SPRAYCAST-X™ SUPERALLOY FOR AEROSPACE APPLICATIONS

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Abstract

Howmet Corporation licensed and modified the Osprey process to produce aerospace quality nickel based superalloys. The modified process, known as the Spraycast-X™ process, combined vacuum induction melting with high purity argon gas atomization to produce billet and ring shape products. A variety of alloys have been processed, including: IN100, IN713, IN718, René 80, René 125, René 41, René 95, René 88DT, MERL 76, Waspaloy, and AF2-1DA-6. Electron beam melting of spray cast materials revealed excellent cleanliness. Process parameters were established to produce fine grain size (ASTM 6-8) billet up to 10" diameter and ring shape preforms up to 33" in diameter with porosity levels less than 1%. Macrosegregation and formation of gamma prime eutectic was not observed in the spray cast materials. Full density of the spray cast materials was attained via HIP processing and forging. Mechanical properties of spray cast and HIP'ed MERL 76 (no Hf) were comparable to extruded and gatorized IN100. Tensile and stress rupture properties of spray cast and HIP'ed Waspaloy, as well as spray cast and ring rolled Waspaloy, have exceeded the AMS 5707 specification requirements for wrought product.

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Introduction

Over the past twenty years powder metallurgy has provided improvements in materials processing by reducing chemical segregation and allowing thermomechanical processing of alloys which could not be forged as conventionally cast ingot. However, the cost of P/M components has been steadily escalating due to the stringent quality control measures. Finer powder size fractions have been specified to assure that the amount and size of indigenous oxide inclusions and extraneous contaminants be within tolerable size limits.

Recent developments in fine grain ingot technology are making it possible to process high strength gamma prime superalloys without the need for intermediate powder making steps. There are three competitive advanced casting processes for producing fine grain ingot: (a) Microcast-X® [1], (b) Vader® [2], and Osprey [3-5]. Both Microcast-X (Howmet) and Vader (Special Metals) casting processes are capable of producing sound fine grain ingots with typical grain size ranging between ASTM 2 to 4. However, both these processes have an inherent segregation problem, such as eutectic gamma prime phases, either in interdendritic or intergranular areas. These areas typically require extended "superoverage" thermal treatment preconditioning prior to extrusion and/or forging [6]. Consequently, Howmet recognized the need for a new cost effective method of processing fine grain aerospace materials and subsequently entered into a licensing agreement with Osprey Metals, Ltd., Neath, UK, in 1987.

Osprey Process

The Osprey process is similar to the gas atomization process for making powder. However, rather than allowing the droplets to solidify, they are collected and allowed to solidify on a cold substrate to produce a shaped product. The Osprey product is a highly dense, uniform fine grain material and is typically free from macrosegregation without evidence of prior particle boundaries occasionally present in P/M products. A major benefit of the process is the ability to produce highly alloyed compositions without the restriction imposed by segregation in ingot melting which improves hot workability. The advantage over conventional powder metallurgy products is that many of the steps between atomization and consolidation are eliminated, thus reducing not only cost but also opportunity for inadvertent contamination of the powder. The shaped products are suitable for direct use or subsequent thermomechanical processing. This offers an alternative to materials that could not be forged as conventionally cast ingot [7].

Spraycast-X Process

Concern by aerospace customers for the impact of nonmetallic inclusions on mechanical properties led Howmet to the conclusion that, as with superalloy castings, melt processing and subsequent gas atomization should be conducted under vacuum and high purity inert conditions to promote cleanliness. Since Howmet designs and builds its own vacuum casting equipment, the experience of vacuum casting was integrated with the knowledge acquired from Osprey Metals, Ltd. to design and build a pilot spray cast facility capable of processing up to 650 pounds of superalloy at a spray deposition rate of up to 100 lbs/min. The Howmet Spraycast-X process incorporates vacuum induction melting and atomization with a high purity argon gas to produce aerospace quality superalloy product, e.g. billet and ring preforms. Figure 1 shows a process schematic of the system. The basic system consists of two water cooled chambers. The top chamber is a vacuum melting chamber that contains the induction melting furnace, atomizer, and tundish. The lower chamber contains the deposition collector and programmable motion mechanism with rotational and linear travel capability. The current collector chamber is capable of accommodating a rotating mandrel as large as 33 inches in diameter by 20 inches long.

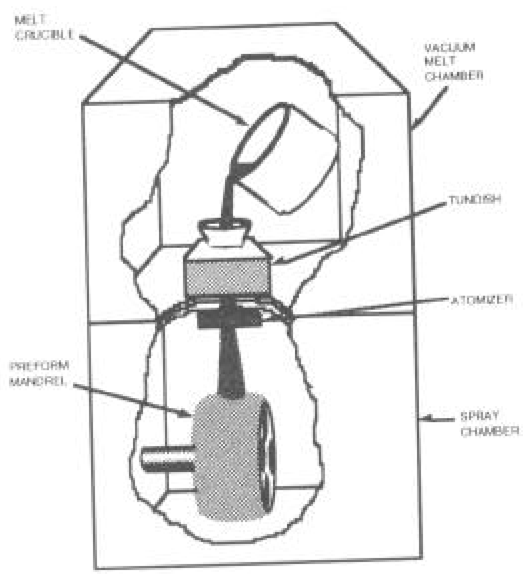
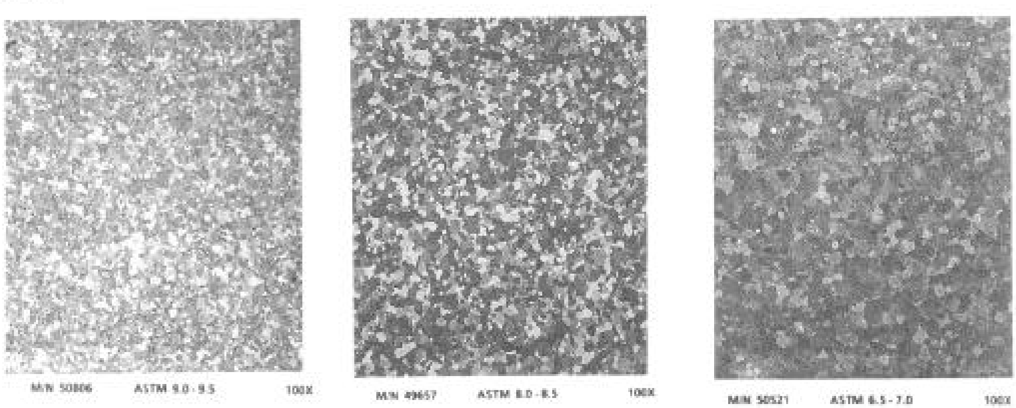


Figure 1 - Schematic of Spraycast-X furnace.

Spraycast-X Process Development

During the past three years Howmet has conducted statistically designed experiments to characterize the Spraycast-X process and to identify the critical processing variables needed to produce high quality billets and rings [8-9]. The initial trials were conducted to produce 6" diameter billet using an 80 pound 50:50 IN713 revert alloy charge and examined the effects of the following parameters: (a) metal flow rates ranging from 20 to 40 lbs per minute, (b) gas pressures from 40 to 150 psi, (c) metal superheat from 100°F to 300°F, (d) spray height from 14 to 24 inches, (e) atomizing gas type (nitrogen and argon), and (f) substrate rotational speed between 100 to 300 rpm. In parallel, statistically designed experiments were conducted to develop a process for ring preforms by investigating the above process parameters, mandrel sizes (12" and 22" diameter), and mandrel reciprocating speeds.

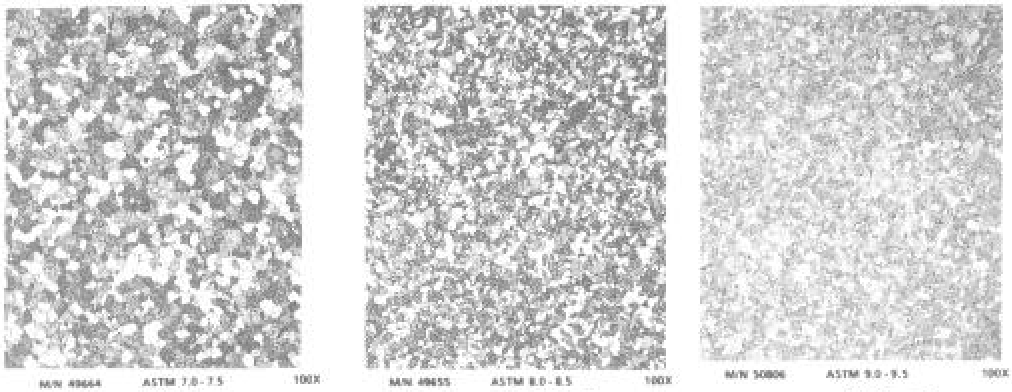
The quality of the billets and ring preforms was measured in four ways: (1) soundness (hot tear), (2) density, (3) grain size, and (4) oxygen and nitrogen content. The most important process variables identified were metal flow rates, atomizing gas pressures, and spray height for both billet and ring preform. For ring preform, both mandrel diameter and mandrel reciprocating speeds also were identified to be critical parameters. Other process variables, e.g., superheat, rotational speed, and atomizer frequency, had only minor effects depending upon the product.



20 lbs/min 30 lbs/min 40 lbs/min

Figure 2 - Effect of metal flow rate on grain size.

The grain size of the spray cast materials increased with the higher metal flow rates (Figure 2) and the lower atomizing gas pressures (Figure 3). Since argon gas has only one half of the heat capacity of nitrogen gas and other factors being equal, atomizing with argon gas generally produced a hotter spray cast deposit, resulting in a larger grain size.



60 psi | 90 psi | 140 psi

Figure 3 - Effect of gas pressure on grain size.

Typical microstructures of as-sprayed IN713 billet consisted of a fine grain, equiaxed nondendritic structure with a grain size ranging from ASTM 7 to 8. The high cooling rates achieved during spray cast processing have avoided the eutectic gamma prime phase typically present in superalloy ingot produced by conventional casting methods. In addition, no prior particle or splat boundaries were evident in the spray cast materials. Argon backfilling was employed after evacuating the system and special seal designs were installed to avoid leakage during operation. The as-sprayed density of the materials processed with argon and nitrogen gas was 98-99% dense. However, the density can vary significantly with both nitrogen and argon gas depending upon the process parameters. The residual porosity in the spray cast materials was isolated and not interconnected. The porosity was eliminated by Hot Isostatic Pressing (HIP), and subsequent thermally induced porosity (TIP) evaluations resulted in porosities less than 0.3% which met the P/M specification requirements.

A variety of commercial superalloys in both cast and wrought compositions have been spray cast processed. Minor differences in alloy responses were observed based on gamma prime content and solidification range. The as-sprayed grain size of higher gamma prime solvus cast alloys was finer than wrought alloys and typically ranged between ASTM 9 and 10. The chemistry of the spray cast superalloy billet and ring products was comparable to the starting ingot, thus indicating no elemental loss during processing (Table I). Due to the short solidification time and incremental deposition of the product, essentially no chemical segregation is observed from the center to surface or from top-to-bottom of the billet.

Starting VIM ingot | Very low leak rate | High leak rate

Figure 4 - EB button cleanliness analysis of Spraycast-X superalloy.

Table I. Chemical Uniformity in Spraycast Materials

Element	MERL 76 (No Hf) Composition Requirements	VIM Heat Howmet 021C18833	Spraycast Billet Top	Spraycast Billet Bottom	Waspaloy AMS 5707G Specificiations	VIM Heat Howmet 49B22580
C	0.015-0.035	0.020	0.021	0.023	0.02-0.10	0.06
Cr	11.50-12.50	11.80	11.81	11.72	18.00-21.00	18.92
Co	17.50-18.50	18.01	18.1	18.05	12.00-15.00	13.53
Mo	2.80-3.60	3.40	3.42	3.33	3.50-5.0	4.12
Cb	1.10-1.50	1.28	1.22	1.24	-	-
Al	4.80-5.15	5.02	5.06	5.08	1.20-1.60	1.33
Ti	4.15-4.50	4.37	4.33	4.47	2.75-3.25	2.93
B	0.016-0.024	0.02	0.016	0.018	0.003-0.010	0.005
Zr	0.04-0.08	0.07	0.06	0.06	0.02-0.08	0.04
Fe	-	-	-	-	2.00 max	1.18
O_2	100 ppm	6 ppm	15	11	-	4
N_2	50 ppm	6 ppm	13	9	-	22
Ni	Bal	Bal	Bal	Bal	-	Bal

Since 1989 Howmet has expended considerable effort to improve the quality of spray cast superalloy product. Both EB button melting and metallographic evaluations of material produced under controlled vacuum leak up rates in the chamber indicated that the undesirable nonmetallic inclusions i.e., oxides and nitrides, in the final product could be reduced by processing under tight vacuum and very low leak up rates (Figure 4). The typical oxygen and nitrogen pickup during processing with argon gas was less than 15 ppm. This suggested that cleanliness equivalent to the starting ingot could be achieved. However, processing with nitrogen gas resulted in a higher residual nitrogen content in the deposits (124 to 564 ppm). The starting IN713 melt stock from Howmet Alloy Division used in these experiments had oxygen and nitrogen contents less than 10 ppm.

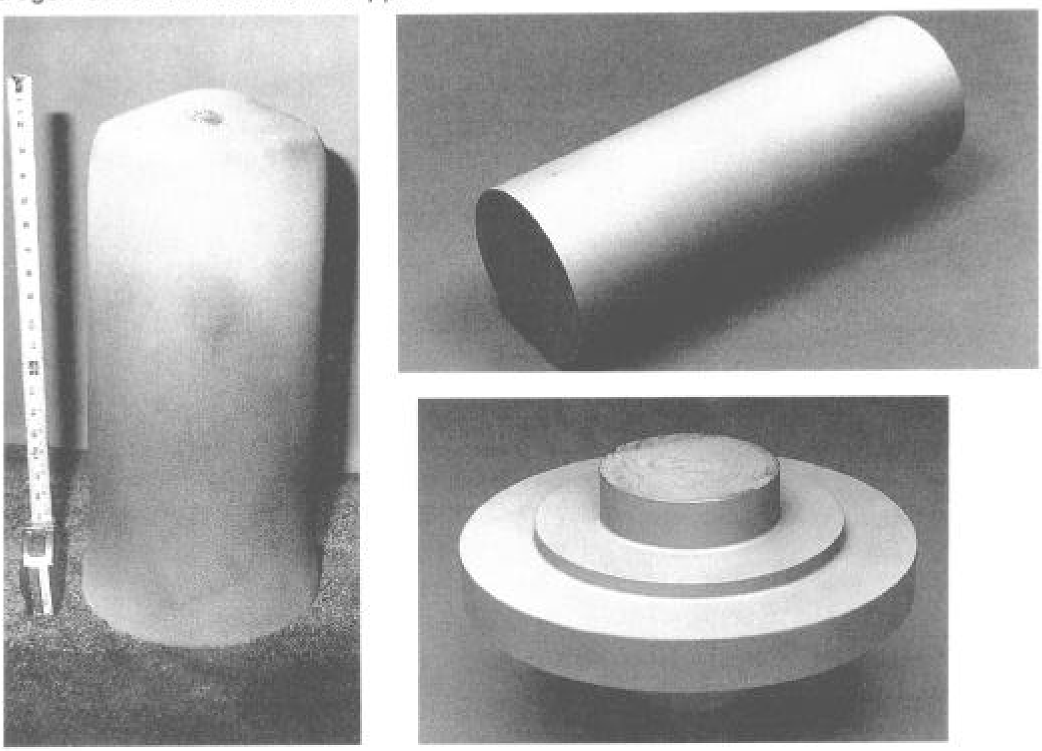


Figure 5 - Spraycast-X MERL 76 (no Hf), extruded forging mult, and turbine disk.

Spraycast-X Applications

Advanced engine design requirements for future turbine components in both military and commercial engines will drive the material selection to higher temperature and less forgeable alloys, e.g., Waspaloy, René 41, MERL 76, U720, René 88DT, and AF2-1DA-6. The Howmet Spraycast-X process has been identified as an alternative process to produce fine grain materials for ring shape components and forged disks. The spray cast process will significantly reduce input material and eliminate several of the current processing steps, resulting in both reduced machining cost and shorter manufacturing lead time. For the past two years Howmet has been working jointly with the major gas turbine engine companies to develop processes and products for jet engine applications.

Turbine Disk Materials

Spray cast processes were developed for 6", 8", and 10" diameter superalloy billets using statistically designed experiments. The average grain size of as-sprayed billets was typically ASTM 6-8 with ASTM 6 at the center of the billet to ASTM 8 at the edge of the billet. Porosity typically was less than 1.0%. A 10" diameter MERL 76 (no Hf) billet was extruded at AMAX using a 6:1 reduction ratio at 2050°F and subsequently isothermally forged into a turbine disk at Ladish. The forged disk is shown in Figure 5. Tensile and stress rupture properties of

Spraycast-X and HIP'ed MERL 76 were comparable to HIP'ed P/M product (Figure 6). Typical microstructures of spray cast MERL 76 showed no gamma prime eutectic nor any presence of grain boundary oxides (Figure 7). Also, 2165°F HIP temperatures did not coarsen the grain sizes in the spray cast material. This is uncommon for wrought counterparts.

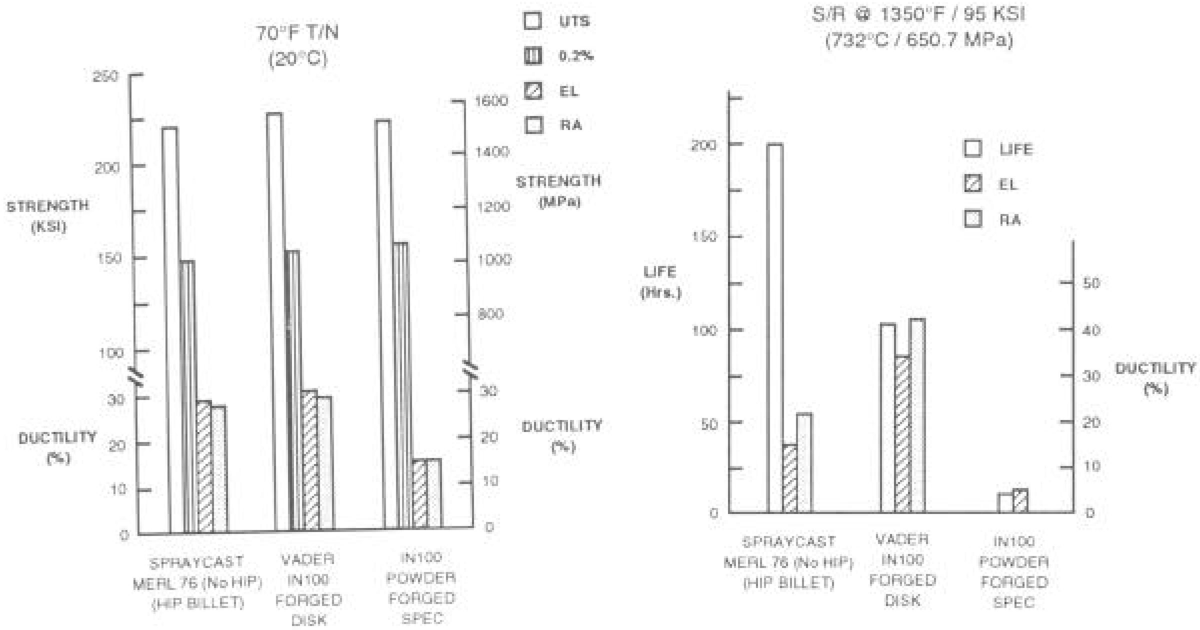


Figure 6 - Tensile properties and stress rupture properties of Spraycast-X + HIP MERL 76 compared to IN100. HIP: 2050°F/3h/15 ksi.
Heat treatment: 2090°F/2h/OQ + 1800°F/1h/AC + 1350°F/8h/AC

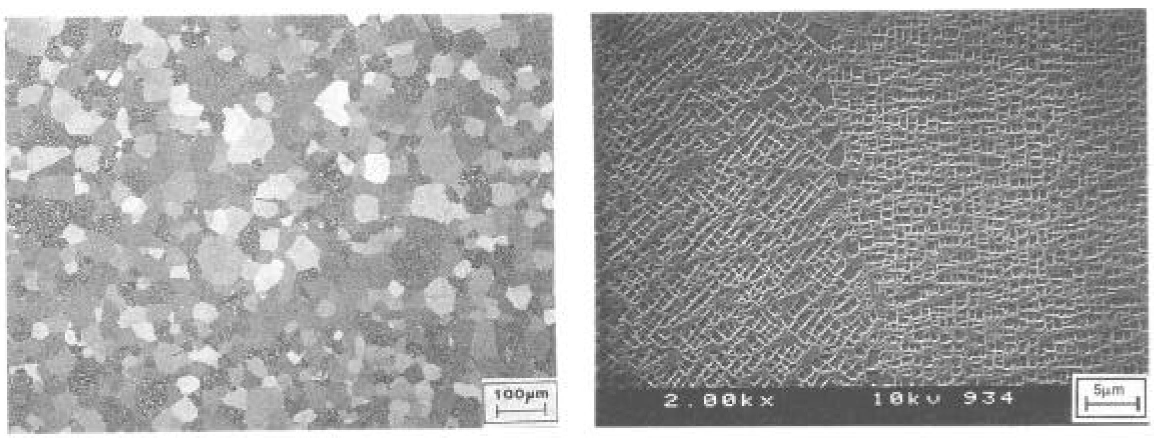
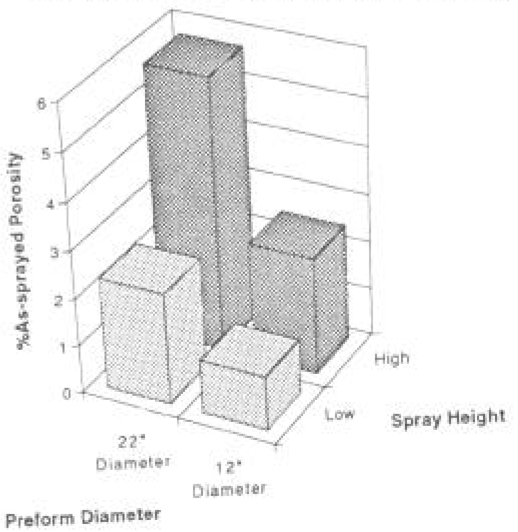


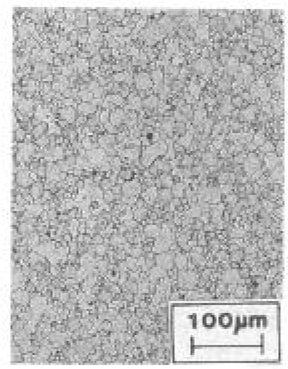
Figure 7 - Microstructure of Spraycast-X MERL 76 in the HIP + heat treated condition.

In addition, 6.75" diameter and 9" diameter spray cast René 88DT billets were produced for forging and mechanical property evaluations. Several thermomechanical processes (TMP), including extrusion and cogging, were investigated to refine the as-sprayed grain size from ASTM 6-8 to ASTM 10-12 to improve ultrasonic inspection sensitivity prior to isothermal forging. Of the various TMP processes investigated, both extrusion and cogging prior to isothermal forging were effective in refining the grain size of the large billet. An F404 HPT disk was isothermally forged from a spray cast plus HIP'ed mult which was used to demonstrate the excellent forgeability of spray cast materials.

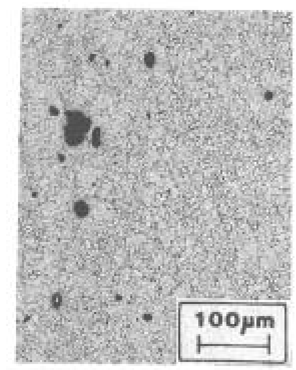
Ring Structures

Several statistically designed experiments were conducted to develop the spray casting process to produce fine grain IN718, René 41, and Waspaloy rings ranging from 12 to 33 inches in diameter. Figure 8 shows the effect of ring diameter and spray height distance on the microstructure and as-sprayed porosity levels. The best combinations of grain size (ASTM 8.5-9.5) and porosity levels (1.1-2.3%) were observed in the 12 inch diameter ring and short spray height distance. The grain size in the 22 inch diameter ring preform was ASTM 10, but the porosity was excessive (2.4-5.7%) using a longer spray height and higher gas pressure. This was not unexpected since the fraction of solidified particles was greater in the spray flux. Rings have been successfully consolidated to 100 percent density by using either HIP or ring rolling. Several ring rolling vendors have rolled spray cast IN718, René 41, and Waspaloy successfully with reductions in wall thickness greater than 50 percent in a single pass, thereby resulting in grain sizes ranging from ASTM 8 to 10 (Figure 9). The grain size in ring rolled material was a uniform ASTM 8 with slightly elongated grains.



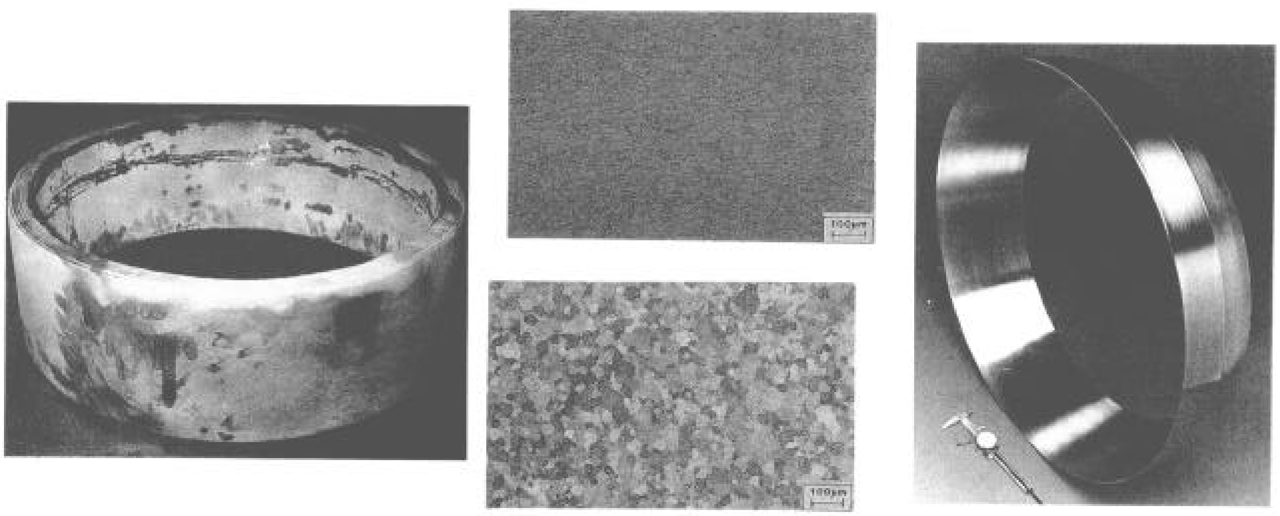


12" Diameter



22" Diameter

Figure 8 - Effect of spray height and ring diameter on the grain size and as-sprayed porosity.



(a) rolled ring

(b) Spraycast-X + HIP + machined

Figure 9 - Spraycast-X Waspaloy rings and microstructure in the ring rolled and HIP condition.

The tensile strength of spray cast Waspaloy in the HIP'ed and ring rolled condition was 50 ksi higher than AMS 5707G specification requirements for wrought product, Figure 10. The average stress rupture lives of the ring rolled Waspaloy and HIP'ed Waspaloy were 85 hours and 45.9 hours, respectively. These values met the 23 hour minimum specification requirements in AMS 5707G. All combination smooth and notched stress rupture bars from spray cast and ring rolled Waspaloy tested at 1350°F/75 ksi failed in the smooth section indicating the material was not notch sensitive. As expected the stress rupture lives of the finer grain Spraycast-X and ring rolled Waspaloy was lower than both Spraycast-X plus HIP'ed and wrought counterparts. Also, tensile and stress rupture properties of the spray cast and HIP'ed Waspaloy did not exhibit any significant directionality when tested in axial, tangential and radial directions, Figure 10.

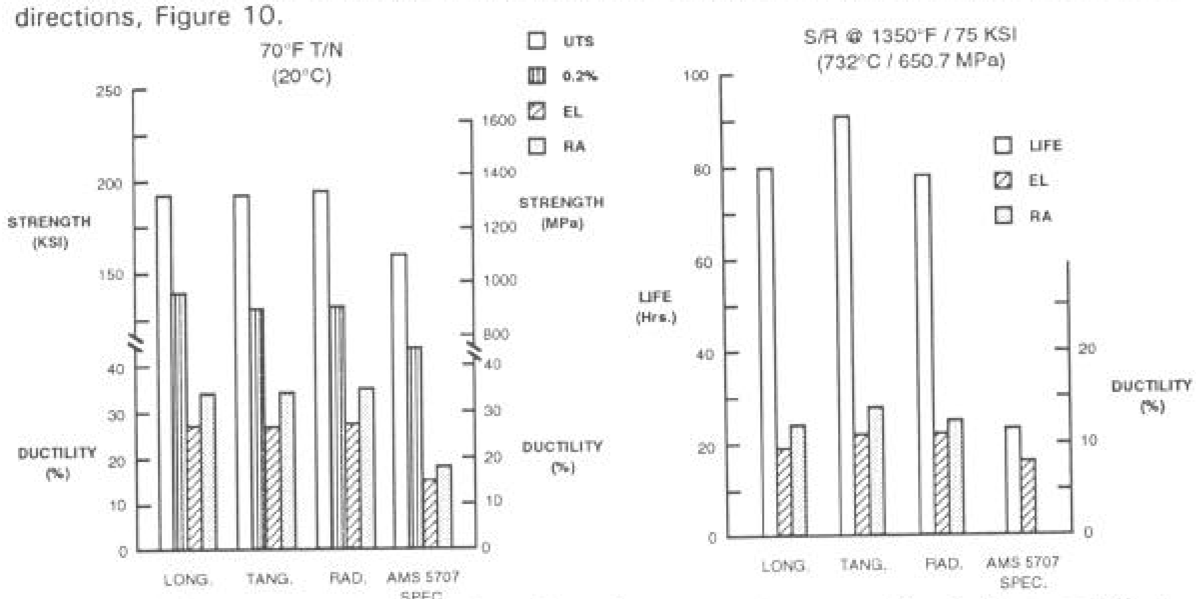


Figure 10 - Orientation behavior of tensile and stress rupture properties in Spraycast-X + HIP Waspaloy rings compared to wrought specification AMS-5707G.

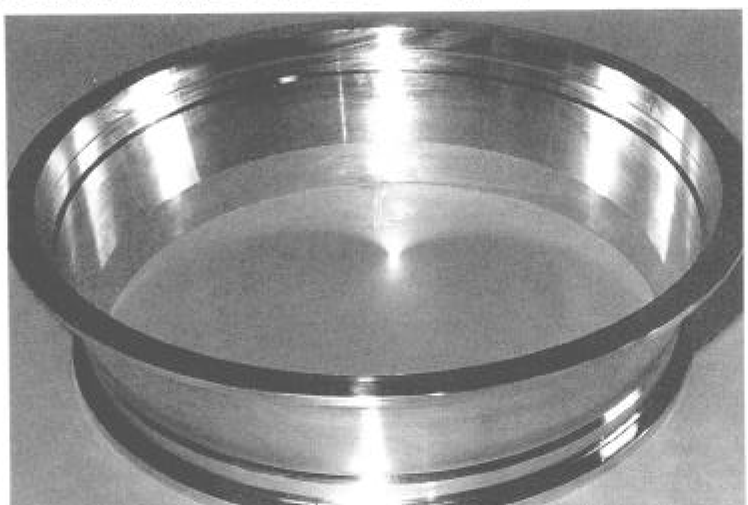


Figure 11 - Shaped and tapered Spraycast-X Waspaloy ring in the HIP and machined condition.

To demonstrate shape making capability, a tapered Waspaloy ring component was machined from a HIP'ed preform (Figure 11). Major advancements appear to be possible by applying more sophisticated preform shaping techniques, such as contour rolling, flow turning, shear spinning, etc., to spray cast ring preforms. Preliminary EB welding evaluations of the fine grain and ring rolled Waspaloy have exhibited weldability at least equivalent to current wrought product.

Conclusions

Howmet has enhanced the Osprey process through the use of vacuum melting technology and equipment design to produce aerospace quality superalloy products. Spray cast processes have been developed to produce billet up to 10 inch diameter and preforms up to 33 inch diameter and weighing as much as 500 pounds.

Spray cast materials typically exhibited a unique fine grain (ASTM 6-8), nondendritic structure without macrosegregation which promotes improved thermomechanical processing relative to the conventional cast and wrought product.

Mechanical properties of spray cast and HIP'ed MERL 76 (no Hf) were equivalent to extruded and gatorized IN100 while the mechanical properties of spray cast and HIP'ed and spray cast and ring rolled Waspaloy were isotropic and favorably comparable to wrought products.

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