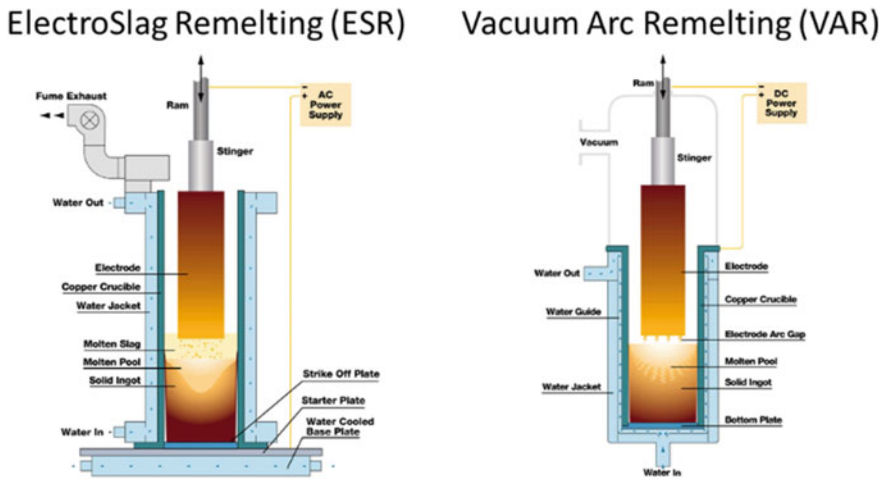


**Fig. 3** Schematic of electro slag and vacuum arc remelting processes

**Table 1** Comparison of electro slag and vacuum arc remelting processes

| Electro Slag Remelting | Vacuum Arc Remelting |
|---|---|
| Removes sulfur | Removes gases, nitrogen retention is difficult |
| Oxidizing process, results in loss of reactive elements | Removes volatile elements, including Mn and Cu at higher concentrations |
| Can greatly improve cleanliness | Moderate improvement in cleanliness |
| Deeper melt pool due to slag skin | Shallower melt pool due to Helium cooling, if used |
| Less sensitive to white spot formation | More sensitive to white spot formation |
| More sensitive to freckle formation | Less sensitive to freckle formation |
| Higher melt rate | Lower melt rate |

However, ESR has a slower solidification rate resulting from the slag insulating the molten pool, which can increase the propensity for some deleterious segregation. The VAR process, being under a vacuum, is considered best for removing gases and other volatile elements and has a faster solidification rate than ESR. A comparison of the advantages of both remelting options can be seen in Table 1.

Regardless of the melting process, the ability to control the process parameters has improved enormously. Remelting process control began as straight voltage control, with a crude aim point, to deliver constant current throughout the melt while manually adjusting the electrode height above the molten pool. Today's remelt furnaces typically run by controlling drip shorts, that is controlling the voltage and ingot gap and/or melt rate control which adjusts the voltage based on the weight of the hanging electrode. These control schemes allow engineers to reduce process variability by

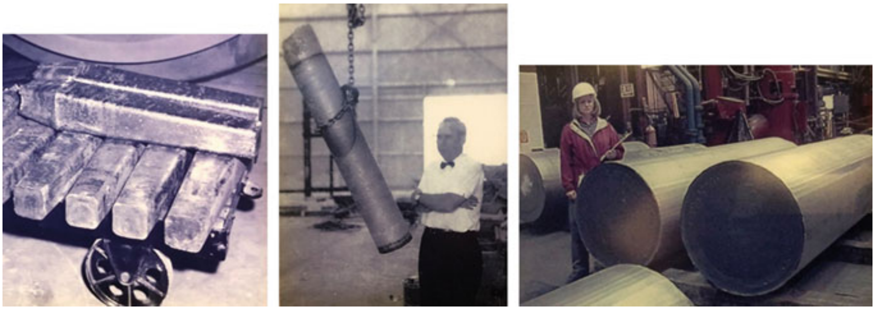

**Fig. 4** Left to right: first VIM ingots, first VAR ingot, large 718 ingots for power generation

maximizing the time with consistent equilibrium solidification conditions. Furthermore, these controls have allowed the diameter of the ingots produced to increase substantially, making for a more cost-effective manufacturing process. Initially VIM ingots were small, 9” diameter, 42” long while VAR ingots grew to roughly 12” in diameter. Today 718 ingots can be made up to 36” inches diameter for power generation applications, Fig. 4. Melt anomalies nearly always relate back to an area of non-equilibrium solidification. As the ingot diameter grows, the requirements for stronger process control increase significantly, both for maintaining chemical homogeneity during the melt and in ensuring the integrity of the solidified ingot for downstream processing.

By the 1960s, in addition to the cast-wrought alloys and processes being developed there were also advances in powder-based superalloys. Initially driven by Pratt and Whitney, powder-based alloys have the advantage of less segregation due to high solidification rates achieved in small droplets that form the powder. While more costly, these alloys can include more complicated chemistries and thermomechanical processing paths. They also extend the temperature range for superalloys in jet engines, which have gotten progressively hotter during operation.

The criticality of controlling the melt process cannot be overstated. All future processing relies on the material behaving consistently in process and in application, and industry has been humbled when any defect has made it to an in-service product, including events with the tragic loss of human life.

## Thermomechanical Processing

Much of the initial thermomechanical processing was developed to obtain a certain geometry for later stage processing. The mills available were limited in size, tonnage, and ability to reheat material so there was little ability to optimize the process. ATI had a simple reversing mill to convert ingots down to the standard rectangles and round-cornered squares required for forgings. There was no intermediate cutting, and a simple barrel furnace would warm the surface between passes. Once the material

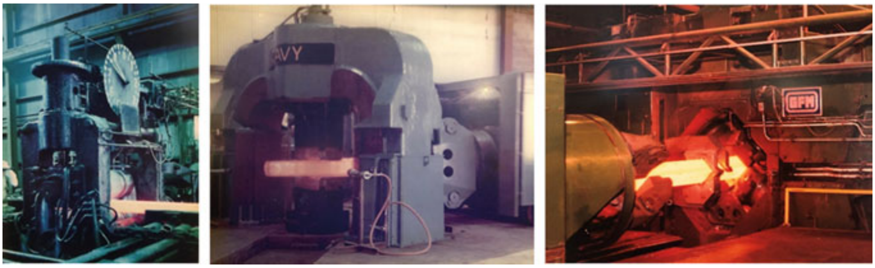

**Fig. 5** Left to right: initial blooming mill, early press, and radial forges installed at Allvac

went into the mill, it was committed. Furthermore, the mills weren't designed for the tonnages required for superalloy processing. As an example, all the rolls broke on one of the first mills Allvac acquired for blooming. The process was full of variability—and the engineers claim they could identify the mill operator by looking at the billet structure. All the operators were compliant with the process instructions, but it was clear there was significant impact from uncontrolled nuances within the processes. This drove an intense focus on process control and understanding, still a focus at ATI today. By the 1960s engineers were tracking every step in the process by hand, mining for differences—a time consuming and manual predecessor to today's drive to fully digitize. What they found drove tighter controls and tolerances on reduction sequences, transfer times and temperatures in all areas. By the 1970s, as the material got tougher with the introduction of new alloys and melt technology that allowed for production of larger ingots, mills with higher tonnage became necessary to process superalloys into useful forms. The company began using a press and radial forge as the forging industry was forced to shift to accepting round vs round-cornered square billet. Photos of the initial blooming mill, press forge and radial forge are shown in Fig. 5.

The shift to round billet was more than a geometry change. The use of new equipment required new recipes and a renewed focus on process variability to obtain the refined, homogenous structures needed for use.

Powder alloys were initially converted into parts from the as hot isostatically pressed (HIP) condition. This proved to be unsatisfactory for the fatigue strength needed for many part applications. As a result, a change was made for as-HIP'd cans to undergo billet conversion such as extrusion or press forging prior to the closed die part forging.

For making parts, Ladish had been forging Astrolloy and Waspaloy since the 1930s, primarily with conventional presses, hammers, and ring rolling equipment. As more complex and powder-based superalloys were developed, controlling the microstructure was the goal. Parts were made by a combination of isothermal forging (where the die and billet are at the same temperature), hot die forging (where the die is heated but not quite as hot as the material) and conventionally forging (colder die) to get the necessary ultrasonic transparency. At the same time parts were growing substantially. While initially billets were 4 inches in diameter, newer engines required

6- and 10-inch billets. With a billet that large, or larger, the chemical homogeneity and fine microstructure play a significant role. The structure is critical to obtain something that is inspectable. In the 80s the typical ultrasonic requirement was a #5 (5/64") flat bottomed hole. Today powder billets are inspected to ~10% of a #1 (1/64") flat bottomed hole. ATI's vertically integrated structure offers advantages for material inspectability as the process history from melt or powder to billet, and to part is readily shared. This has resulted in significant leveraging of learnings across the full ATI value chain.

In addition to parts getting larger, the forged discs got more complicated. The industry moved from a "there's a part in there somewhere" approach to one that cared deeply about material yield and the control of the condition and shape of the part for forging, heat treatment and ultrasonic inspection. Near-net shape forging with minimal material waste and consistent processes became the key focus. This requires expert die design and know-how. Initially there were no computers to help with forging design. Engineers used wood and plasticine models to watch die fill and lap formation. With the growth of computing resources, engineers could focus on temperature rise, strain, tonnage, last areas to fill as well as lapping and folding, but this did not provide a fast solution. A model could run for days for a single axisymmetric disc evaluation. Today's models and advanced computer resources are much faster.

As the aeroengine industry has largely moved their design focus from microstructural control to designs which minimize the defect flaw size the superalloy forgings used in discs are primarily hot die or isothermally forged. Some, but far fewer, are still conventionally forged 718 parts. Just as a forging billet requires homogeneity and fine structure, the requirements for final part structures have become more specific. The industry has improved its ability to design and control the forging and heat-treating process. Designs moved to be more damage tolerant by requiring a coarser grain size to improve crack propagation. This requires heat treating above the solvus and a tight control over cooling. The SuperCooler shown in Fig. 6 was designed in the late 90s to meet this need. The device allows for tailored grain sizes and reduces residual stress in a given location. The equipment controls the cooling rate over a broader range than liquid quenching or ducted air nozzles. This precise, computer-controlled cooling profile results in improved mechanical properties, reduced residual stresses and higher yield since the as-forged shape requires less additional machining.

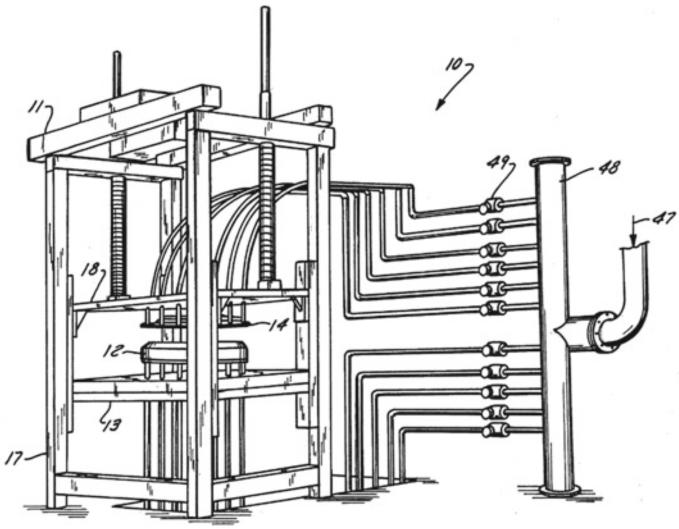


**Fig. 6** Schematic of the supercooler

## Computational Process Simulation and Modeling

Modeling has been used since the early stages of metallurgical working and the growth of computing power and characterization tools has only strengthened its role. Physics-based models can be more accurate, but they are time consuming, expensive, and challenging to produce. Advances in machine learning have allowed for complementary empirical models that may accelerate physics-based models by narrowing their focus to targeted areas. The expanding development and use of new characterization tools such as electron backscattered diffraction (EBSD) help reveal the impact of processing far beyond an average grain size. Tool advances help drive understanding as the debits in properties are usually related back to a local anomaly, a larger grain, area of segregation, etc. The ability to see and measure these rarities drives the ability to reduce, and ultimately eliminate them.

Compositional modeling has grown with the ability to leverage combinatorial methods to predict properties. High-throughput automated methods allow for rapid screening to confirm results. These methods were initially used primarily for chemical composition to strengthen Calculation in Phase Diagrams (CALPHAD) thermodynamics databases. Today there are automated methods to look at microstructures, suggest process conditions and test mechanical properties of materials. Much of this remains in research laboratories, but industry has implemented automated testing and analysis (mechanical, or microstructural) of materials. ATI uses Monte Carlo simulations to understand process sensitivity around chemical composition, for example. This allows an understanding of how tight the processing window needs to be and what is controllable to meet the specification requirements.

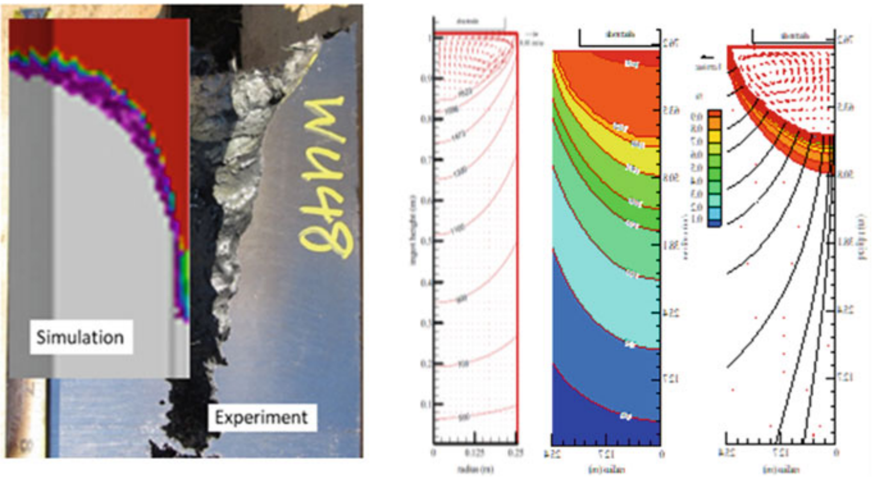


**Fig. 7** Left to right: simulation and physical trial of a VIM melt and simulation of a VAR melt

The job of the melter is to be clean and maximize throughput by going fast in large diameters. However, advanced alloys push melting processes slower and in smaller diameters to maintain cleanliness and chemical homogeneity. Two dimensional, and some three-dimensional models exist. Fig. 7, left, shows the modeling results and physical trial side by side to predict the shrink pipe of a VIM electrode. On the right side, Fig. 7 shows the temperature and melt pool shape of a VAR ingot.

The models can get quite sophisticated balancing the complicated dynamics in a melting process and can be used to develop melt profiles or aid in a defect investigation. There continues to be room for advancement in melt modeling. It is known that equilibrium solidification is key to a clean melt but there remain portions of the melt process and melt pool that are invisible today. The ability to link a process controller directly to the melt pool would be powerful.

Process modeling is routinely used to evaluate the conversion of ingots to fine uniform grain-sized billet. The thermomechanical history as well as grain size evolution can be predicted by this means. Figure 8 shows an example of temperature monitoring during open-die modeling. Billet conversion modeling requires the stringing together of a long sequence of heating and deformation simulation steps. While software tools exist that have made this up-front process definition simple, there continues to be room for improvement. This includes a realistic definition of the sequence of operations (for example matching elapsed times and die speeds), as well as limitations on the size of finite element mesh that will yield reasonable run times.

At ATI every new part forging is modeled. Whether at a high level to quote an opportunity or for a detailed process design to target specific properties in the final product. Advances in computer time now allow dozens, or even hundreds of models to be completed prior to a single push. This saves time and money. Furthermore, the use of automated recipe-based production systems ensure that the engineer's

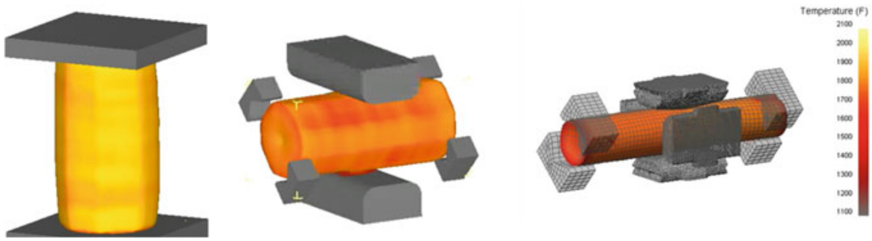


**Fig. 8** Open die modeling of ingot conversion processes: upsetting, cogging, and radial forging

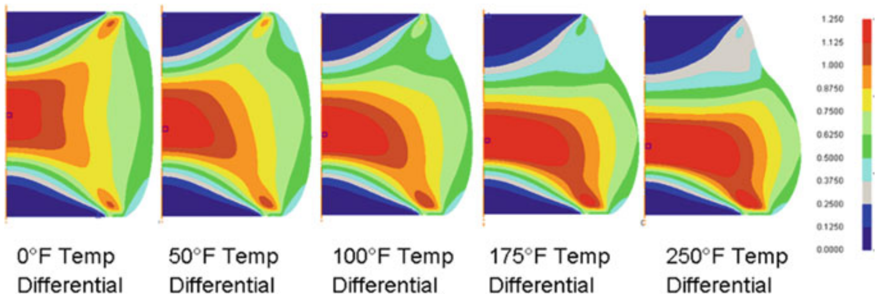


**Fig. 9** Impact of temperature non-uniformity in a forged part

intended process is what the part sees, reducing variability. Our goal at ATI is to get to the point where we can accurately model everything we do. When combined with doing everything in a consistently repeatable way at production scale it has the potential to allow the creation of the ultimate digital twin containing all the process information from the first melt to the final machine operations. Figure 9 shows the impact of temperature non-uniformity in a forging process.

Advances in modeling have also shown the benefit of concurrent engineering. Bringing together the system designer and the part fabricator allows for an efficient process to produce a manufacturable part in the most cost-efficient manner. Rather than designing in silos, working together can allow for part reduction, modest adjustments for a big benefit to both parties and a better understanding of intent and need. Materials suppliers, including ATI, often work closely with jet engine manufacturers years before their new engines are introduced to ensure manufacturability of the parts and components.

Additive manufacturing continues to bring growth in alloy 718 and its derivatives. Opening the doors to integrate and model new shapes and designs that were not possible before, along with a whole new process to understand. The potential to reduce weight and handle, or change, loading conditions not just on one part but potentially on an entire system is huge. Industrial uses of new processes require a pay-off, but we are seeing clearly today that may come less from cheaper parts, although possible, and more from better performance at the part or system level.

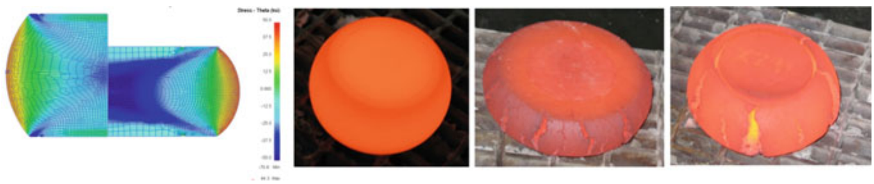

**Fig. 10** Finite element modeling compared with physical trial results

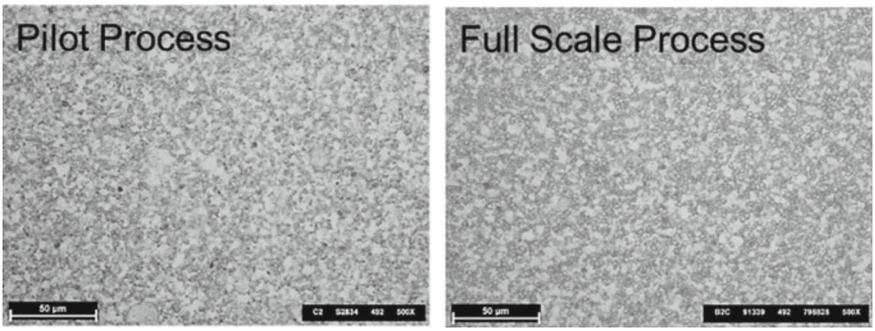


**Fig. 11** Microstructures taken from a subscale powder billet (left) processed on pilot scale equipment designed to simulate full size billets processes on production equipment (right)

Finally, this paper would be incomplete without stressing the importance of physical experiments performed at the pilot scale. While modeling is fast, it requires physical validation. ATI's experience shows that the proper design of pilot scale experiments can rapidly, and cost effectively, advance materials to production sizes and specification requirements. Finite element modeling can accurately predict the shape, thermal profile, adiabatic heating, and strain. However, these models are not yet able to fully capture the probability of cracking related to differences in reduction and die dwell as shown in Fig. 10.

Pilot scale trials are most valuable when they can both combine with modeling and represent an accurate simulation of the production process. Microstructural results are shown in Fig. 11 comparing the results of a subscale powder billet processed on ATI's pilot scale equipment compared to the results obtained from a full-size billet on ATI's production equipment. The microstructures showed a difference of only 0.5 ASTM grain size (12.5 at subscale versus 13 at full scale). The value of a strong pilot scale process laboratory cannot be overstated.

## Conclusions

A rigorous focus on consistent, repeatable processing at scale is important to ATI, and other materials suppliers. Knowledge and understanding of materials processing is compiled into models and pilot scale work to advance even the most challenging derivatives. The improvements seen in the sixty-plus years of alloy 718 and its derivatives are directly tied to improvements in process control and understanding. It is worthwhile to revisit the history of these developments periodically to remove artificial constraints. Advances in understanding, inspectability, measurability, and controllability allow a deeper understanding and highlight more aspects to evaluate.

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# Contents

## Part V High Temperature Fe-, Ni, and, Co-based Alloys



## Part VI Additive: Powder and Processing

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# Part I
# Melting, Forging, and Wrought Processes

# The Formation of Downward Freckles in Nb-Containing Superalloy Remelt Ingots

**A. Mitchell and S. Hans**

**Abstract** A revised mechanism for the formation of downward freckles is proposed. The mechanism accounts for the observations of freckle formation in industrial ingot production. In particular, the association of freckling with process instability is emphasized and is part of the proposed mechanism. Additionally, we suggest that the shrinkage which takes place as the final eutectic solidifies can explain the formation of freckling when the basic gravitational force produced by negative buoyancy in the solidifying liquid appears to be insufficient for the initiation of interdendritic fluid flow. We conclude that the key factor in preventing freckle formation in industrial ingot remelting is the maintenance of process stability.

**Keywords** Freckle · Superalloy · Remelting

## Introduction

The segregation feature known as "freckle" is unfortunately familiar to producers of superalloy ingots and has been frequently reported in publications [1–4]. Although the industry has been able to develop melting parameters which produce alloy ingots of most superalloys not containing freckle, the very occasional occurrence of the defect is of concern. In Nb-containing superalloys, the freckle takes a form different from that found in many other superalloys. The freckle appears to have originated from liquid flow downwards in the structure as opposed to the more general case of upward flow. This difference lies in the segregation mechanism which produces a remaining liquid on solidification which is denser than the bulk liquid rather than less so as in the other superalloy classes. This feature is due principally to the segregation tendency of niobium and molybdenum as well as the inverse segregation of chromium and iron [5]. The downward freckle mechanism has been studied and the presently

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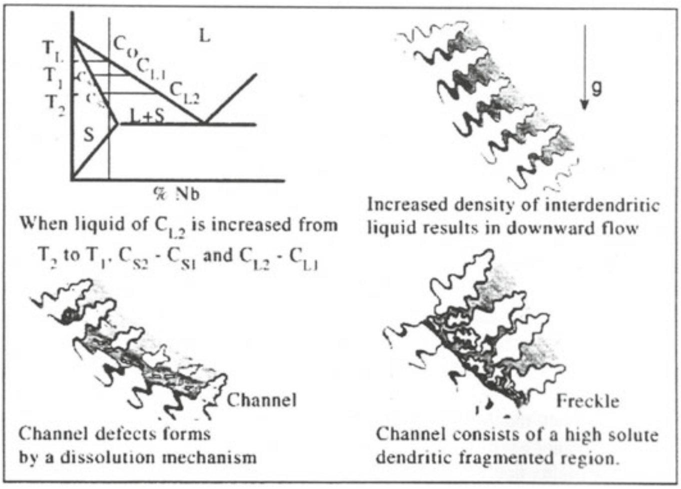


**Fig. 1** Proposed downward freckle formation mechanism [6]

accepted model is that proposed by Brooks [6], as shown in Fig. 1. The heavy liquid is assumed to flow downwards in the columnar-dendritic structure at an angle that is slightly more horizontal than the ingot isotherms. In doing so, the liquid enters a higher temperature region and is able to dissolve secondary dendrites and increase the local permeability. The process terminates as the ingot progressively freezes. The model has been studied using CFD approaches [7] from which it has been proposed that the process can be represented by the dimensionless Rayleigh Number (Ra). Following Valdes [8], freckling in the Nb-containing superalloys is predicted for a range of Ra values (0.4–0.8) depending on the individual alloy content, which concept has been used to design melting parameters for both ESR and VAR. There are two notable features of the reports of Ra computations. First, it appears that there is no unique universal value of Ra at which freckles should form. Second, it appears that the Ra values found for freckle formation are alloy dependent but it is unlikely that the alloy dependence arises solely from uncertainties in the alloy properties.

## The Freckle Process Model

The existing models for computing the Ra values relevant to freckle formation contain the assumption derived from the Blake-Korzey equation [9] that the permeability coefficient (k) governing the freckle flow is approximately $10^{-10}\text{m}^2$ given the general conditions of solidification rate (in the region of 0.1 K/s) in the freckle-prone regions of a remelt ingot. However, experimental and theoretical studies [9, 10] on the permeability of a columnar-dendritic network similar to that found in the mid-radius region of a remelt ingot have shown that the permeability coefficient in the "normal direction" (across the primary growth direction) is $10^{-12}$m$^2$ at a fraction solid (Fs) corresponding to the composition of the computed maximum remaining liquid density in these alloys (Fs approximately 0.6–0.7) [1]. Reports have suggested that the average freckle composition in IN718 is 9.3%Nb [5], 9.5%Nb [11], and 11.5%Nb [12]. It is to be noted that the "average" composition of the freckle is difficult to determine by a scanning EDAX analysis of the area due to the inhomogeneous nature of the freckle. However, careful adjustment of successive analysis windows [13] indicates a value of between 12.5 and 13%Nb for the lower part of the freckle which is assumed to represent the liquid initially flowing before substantial dilution by dendrite solution has taken place. The lower Nb content values reported represent the average content of the area covered by the disturbed structure between the points at which the regular dendritic structure can be observed. The value of 11–13%Nb corresponds to the liquid composition at a fraction solid of 0.6–0.7% in IN718 [14]. This latter value has a permeability coefficient which then is too small to permit significant flow under the calculated gravity-driven negative buoyancy. In consequence, it is clear that a freckle can form once flow starts and dissolves a small section of the dendrite network, but in a regular dendrite array such as the ones typically found in remelt ingots, it is unlikely for substantial flow to spontaneously start under the negative buoyancy force in the solidification structure present at $0.6 < Fs < 0.7$.

The negative buoyancy arising from the gravitational effect of the density gradient in the interdendritic liquid varies considerably from alloy to alloy. Figure 2 illustrates computed values for the liquid density in several Nb-containing alloys. It can be seen that the largest values are those for IN718, which (as found in practice) is hence very freckle-sensitive. IN625 is less so, but IN706 presents almost zero density change during solidification and should not freckle. However, IN706 has been found to produce freckled ingots (Fig. 3) [15] in both ESR and VAR ingots when melted under conditions which were not substantially different from normal freckle-free production values.

It is observed in practice that ingots produced from ESR furnaces are more likely to contain freckles than those from VAR. The generally accepted reason is that the thermal balance differs between the processes and hence the interdendritic spacings at any given point in the ingot are smaller in VAR than in ESR. However, computations of the thermal gradients in typical ingots of the two processes, when carried out at the same melting rate and same ingot diameter, do not show a very substantial difference in dendritic structure [16, 17]. Both processes should exhibit the same tendency of freckle formation since the permeability of the dendrite network is similar.

Observations of freckling in industrial ingots show two features that must also be explained by the model. First, freckling exhibits a degree of randomness with occasional ingots showing a small number of freckles distributed at various points in the ingot's vertical growth. Second, the freckle trail is often seen to follow the isotherm pattern rather than being consistently at a lesser angle to the growth direction as required by the model.