SOLIDIFICATION PROCESS CONTROL FOR ADVANCED SUPERALLOYS

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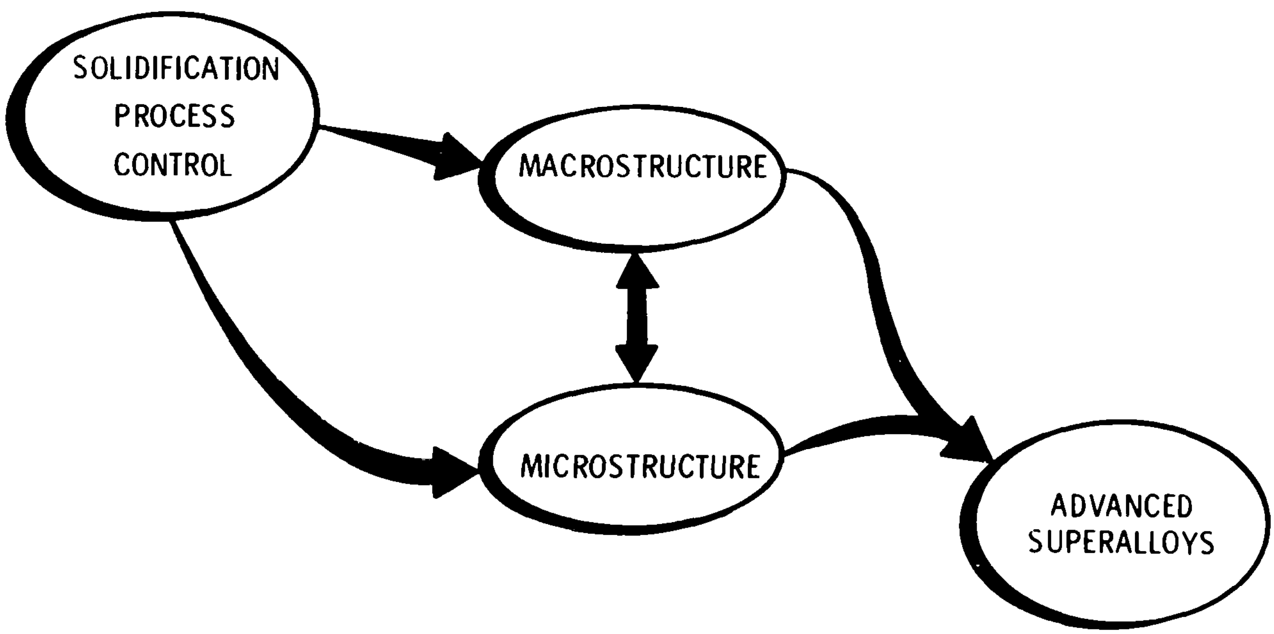
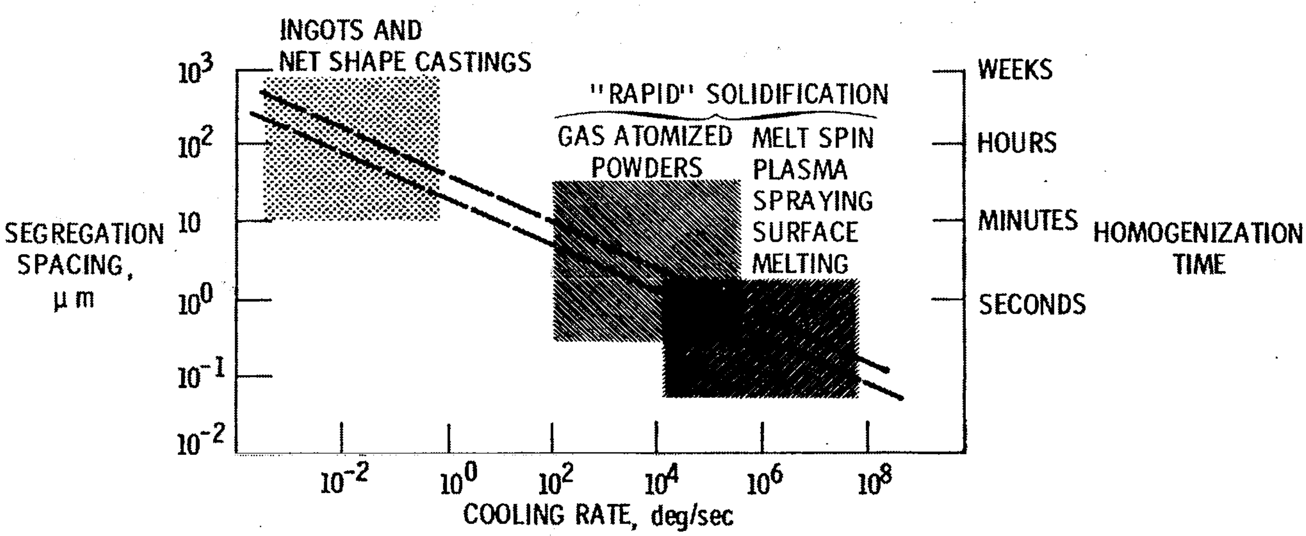
Advances in performance and reduction in fuel consumption in aircraft gas turbines have, in the past, been the result of advances in both design techniques and high temperature alloy technology. The alloys used in the hotter sections are nickel-base superalloys which have undergone remarkable growth in use temperatures (~ 1500 to ~ 1800^{o}F) during the three decades of jet turbine transport. In this presentation we will show the importance of understanding and controlling the basic solidification process. Resultant tailoring of the superalloy macro- and microstructure offers significant potential for continued advances in superalloy use temperatures in turbine engines.



SOLIDIFICATION PROCESS CONTROL FOR ADVANCED SUPERALLOYS

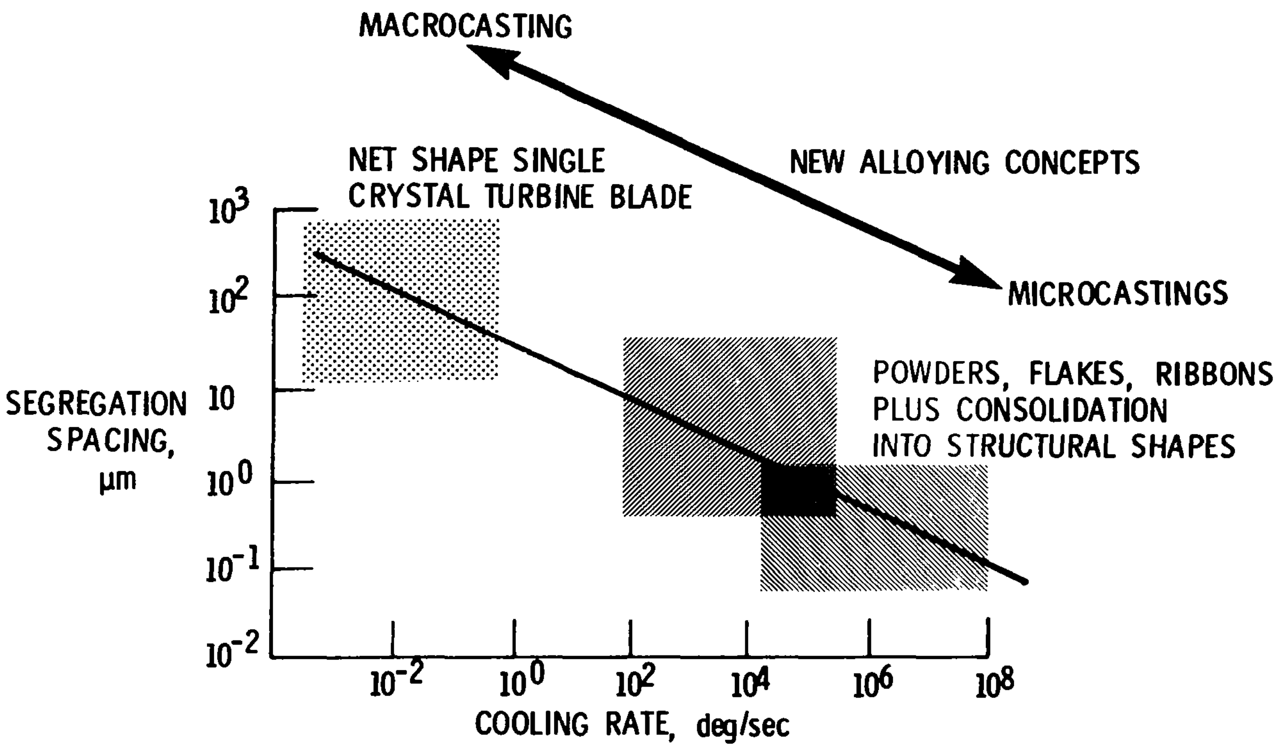
An important parameter in cast metals relates to the segregation spacing of chemical alloying elements. Segregation may lead to inferior mechanical properties and as the spacing becomes large, long times at high temperatures are required to homogenize the castings. If the segregation spacing is reduced then shorter, lower temperature, more economical processes become possible and properties are improved. The segregation distance is a strong function of the solidification rate (ref. 1). The segregation spacing varies from several millimeters (mm) in ingot castings with cooling rates of a few degrees per minute to 10^{-1} micrometers (μm) for surface melted material solidified at about 10^7 degrees per second. The slope of the linear relation between segregation spacing and cooling rate varies somewhat for various alloy systems and even varies slightly for different alloy compositions within the nickel-base superalloy family. Advanced superalloys are being investigated throughout the aerospace industry covering a broad range of solidification rates.



(ADAPTED FROM MEHRABIAN)

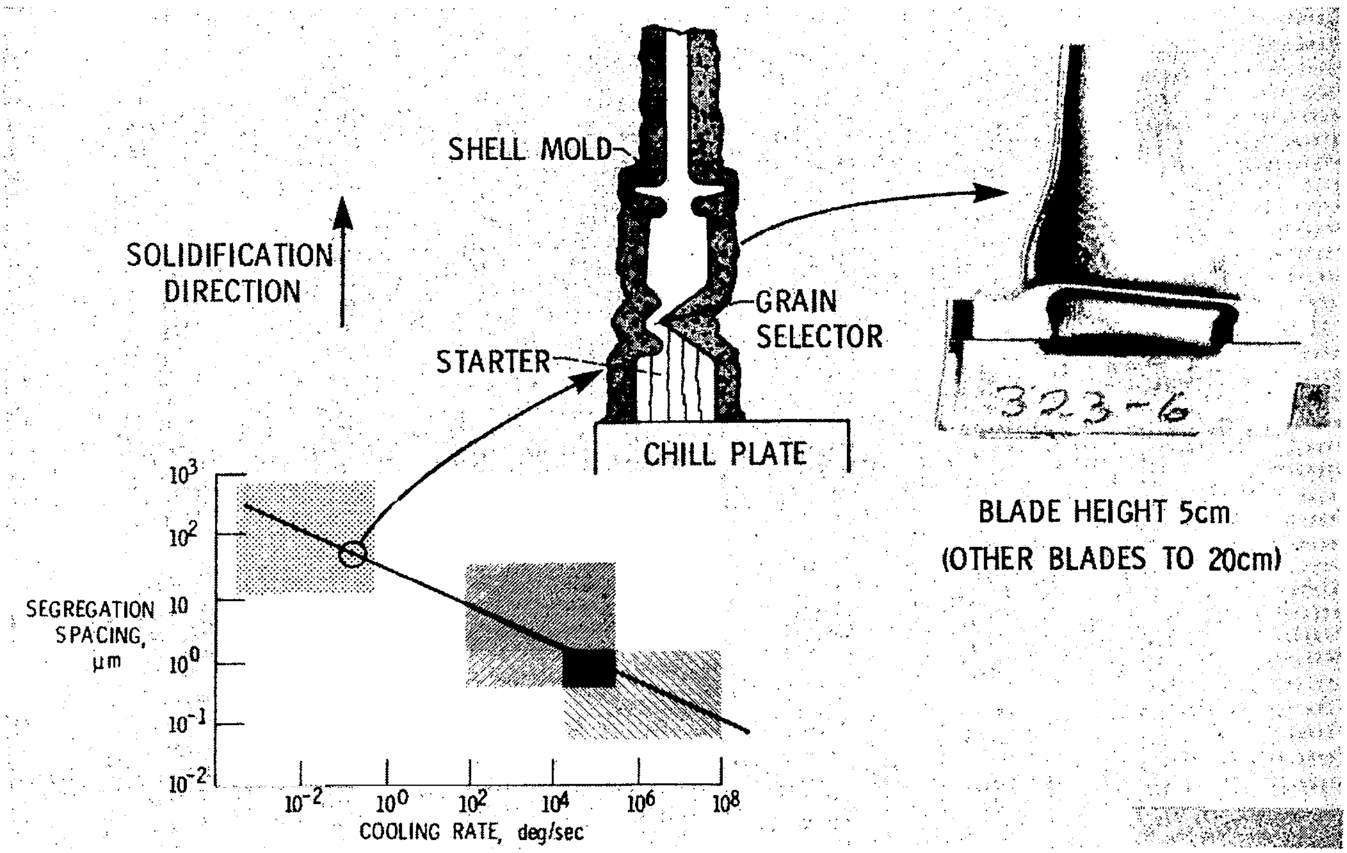
NEW ALLOYING CONCEPTS

In order to fully exploit the advantages offered by controlling the solidification process and rate, one must apply appropriate alloying concepts. In some cases solidification control permits the use of new alloying concepts. In this presentation we shall briefly describe programs at the Lewis Research Center in single crystal turbine blades, powder metallurgy turbine components and the recently initiated program concerned with rapidly solidified flakes and ribbons. These programs span the solidification rate spectrum and range from net shape MACROCASTINGS to extremely small MICROCASTINGS which then must be consolidated into usable structural components.



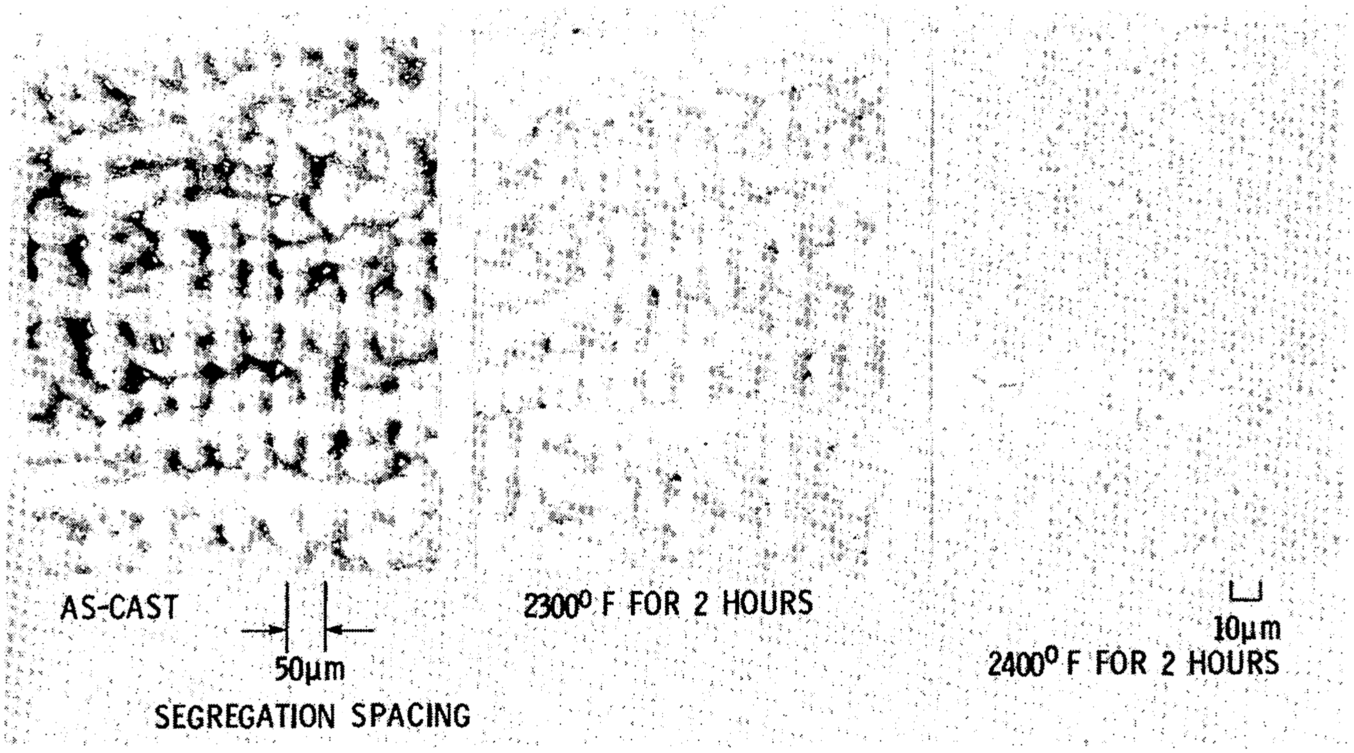
SINGLE CRYSTAL TURBINE BLADES

Single crystal turbine blades are cast by causing solidification to occur in a unidirectional manner and by using a geometrical restriction to allow only one grain to grow from the starter to the blade. The unidirectional solidification is accomplished by casting on a water cooled chill plate which causes the heat flow to be directional into the plate. This process typically results in rather low solidification rates in the order of 10^{-1} degrees per second. Both solid and air-cooled turbine blades in a large range of sizes are currently being evaluated for or are in use in turbine engines (refs. 2 and 3).



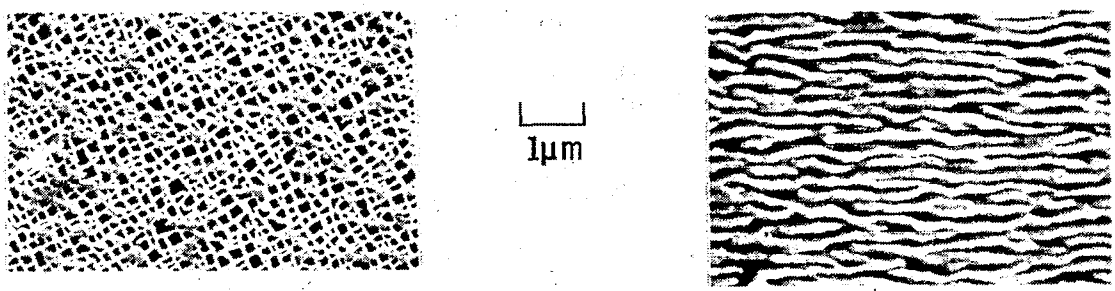
SINGLE CRYSTAL SUPERALLOYS
MICROSTRUCTURAL HOMOGENEITY THROUGH COMPOSITIONAL ADJUSTMENT AND HEAT TREATMENT

The casting process used to produce single crystal superalloys results in segregation spacings of about 50 μm. In order to produce optimum mechanical properties this chemical segregation is reduced through the use of high temperature heat treatment. It can be seen that 2 hours at 2400^{o}F results in good homogeneity for the alloy shown while after 2 hours at 2300^{o}F considerable casting segregation remains (ref. 4). In order to allow the single crystal superalloys to be annealed at these high temperatures without melting, it is necessary to alter their chemical compositions to raise the melting points. A typical nickel-base superalloy may contain 15 Cr, 10 Co, 5(Mo+W), 7 (Al+Ti), and 0.02-2(B, C, Hf, Zr)(all in weight percent). However, for single crystals, alloying elements such as B, C, Hf, Zr which are melting point depressants are removed, thus permitting heat treating at higher temperatures without melting. It should also be noted that, since the traditional role of these alloying elements is to strengthen the grain boundaries of polycrystalline nickel-base superalloys, they are indeed unnecessary for single crystal alloys.



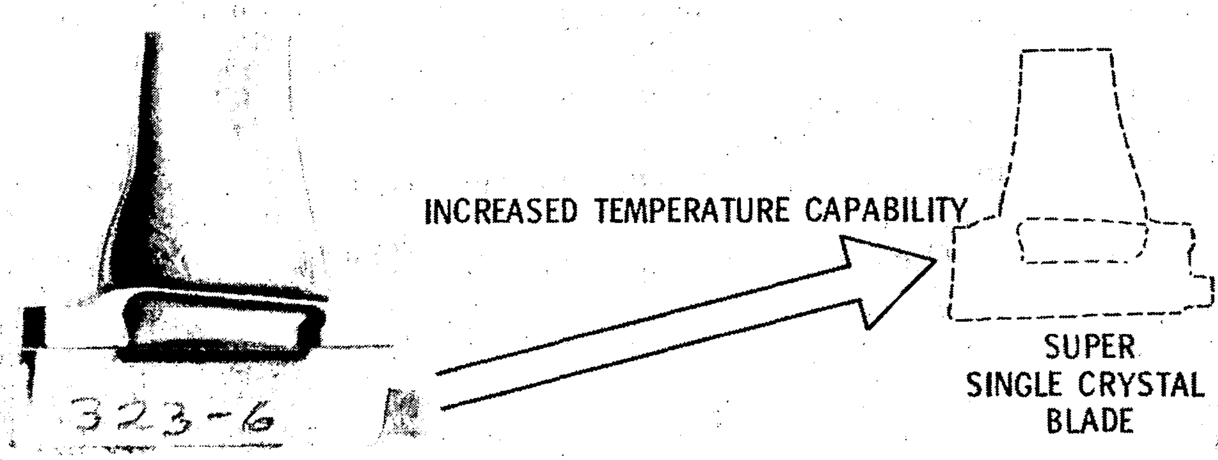
SINGLE CRYSTAL SUPERALLOYS
INCREASED STRENGTH BY CONTROL OF FINE MICROSTRUCTURE

High temperature strength improvements have been achieved in single crystals by careful control of the fine microstructure. Specifically, achievement of the very homogeneous composition described in the previous figure now permits precise control of the size and amount of the gamma prime (γ') phase which is the strengthening phase in nickel-base superalloys. Up to 60 volume percent can be precipitated in a fine, controlled network thus providing optimum strengthening. Recent research has shown that the high temperature load carrying capacity of the single crystal superalloys can be further increased by causing the fine γ' phase to form small platelets or "rafts" (ref. 5). Work is currently in progress at the Lewis Research Center on these super single crystals in order to more fully understand the basic phenomena which cause the rafted microstructure.



60% FINE γ' STRENGTHENING PHASE

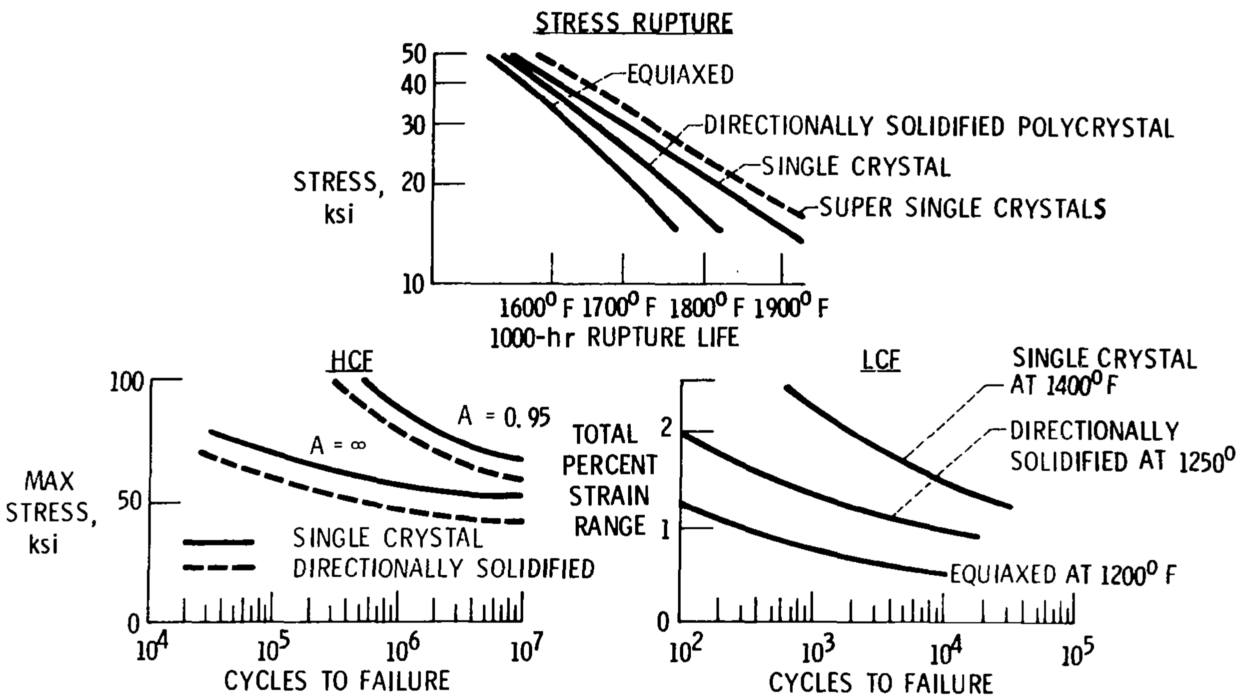
SPECIALLY PROCESSED RAFTED γ'



SINGLE CRYSTAL BLADE

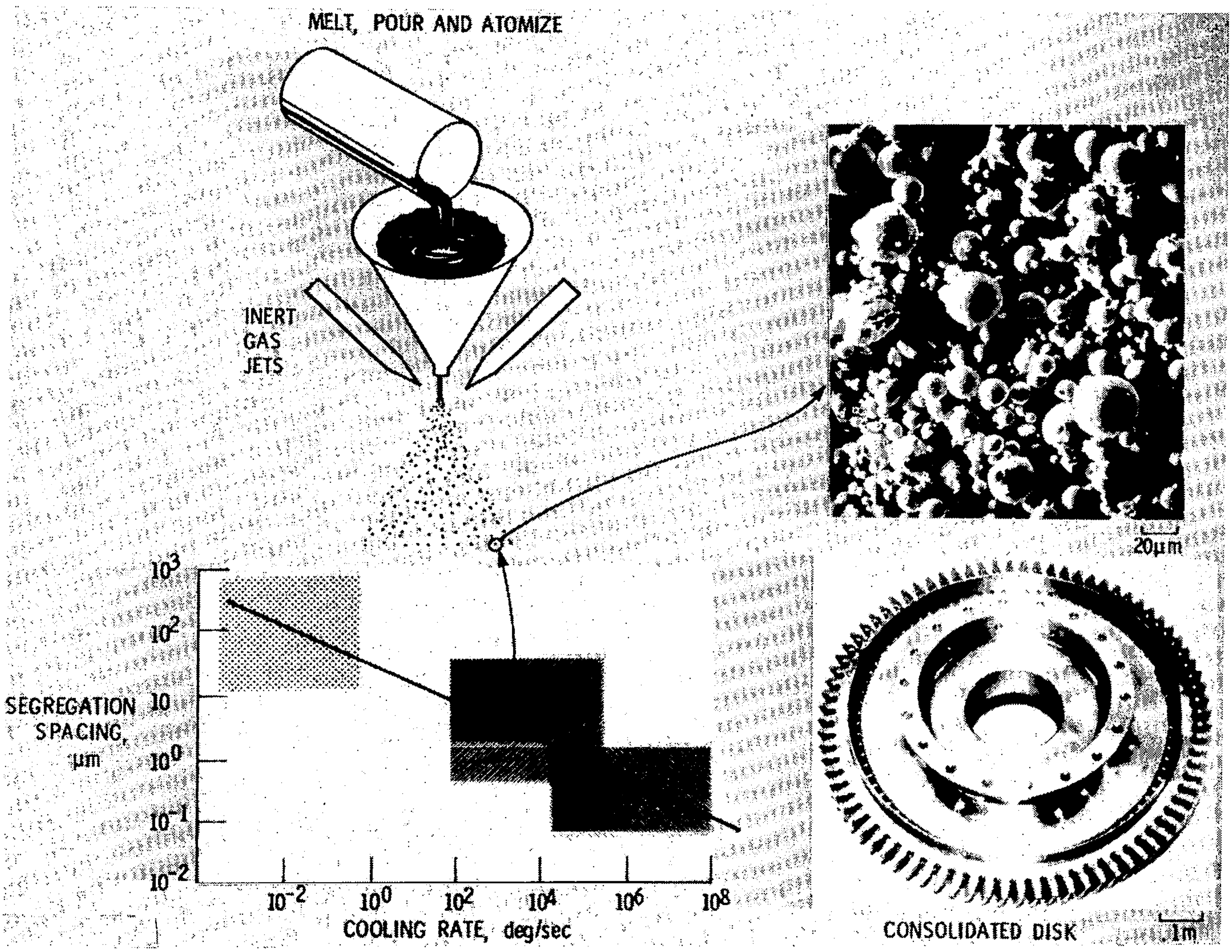
IMPROVED PROPERTIES THROUGH MACRO/MICROSTRUCTURAL CONTROL

The objective of controlling the structure shown in the previous figure has been to increase the capability of the alloys to perform at higher temperatures. In the top figure it can be seen that at a stress of about 25 ksi, the temperature for 1000 hours life is raised from about 1670°F for an equiaxed alloy to about 1800°F for a rafted or super single crystal. Directional solidification and single crystal processing each allowed a 45°F increase in temperature capability. The lower figures show that both the high cycle and low cycle fatigue behavior also benefit from single crystal processing (ref. 3). It is important to recognize that these three mechanical properties and several other mechanical, chemical and physical properties need to be mutually optimized to permit a turbine blade to operate successfully at higher temperatures.



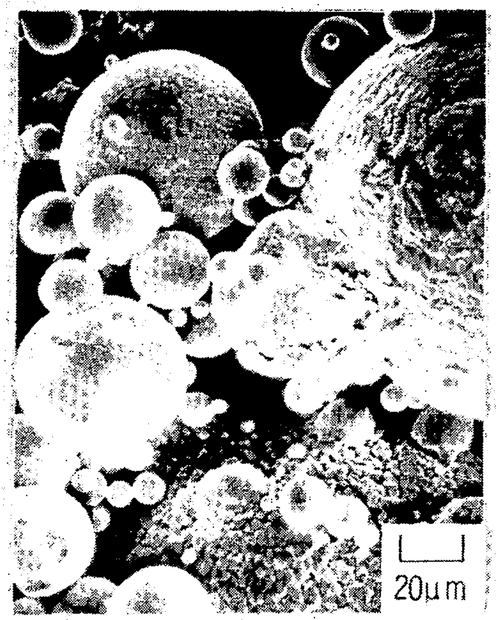
ATOMIZED POWDER TURBINE COMPONENTS

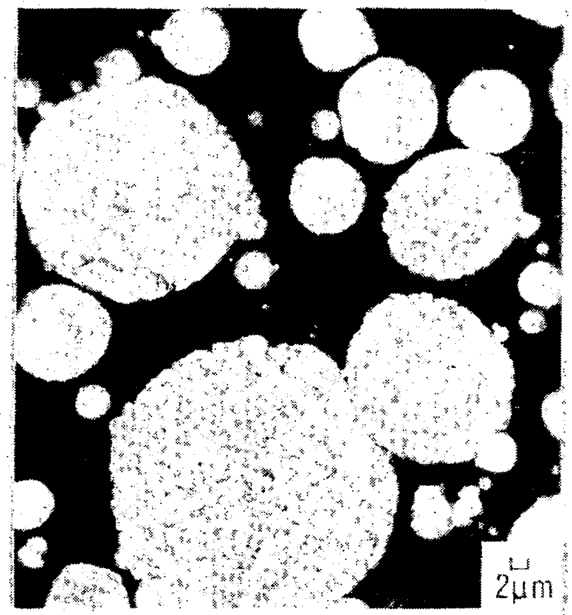
Gas atomized metal powder demonstrates another regime of solidification process control. Superalloys produced by gas atomization processes have been estimated to have solidification rates of about 10^3 degrees per second. The resultant segregation spacing is about 2 μm. As a result it is possible to process alloys having larger amounts of strengthening elements with reduced segregation than through ingot metallurgy and forging. These powders must then be consolidated to a structural shape, such as a turbine disk, as will be discussed subsequently.



ATOMIZED SUPERALLOY POWDER

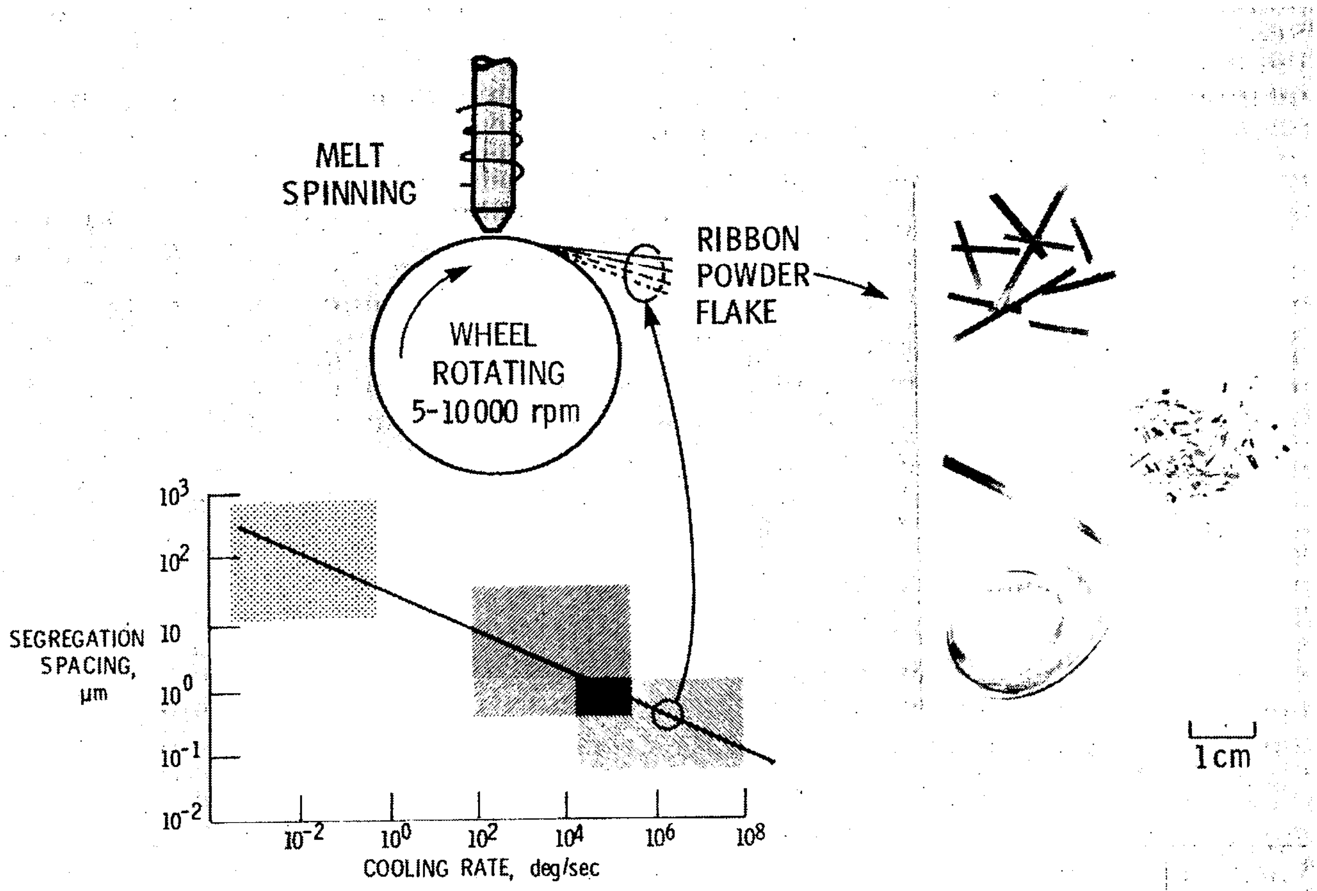
The atomized powder particles are essentially microcastings. The figure shows the cast structure of the powder spheres and illustrates the fine scale of the segregation spacing. The cooling rate and resultant segregation spacing are a function of the particular method of atomization and the particle size. The smaller particles solidified at faster cooling rates. Within reasonable constraints, one can tailor the cooling rate of the material. As was the case with single crystal alloys, it was found beneficial to alter the chemical composition of powder alloys to more fully take advantage of the process. Specifically, the amount of alloying elements such as C and/or Hf is usually reduced in powder superalloys.





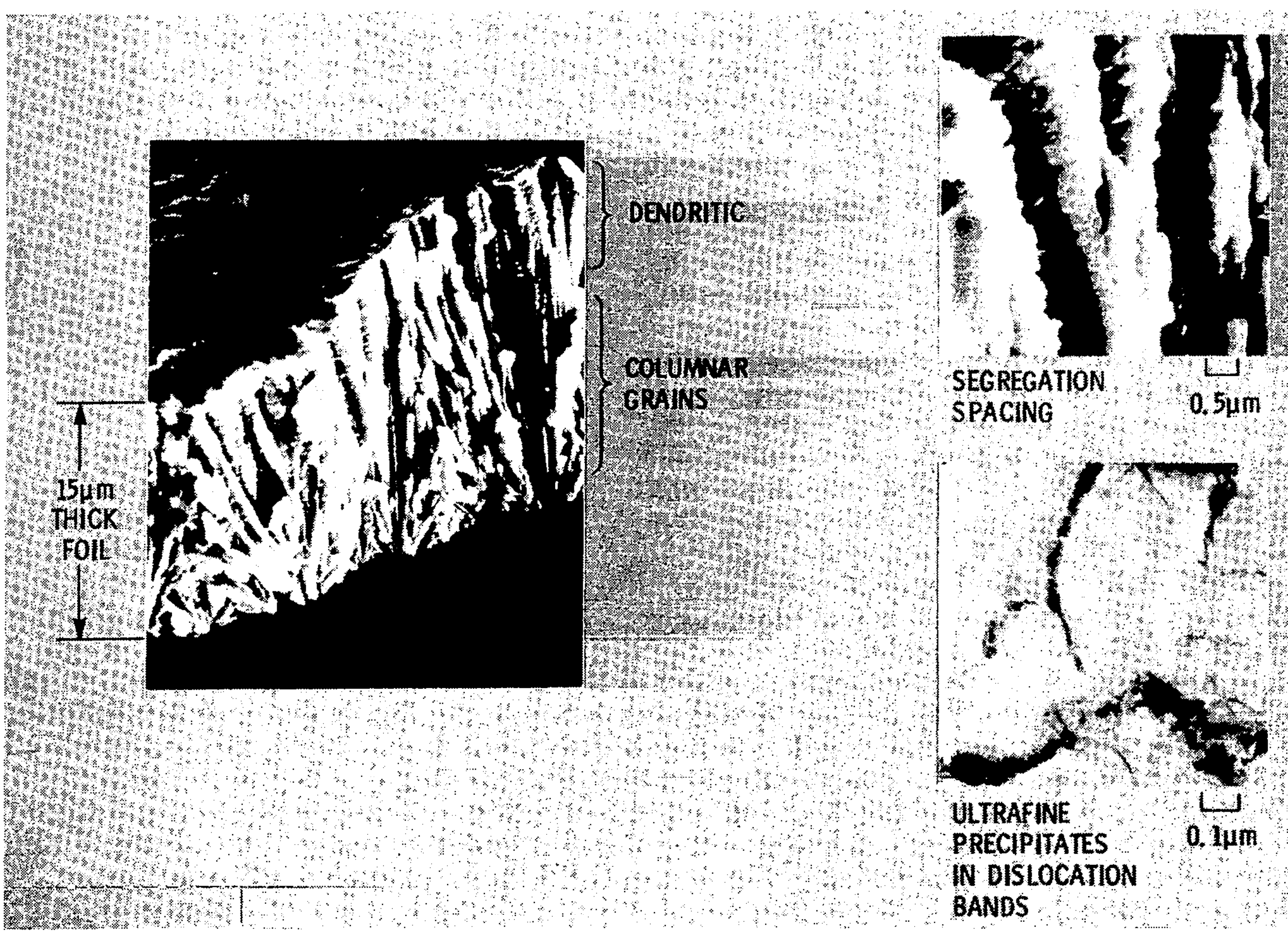
SEGREGATION SPACING

The melt spinning process is capable of solidification rates of about 1,000,000 degrees per second. The superalloy charge is melted in a crucible in a vacuum chamber and then ejected through a hole(s) or slit in the bottom of the crucible by pressurization. The molten metal stream impinges on the surface of a wheel rotating at several thousand revolutions per minute. Wetting conditions and heat extraction rates can be carefully controlled by proper selection of wheel material, surface conditions and temperature. Thus, a variety of microcasting morphologies ranging from fine powder to flake and continuous lengths of ribbon can be produced. A systematic study of the interrelationships between processing variables and the resultant structure of the microcastings is currently under way in a NASA Lewis research program.



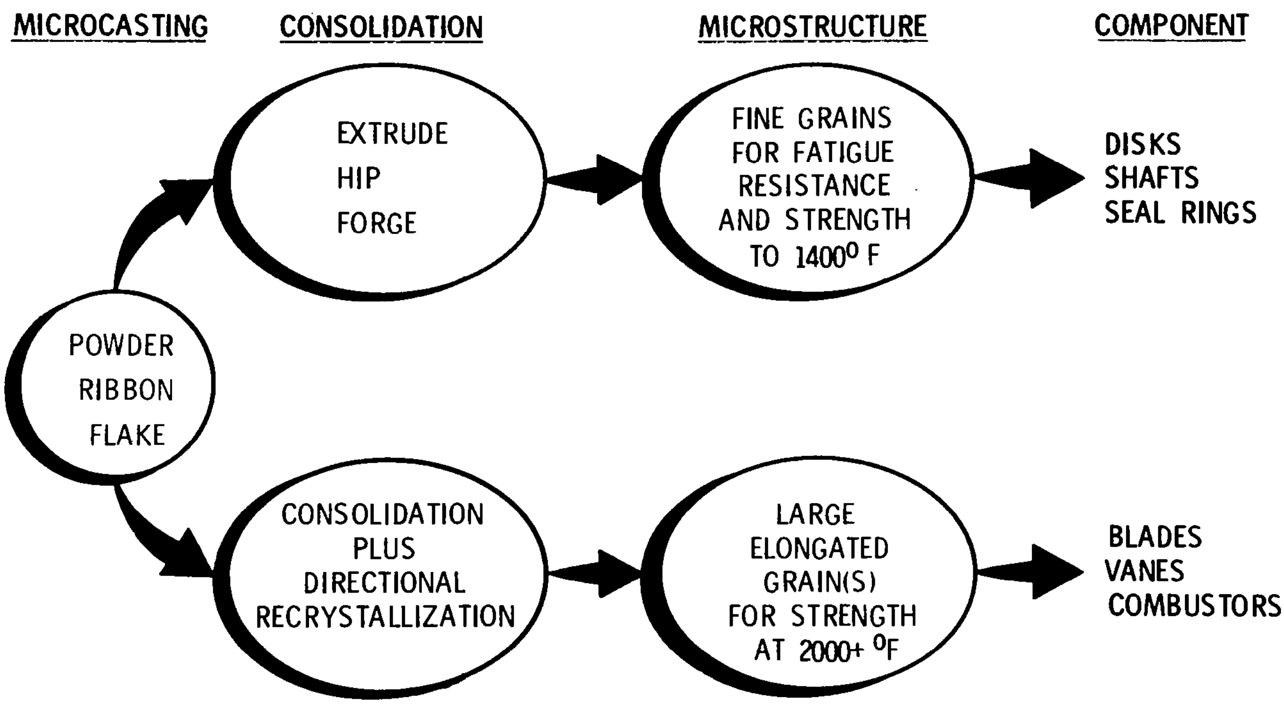
RAPID SOLIDIFICATION PRODUCES ULTRAFINE, UNIQUE MICROSTRUCTURES

A typical nickel-base superalloy, 713 LC, was recently solidified at a wheel surface speed of about 3000 feet per minute in order to produce a relatively thick foil of 15 μm. The cross section of this foil when viewed at high magnification provides a pictorial history of the rapid solidification process. The bottom of the foil which was in contact with the quenching wheel solidified at the fastest rate thus producing fine grains near the bottom surface. These grains gradually transitioned into fine columnar grains in the lower half of the foil and then dendritic grains in the slower cooling upper portion of the foil. However, even the dendritic structure is extremely fine (0.5 μm) because the solidification rate is indeed significantly more rapid than processes described earlier in this paper. Ultrafine precipitate particles are contained in the dislocation tangles as shown in the transmission electron micrograph taken at 70,000x. Thinner foils representative of only the lower columnar grain portion of this foil have been produced simply by quenching onto a wheel rotating at a faster speed. Entirely new classes of alloys with extended solid solubilities and metastable phase strengthening concepts are being evaluated in our current program.



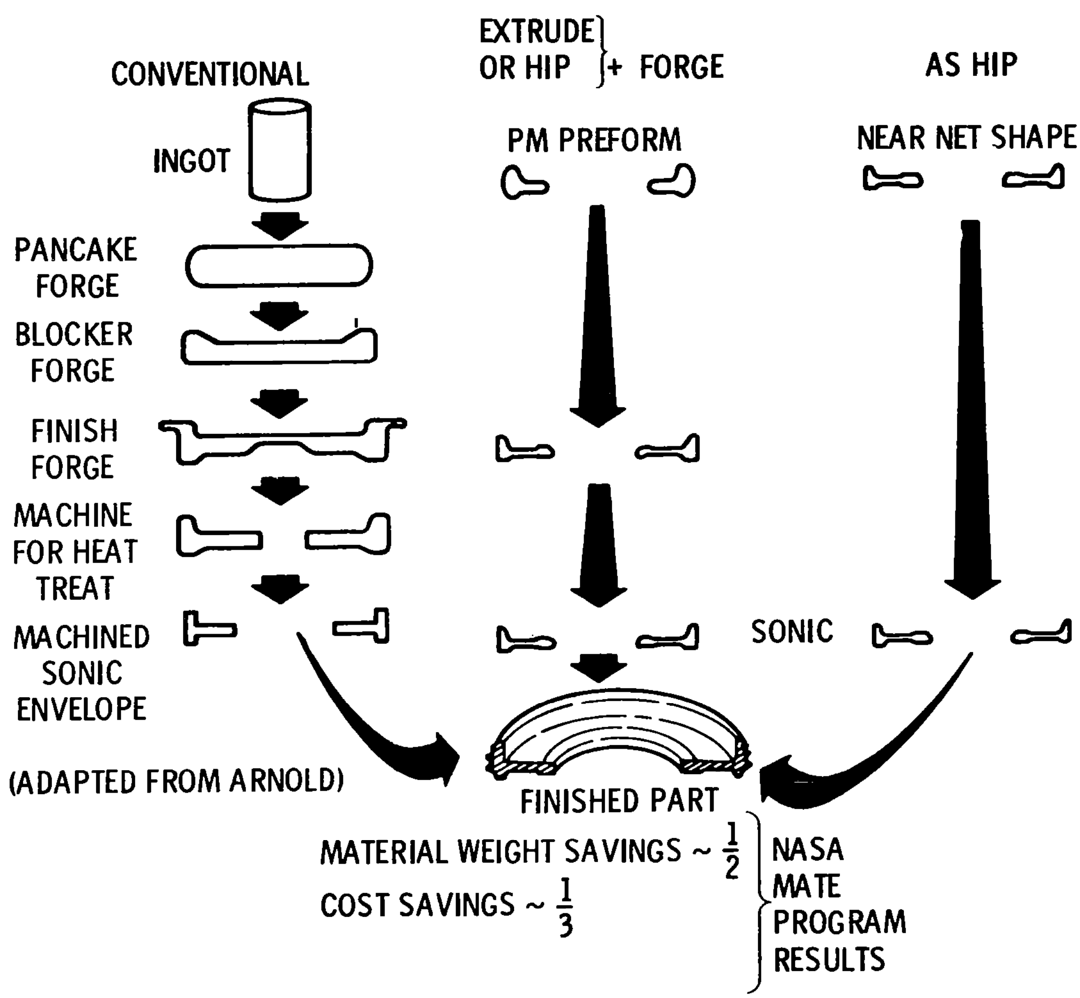
RAPIDLY SOLIDIFIED SUPERALLOY TURBINE COMPONENTS

As discussed previously, all of these rapid solidification processes are designed to produce microcastings of various controlled sizes and morphologies -- powder, flake, or ribbon. It is essential that these microcastings be consolidated for their eventual use as structural materials. Control of the macro/micro-structure of these materials during and after consolidation is critically related to their intended application. Consolidation processes may include extrusion, hot isostatic pressing (HIP) and/or isothermal forging. Each of these processes will produce a microstructure consisting of fine, equiaxed grains which is ideal for high-strength and high-fatigue-resistant turbine applications up to about 1400°F, such as disks, shafts and seal rings. However, if the desired application is intended for higher use temperatures, such as blades, vanes, or combustors, the consolidated microcastings must be subjected to an additional process called directional recrystallization. This process converts the fine grains to large, elongated grains necessary for strength at 2000+°F.



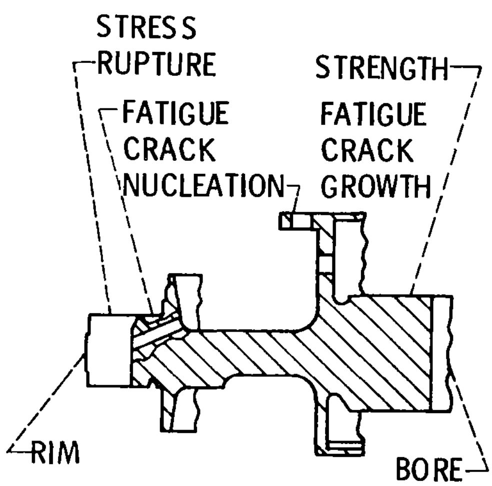
POWDER SUPERALLOYS CONSERVE MATERIALS AND DOLLARS

The conventional process of producing turbine disks from cast ingot materials involves a substantial number of forging steps, heat treating steps, and a lot of machining (ref. 6). The ratio of the initial materials input weight to final component weight may range from 10:1 to 20:1 depending on the actual configuration of the turbine disk. Obviously large amounts of expensive and strategic metals as well as huge amounts of energy are consumed in such conventional processing. Powder metallurgy processing permits significant savings in quantities of starting materials, energy consumption, and amount of machining time and chips. Powders have been consolidated by extrusion or HIP followed by isothermal forging to near net shape. Alternatively powders have been consolidated by HIP directly to net sonic shape. Several recent NASA MATE (Materials for Advanced Turbine Engines) programs have demonstrated input material weight savings of ~ 1/2 and cost savings of ~ 1/3 relative to conventional processing (refs. 7 to 9).

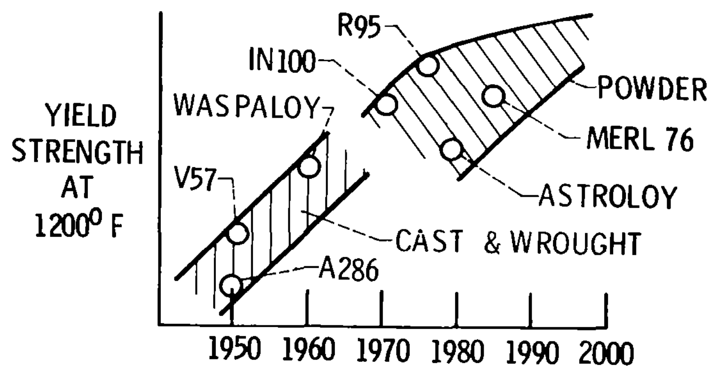


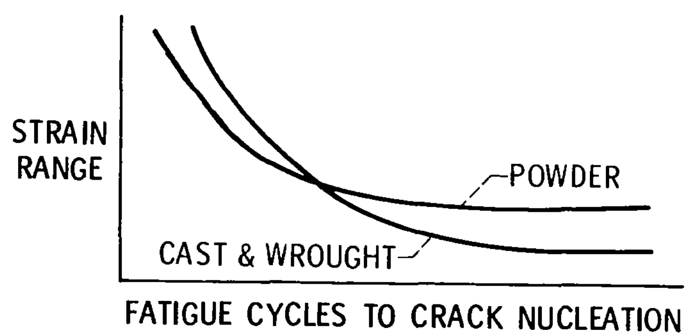
POWDER SUPERALLOYS KEY TO ADVANCED DISKS

In addition to material and cost savings, powder metallurgy processing offers a unique opportunity to solve current problems and provide for future advancements in disk operating conditions. Turbine disks operate over a wide range of temperatures, up to ~ 800°F near the bore and up to ~ 1400°F at the rim. Yield strength, stress rupture strength, and resistance to fatigue crack initiation and propagation are the critical mechanical property requirements for disks. Significant improvements have been achieved in increasing strength and resistance to fatigue crack initiation via powder metallurgy because the microcastings contain a greater amount of and a more uniform distribution of strengthening phases in their microstructure. However, the crack propagation characteristics of these high-strength alloys are relatively poor. A current Lewis Research Center research program (refs. 10 to 12) is focused on a basic understanding of the relations between alloy processing - microstructure - crack propagation behavior of these materials in order to increase the cyclic life of turbine disk alloys.



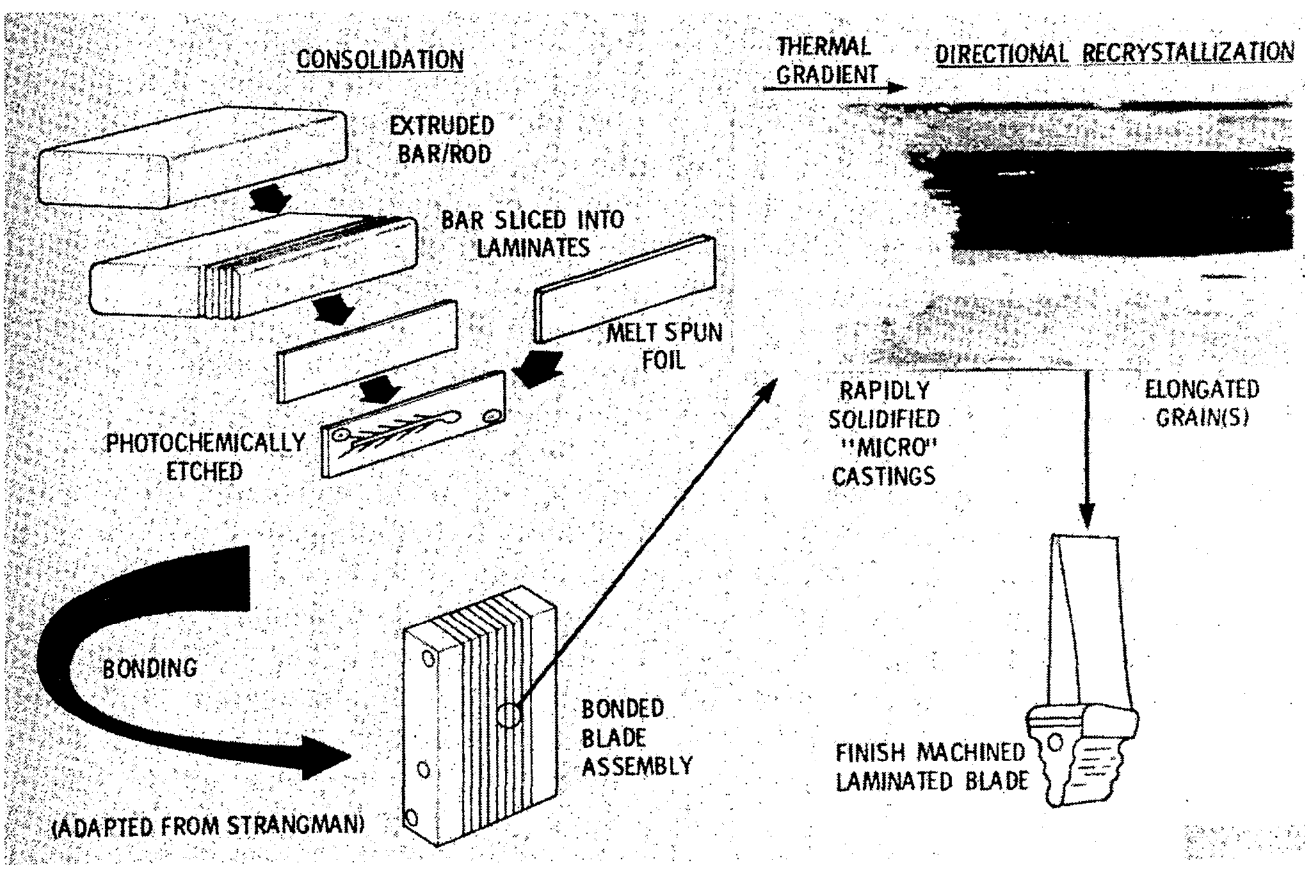
PROPERTY REQUIREMENTS FOR TURBINE DISKS





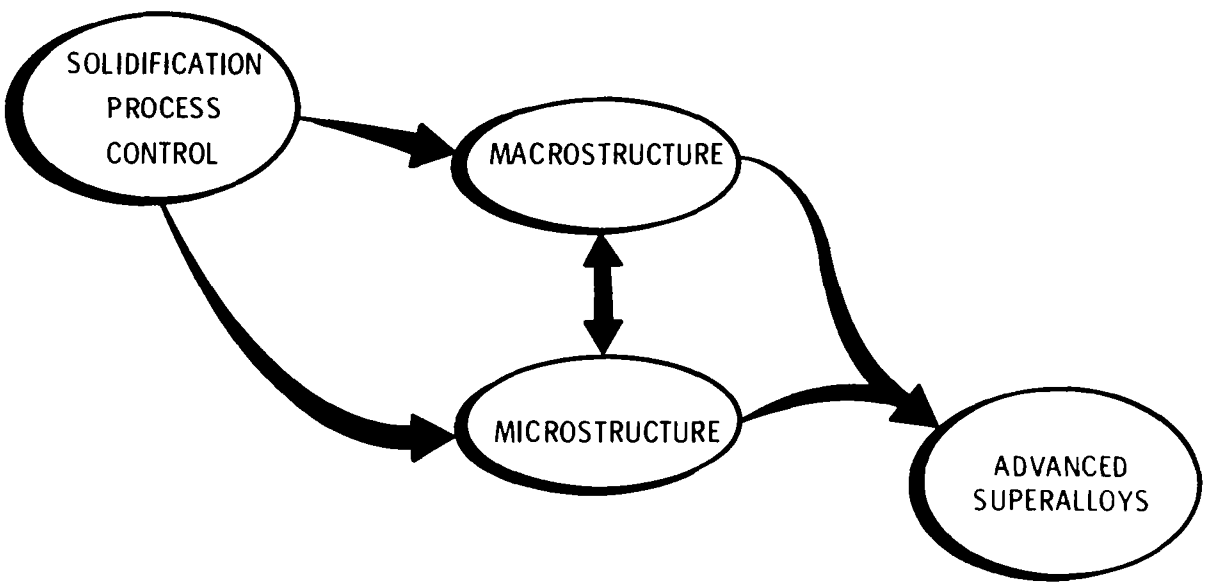
RAPIDLY SOLIDIFIED SUPERALLOYS HAVE POTENTIAL FOR HIGH-TEMPERATURE APPLICATIONS

As mentioned previously, rapidly solidified microcastings must not only be consolidated, but must also have their initial fine-grain structure converted to large elongated grains for strength at high temperatures. Powders or flakes can be consolidated by the previously described process of extrusion into bar or rod and then sliced into sheet or laminates (Strangman, T. E., AiResearch Co., private communication), or split blade halves. Alternatively, melt spun foil may be used directly. Complex air cooling passages may be photochemically etched into the laminates prior to subsequent bonding into a blade assembly. The critical step in converting the fine grain into large, elongated grain(s) is called directional recrystallization. The laminates or the bonded assembly are passed through a steep temperature gradient at a slow, controlled rate. This causes the grains to grow in size and parallel to the direction of the thermal gradient. It is even possible to control the process so that only one grain survives, thus resulting in a single crystal produced in the solid state rather than by solidification as described previously.



SOLIDIFICATION PROCESS CONTROL FOR ADVANCED SUPERALLOYS

We have described research programs conducted at or sponsored by the Lewis Research Center which rely on solidification process control to achieve improvements in nickel-base superalloy turbine components. These programs include single-crystal turbine blades, powder metallurgy components, and melt-spun flake or ribbon technology. These programs span the solidification rate spectrum and result in net-shape macrocastings or extremely small microcastings which then must be consolidated into usable structural components. Continued advances in turbine engine performance and reductions in fuel consumption can be realized by understanding and control of superalloy solidification processing. Concurrent tailoring of superalloy macro- and microstructure offers significant potential for further increases in superalloy use temperatures.



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