Processing of Superalloys

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PROCESS	DESCRIPTION	DIGITAL RESOURCE	SELECTED REFERENCE
Vacuum Induction Melting	Vacuum induction melting is used as the standard melting practice for the preparation of superalloy stock. Raw metallic materials including scrap are charged into a refractory crucible and the crucible is maintained under a vacuum during melting of the charge. Typically, more than 30 elements are refined or removed from the superalloy melt during VIM processing. A final step involves the decanting of the liquid metal from the crucible into a pouring system, and the casting of it into moulds under a partial pressure of argon. [after R. Reed]	"Vacuum Induction Melting", Superalloys: Melting and Conversion, TMS Video Excerpt	R. Reed, "Vacuum Induction Melting of Superalloys", Materials Technology@TMS, www.materialstechnology.org G.L.R. Durber, C.L. Jones, and A.J. Dykes, "VIM + ESR Alloy 718—An Assessment of Chemistry Control, Alloy Cleanliness and Mechanical Properties" Superalloys 1984, pp. 433-442 T V. Satya Prasad and A. Sambasiva Rao, "Electroslag Melting for Recycling Scrap of Valuable Metals and Alloys", Recycling of Metals and Engineered Materials IV, 2000, pp. 503-516
Investment Casting	The investment casting or 'lost-wax' process is used for the production of superalloy components of complex shape, e.g. turbine blading or nozzle guide vanes. A wax model of the casting is prepared by injecting molten wax into a metallic 'master' mold. These are arranged in clusters connected by wax replicas of runners and risers; this enables several blades to be produced in a single casting. Next, an investment shell is produced. Finally, the mold is baked to build up its strength. After preheating and degassing, the mold is ready to receive the molten superalloy, which is poured under vacuum. After solidification is complete, the investment shell is removed and the internal ceramic core leached out by chemical means, using a high pressure autoclave. [after R. Reed]	"A Design Study in Nickel-Based Superalloy Castings", American Foundry Society, On-line Case Study A. Partridge, "Manufacture and Casting of Superalloys", video, University of Cambridge / Firth Rixson, Inc.	R. Reed, "Investment Casting of Superalloys", Materials Technology@TMS, www.materialstechnology.org Mei Ling Clemens, Allen Price, and Richard S. Bellows, "Advanced Solidification Processing of an Industrial Gas Turbine Engine Component", JOM, March 2003, pp. 27-31. M. Konter, E. Kats and N. Hofmann, "A Novel Casting Process for Single Crystal Gas Turbine Components" Superalloys 2000, pp. 189-200. M. Gell, D.N. Duhl, and A.F. Giamei, "The Development of Single Crystal Superalloy Turbine Blades", Superalloys 1980, pp. 205-214. G.E. Fuchs and B.A. Boutwell, "Calculating Solidification and Transformation in As-Cast CMSX-10", JOM, January 2002, pp. 45-48.

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Secondary Melting (Vacuum Arc Remelting / Electroslag Remelting)	For many applications, a secondary melting process needs to be applied to increase the chemical homogeneity of the superalloy material and to reduce the level of inclusions. After VIM processing, it would be normal for the cast ingot to possess a significant solidification pipe and extensive segregation. Removing the pipe reduces productivity and the segregation can lead to cracking and fissuring during subsequent thermal-mechanical working. Furthermore, VIM can leave non-metallic (ceramic) inclusions present in the material which can be harmful for fatigue properties. Application of the secondary melting practices can reduce the problems associated with these effects. Vacuum arc remelting (VAR) or electroslag remelting (ESR) are used for this purpose, sometimes in combination with each other. [after R. Reed]	"Vacuum Arc Remelting", Superalloys: Melting and Conversion, TMS Video Excerpt James A. Van Den Avyle, John A. Brooks, and Adam C. Powell, "Reducing Defects in Remelting Processes for High-Performance Alloys", QuickTime Clips, JOMe	R. Reed, "Secondary Melting Processes for Superalloys", Materials Technology@TMS, www.materialstechnology.org L.A. Bertram, P.R. Schunk, S.N. Kempka, F. Spadafora, and R. Minisandram, "The Macroscale Simulation of Remelting Processes", JOM, March 1998, pp. 18-21. Mei Ling Clemens, Allen Price, and Richard S. Bellows, "Advanced Solidification Processing of an Industrial Gas Turbine Engine Component", JOM, March 2003, pp. 27-31. D.K. Melgaard, R.L. Williamson, and J.J. Beaman, "Controlling Remelting Processes for Superalloys and Aerospace Ti Alloys", JOM, March 1998, pp. 13-17. Laurentiu Nastac, Suresh Sundarraj, Kuang-O Yu, and Yuan Pang, "The Stochastic Modeling of Solidification Structures in Alloy 718 Remelt Ingots", JOM, March 1998, pp. 30-35

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Conversion: **Cogging and Homogenization**	The superalloy ingots produced by the remelting processes are unsuitable for mechanical applications: they must undergo thermal-mechanical working in order to break down the as-cast structure and to reduce the grain size to acceptable levels. This is known as ingot conversion. During this process, the diameter of the cylindrical ingot is reduced in size by a factor of approximately two. The conversion is generally achieved in a series of stages, or heats. The ingot is placed in a furnace. Upon removal, forged or cogged. Typically the ingot is deformed twenty to thirty times at various points along its length, with the pattern repeated with the ingot rotated. The deformation applied to the ingot causes substantial recrystallization to a finer grain structure. After reheating the whole process is repeated. (after R. Reed)	"Conversion", Superalloys: Melting and Conversion, TMS Video Excerpt "Homogenization", Superalloys: Melting and Conversion, TMS Video Excerpt	R. Reed, "Thermal-Mechanical Working of Superalloys", Materials Technology@TMS, www.materialstechnology.org Robin M. Forbes Jones and Laurence A. Jackman, "The Structural Evolution of Superalloy Ingots during Hot Working", JOM, January 1999, pp. 27-31 B. F. Antolovich and M.D. Evans, "Predicting Grain Size Evolution of UDIMET® Alloy 718 during the "Cogging" Process through Use of Numerical Analysis", Superalloys 2000, pp. 39-47. C.A. Dandre, C.A. Walsh, R.W. Evans, R.C. Reed and S.M. Robe, "Microstructural Evolution of Nickel-Base Superalloy Forgings During Ingot-to-Billet Conversion: Process Modeling and Validation", Superalloys 2000, pp. 85-94.

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PROCESS	DESCRIPTION	DIGITAL RESOURCE	SELECTED REFERENCE
Powder Metallurgy	The need for powder metallurgy (P/M) first arose for the production of some high-integrity superalloy components such as turbine discs. P/M is an expensive processing route but it is used for producing heavily alloyed alloys with acceptable chemical homogeneity. Powder metallurgy is used only for alloys which will be used in fatigue-critical applications - for example turbine discs which are spinning very fast in the engine.The first step in the production of P/M product is inert gas atomization from master melts produced by VIM processing. Consolidation of the powder usually involves processing by extrusion. The powder is first packed into a steel container which has been cleaned carefully. This is evacuated to encourage outgassing, sealed and then compacted either by hot isostatic pressing (HIPing) or occasionally using closed die forging. Isothermal forging - in which the billet is deformed at the same temperature as the dies, both being held in a well-instrumented furnace - is the preferred route by which P/M superalloy product is shaped after powder consolidation. [after R. Reed]	"Discrete Element Method Animations - Powder Metallurgy", GPM2 Laboratory, animations "Designing for Powder Metallurgy", Metal Powder Industries Federation Video Clips	R. Reed, "Powder Metallurgy and Superalloys", Materials Technology@TMS, www.materialstechnology.org J. Huez, J-L. Noyes, F. Pouey, and J-F. Uginet, "Improvement of a Powder Generation Turbine Disc Process Using a Finite Element Model Incorporating Metallurgical Parameters", Superalloys 718, 625, 706, and Derivatives, 2001, pp. 203-211. C. P. Blankenship Jr., M. F. Henry, J. M. Hyzak, R. B. Rohling, and E. L. Hall, "Hot-Die Forging of P/M Ni-Base Superalloys", Superalloys 1996, pp. 653-662 S.K. Jain, B.A. Ewing and C.A. Yin,"The Development of Improved Performance PM UDIMET® 720 Turbine Disks", Superalloys 2000, pp. 785-794. G. E. Maurer, W. Castledine, F. A. Schweizer, and S. Mancuso, "Development of HIP Consolidated

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PROCESS	DESCRIPTION	DIGITAL RESOURCE	SELECTED REFERENCE
Spray Forming/Casting	The typical spray forming/casting process begins with vacuum-induction melting. The molten metal is then delivered to a tundish and metered from the tundish through a controlled orifice or nozzle. This metered alloy stream is then "atomized" nto very fine droplets by high-purity argon gas impingement. When producing billets, the spray is then deposited onto a preheated carbon steel mandrel, which rotates under the spray. Spray-formed rings can also be produced by spraying onto a rotating mandrel. The spray-formed/cast material may then be HIPed and/or subjected to deformation processing. [after G. A. Butzer]		S Alan Leatham, "Spray Forming: Alloys, Products, and Markets" , JOMe, April 1999 Gregory A. Butzer, "The Production-Scale Spray Forming of Superalloys for Aerospace Applications", JOMe, April 1999 The CMSF Process: The Spray Forming of Clean Metal" (JOM-e: Overview), W.T. Carter, Jr., M.G. Benz, A.K. Basu, R.J. Zabala, B.A. Knudsen, R.M. Forbes Jones, H.E. Lippard, and R.L. Kennedy, April 1999. T. Shifan, Z. Xianguo, R. Liping, L. Zhikai, L. Zhou, M. Guofa, and J. F. Radavich, "Microstructure and Properties of Spray Atomized and Deposited Superalloys", Superalloys 1996, pp. 729-736 H.E. Lippard and R.F. Jones, "Characterization and Thermomechanical Processing of Sprayformed Allvac® 720 Alloy" Superalloys 2000, pp. 151-157.

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PROCESS	DESCRIPTION	DIGITAL RESOURCE	SELECTED REFERENCE
Deformation Processing	Deformation processing of worught superalloys is performed to alter the cross-section of the material as well as to impart the approriate microstructural refinement. Typical processes include forging, hot rolling and ring rolling. Forging can be done in closed dies, where the metal is constrained or in open dies, where it is not. Hot rolling to produce sheet and bar products must be done at very high temperatures with many reheats in between rolling passes. Ring rolling is a forging process used to produce a hollow-centered round forging.	A. Partridge, "Open Die Forging", video, University of Cambridge / Firth Rixson, Inc. A. Partridge, "Ring Rolling Operations", video, University of Cambridge / Firth Rixson, Inc.	A. Kermanpur, S. Tin, P.D. Lee, and M. McLean, "Integrated Modeling for the Manufacture of Aerospace Discs: Grain Structure Evolution", JOM, March 2004, p. 72-78. G. Shen, J. Rollins, and D. Furrer , "Microstructure Modeling of Forged Waspaloy Discs", Superalloys 1996, pp. 613-620. K.H. Schönfeld, B. Donth, M.G. Cambi, S.V. Thamboo, and M.P. Manning, "Manufacturing and Properties of a Large Alloy 706 Disc Made by the Open Die Forging Process", Superalloys 718, 625, 706, and Derivatives, 2001,pp. 185-192. J.M. Moyer, L.A. Jackman, R.S. Minisandram, and T.W. Miles, "Effects of Process Variables on the Structure and Properties of Hot Rolled 718 Bar", Superalloys 718, 625, 706, and Derivatives, 2001,pp. 259-269. Martin C. Mataya, "Simulating Microstructural Evolution during the Hot Working of Alloy 718", JOM, January 1999, pp. 18-26. J. Huez, J-L. Noyes, and J. Coupu , "Three-Dimensional Finite-Element Simulation of Hot Ring Rolling", Superalloys 718, 625, 706, and Derivatives, 2001, pp. 249-258.

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Heat Treatment	The term "heat treatment" when applied to superalloys may mean many different processes, including stress relieval, in-process or full annealing, solution treating, precipitation hardening or diffusion of coatings. In-process annealing may be used after welding to relieve stress or in between severe forming operations. Full annealing is used to obtain a fully recrystallized, soft and ductile structure. Solution treating is done to dissolve second phases so that the additional solute is available for precipitation hardening. Precipitation hardening (also called age hardening) is used to bring out strengthening phases and to control carbides and the topologically close packed phases. Applications of coatings also involve exposures to elevated temperatures.		D.U. Furrer, R. Shankar, and C. White, "Optimizing the Heat Treatment of Ni-Based Superalloy Turbine Discs", JOM, March 2003, pp. 32-34 B.C. Wilson, J.A. Hickman, and G.E. Fuchs, "The Effect of Solution Heat Treatment on a Single-Crystal Ni-Based Superalloy", JOM, March 2003, pp. 35-40.
Coating	Since superalloys are prone to hot corrosion ond oxidation at temperatures below which these alloys are designed to operate, protective coatings of three basic types have been developed: aluminide (diffusion) coatings, overlay coatings and thermal barrier coatings. The aluminide coatings (usually CoAl or NiAl) are formed by a "pack diffusion" method which is a form of chemical vapor deposition. The coatings are protective because of the alumina which forms on the coating but they degrade as that oxide spalls. Overlay coatings, called MCrAlY, where M can be iron, nickel, cobalt or a combination, are two phase coatings, i.e. an aluminide in a ductile matrix. These coatings are more ductile than the aluminide coatings. Ceramic thermal barrier coatings protect by providing insulation to lower the temperature of the superalloy component by 150°C or more A thermal barrier coating system is comprised of a ceramic layer (top coat) over a metallic layer (bond coat). Each coating type has its advantages and limitations.	T. Sourmail, "Coatings for high temperature applications", University of Cambridge	K.A. Ellison, J.A. Daleo and D.H. Boone, "Interdiffusion Behavior in NiCoCrAlYRe-Coated IN-738 at 940° and 1050°C", Supearlloys 2000, pp. 649-654. N.M. Yanar, M.J. Stiger, G.H. Meier and F.S. Pettit, "Processing Effects on the Failure of EBPVD TBCs on MCrAlY and Platinum Aluminide Bond Coats", Superalloys 2000, pp. 621-628. J.A. Thompson, W. Ji, T. Klocker and T.W. Clyne, "Sintering of the Top Coat in Thermal Spray TBC Systems Under Service Conditions", Superalloys 2000, pp. 685-692.