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P/M Superalloys – A Troubled Adolescent?

R. L. Dreshfield and H. R. Gray
Lewis Research Center
Cleveland, Ohio

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R. L. Dreshfield and H. R. Gray

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

As powder metallurgy (P/M) superalloy technology passes through its adolescent years, it is appropriate that we review the growth of the technology. In its childhood in the early 1970's P/M superalloy technology offered the potential of combinations of both higher performance and lower cost compared to ingot metallurgy. As the technology entered its teen years, a combination of unrelated, unforeseen events occurred. They appeared to have strongly influenced and perhaps retarded the technology's growth to the current state-of-the-art which is to be presented in detail elsewhere in this seminar. This paper will review the history of P/M superalloy technology, comment on the state-of-the-art, and speculate on the technology's future potential growth and maturity.

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INTRODUCTION

The application of powder metallurgy (P/M) to superalloys was initiated in order to overcome difficulty encountered during forging and heat treating of advanced, highly alloyed, nickel-base superalloys such as Astroloy. In 1968, Allen and his co-workers at Pratt & Whitney Aircraft reported that they had demonstrated that powder metallurgy Astroloy could be processed to produce a 23 kg pancake forging (ref. 1). The forging had mechanical properties comparable to conventionally forged Astroloy and the recrystallized microstructure showed no evidence of massive segregation or the P/M origins of the metal. The key to their success was that they used powder having low oxygen content (below 100 ppm) and performed all operations in the absence of air.

Sired, in part, by Pratt & Whitney's success, an infant powder metallurgy superalloy industry was born. This emerging technology offered expectations of both lower cost and higher performance rotating structures for gas turbine engines. By the mid-70's, P/M superalloys were appearing as "bill-of-materials" for advanced military engines (refs. 2 and 3). For these applications wrought material was produced from P/M billets.

As the decade progressed, technology for superalloys which are hot isostatically pressed and heat treated (as-HIP) advanced and offered the potential of even greater cost benefits than wrought powder technology. By the end of the 70's, as P/M superalloys approached its teens, as-HIP components were flying in both military and civil applications (refs. 4 to 6). During the same period, the cobalt producing region of Zaire, Africa, was invaded, an event which we will later show had a significant effect on the growth of P/M superalloy technology.

In the autumn of 1980 an aircraft accident was attributed to the failure of an as-HIP P/M superalloy disk (ref. 7). While the incident was never conclusively related to any shortcomings inherent in P/M superalloy technology, its occurrence had a profound impact on the direction that future P/M superalloy technology would take.

This paper will briefly review the history of P/M superalloy technology. We will attempt to show how unforeseen events such as those mentioned above have shaped the directions that P/M superalloys are taking during their adolescent years. Finally, we will speculate on the technology's future potential growth and maturity.

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BACKGROUND

The early years of P/M superalloys were ones of great expectations. For example, in 1971 it was suggested that in 5 years, 20 to 25 percent of the weight of advanced engines would be P/M superalloys (ref. 8). While that level of use has not been achieved, P/M superalloys have been successfully applied to Pratt & Whitney F100 engines since the early 70's. Figure 1 shows that over 30 000 wrought P/M superalloy parts have been manufactured for that series of engines (refs. 9 and 10). Nine different parts including compressor and turbine disks are manufactured from P/M IN 100 billets having an input weight of about 450 kg per engine. As shown in table I, wrought and as-HIP P/M superalloy parts have been successfully used in at least eight production aircraft propulsion gas turbine engines.

As shown in figure 2, in the early 80's P/M superalloy production peaked at about 600 000 kg of consolidated product per year.[1] It is currently about 75 percent of that amount. As-HIP production also peaked at the same time at about 200 000 kg and is now about 30 percent of the maximum. However, the total P/M superalloy production is only about 2 percent of the total amount of superalloy produced (ref. 11).

Economic Considerations

It might be argued that the initial interest in P/M superalloys was technical because it was thought (and later shown) that the reduced segregation in P/M superalloys compared to ingot superalloys would make them more readily forgable. This suggests that a greater yield of acceptable product would be anticipated using a P/M approach, therefore, lower costs. In a broader sense the final acceptance of P/M superalloy technology is based on an economic benefit to the user such as an airline or the military services.

[1]Private communication, Steve Reichman, Wyman-Gordon Company.

The benefits to airlines can be assessed relatively easily in terms of direct operating costs or return on investment. For a military aircraft benefits might be measured by life cycle cost or thrust to weight ratio. Whatever the economic benefit, one can relate it to factors effecting various cost aspects of aircraft procurement or operations.

An economic factor with which we are all familiar is the cost of money - interest rates. For the purpose of this paper we have chosen three month United States Treasury Bills as a representative interest rate. At the time the currently certified engines were designed in the 50's and 60's, typical interest rates were less than three percent. Figure 3(a) shows the trend of interest rates since 1975 (ref. 12 and 13). From 1975 to 1981 the cost of money approximately tripled. Toward the end of 1983 the rate had decreased and was about 9 percent.

The impact of periods of high interest rates on P/M superalloy is as follows. P/M technology (particularly as-HIP) was initially proposed to offer substantial cost savings compared to forgings. As will be suggested later these savings were largely unrealized in many cases. Thus when the cost of money is high, it is desired to reduce overall costs by decreasing the purchase price of an engine thereby reducing interest costs. One might therefore tend toward "lower technology" material selections when interest rates are high.

The second factor (shown in fig. 3(b)) is the cost of jet fuel. The bulk of the engines for commerical aircraft being used today were designed when fuel was about 10 cents per gallon. At that time fuel costs were about 1/4 the direct operating expense of an aircraft. Since 1975 fuel costs have increased from about 34¢ to a peak of $1.15 per gallon in 1981. Fuel price has recently decreased slightly to about $1.05 per gallon. With fuel costs at a level in excess of $1.00 per gallon, about 1/2 the direct operating cost of a commerical aircraft is fuel. In this environment, there is a strong incentive to use technologies which reduce fuel consumption, such as high performance alloys which allow more efficient turbine operation. The most advanced strength superalloys used for disk applications are P/M superalloys such as IN 100 and René[2] 95, as shown in figure 4. These alloys, except for Astroloy, are virtually impossible to economically reliably produce from cast and forged ingots.

The third economic factor in figure 3(c) is the cost of the element cobalt. Following a brief invasion of the cobalt producing region of Zaire in 1978, cobalt prices rapidly increased from about $5.00 per pound to about $25.00 per pound in 1980 (ref. 14). The cost of "spot" prices in fact approached $50.00 per pound. Today cobalt is again about $5.00 per pound. As one can see in table II the four P/M superalloys, Astroloy, IN 100, René 95, and MERL 76 contain from 8 to 18 percent cobalt. The increase in cobalt price and related problems associated with cobalt availability encouraged P/M superalloy users to switch to lower cobalt level alloys such as Waspaloy[3] and Inconel[4] 718 to both save money and make cobalt available for their other more essential

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[2]René is a tradename of the General Electric Company.

[3]Waspaloy, MERL, and Gatorizing are tradenames of United Technologies Corporation.

[4]Inconel is a tradename of the INCO families of companies.

applications. While cobalt is again plentiful and low in cost, it is doubtful that the higher Co-containing alloy will be reintroduced in existing engines in the near future.

Of course the overall economic climate has a strong impact on superalloy sales. As we are all keenly aware, we are just now recovering from a severe economic recession which, combined with deregulation of the air transport system in the United States, had a severe impact on commerical aircraft sales. For example, in 1982 Boeing had its poorest sales year since 1971 (ref. 15). Obviously if aircraft sales are down, then superalloys which are largely used in engines will also suffer a decline in production.

Other Considerations

Another event which strongly influenced the direction of P/M superalloy technology, especially as-HIP, was the loss of an F/A 18 aircraft in September 1980 (ref. 7). The crash was attributed to the failure of a P/M superalloy low pressure turbine disk. The cause of the disk failure has not been conclusively established as portions of the failed disk critical to the failure analysis were not recovered. Figure 2(b) shows that shortly after the F/A 18 crash, the production of as-HIP P/M superalloys decreased dramatically. The decrease in the use of as-HIP superalloys was, in part, due to a reevaluation of application of as-HIP superalloys and the subsequent change to alternate, more conventional, materials in new production engines.

A plausible explanation for the failure of that turbine disk is that it contained a large undetected flaw which propagated due to low cycle fatigue until it became critical and fracture occurred (ref. 16). The importance of flaw size and LCF behavior had been previously recognized, (ref. 17) and the size of powder used in these disks had previously been changed from -60 mesh to -150 mesh to reduce the maximum size defect (e.g., ceramic) which might be in a critical section of a part (ref. 7). This will be discussed in greater detail later.

A direct result of changing to finer mesh powder as just described is that product yields relative to atomized metal are generally lower. In 1980, one would have anticipated that about 20 percent of powder was between -60 and -150 mesh. That 20 percent loss in metal would obviously raise costs. Now even finer powder cuts are used and the yield has decreased more.

In addition to finer powder cuts being used, quality control tests for P/M parts have had to become more sophisticated and hence, more costly than those envisioned in the early 70's. For example, virturally all powder is now examined by water elutriation to assess the amount and size of ceramic inclusions present. Specifications allow only "clean" powder blends having less than 20 particles per kg to be subsequently processed (ref. 18). For some as-HIP parts, LCF tests of consolidated powder blends have been required. All of these quality assurance procedures add to the cost of the final product and are another reason why anticipated cost advantages of as-HIP P/M processing have not been realized for rotating high performance parts.

To summarize, table III shows those factors which would increase the use of P/M superalloys. Not shown is the most important - increased aircraft engine sales. At the birth of the P/M superalloy industry in the late 60's few of us recognized the turmoil that would influence fuel costs, metal prices and interest rates. We also became acutely aware of the significance of defect tolerance in the newer high performance alloys. The net result was that the P/M superalloy industry today, while having demonstrated significant success and growth, has not achieved the success that was projected in its emerging years.

CURRENT STATUS OF POWDER METALLURGY TECHNOLOGY

Superalloys

Substantial improvements in the strengths of turbine disk superalloys have been achieved in the previous two decades. Through the 1960's conventional casting and forging approaches were used to process alloys such as Inconel 718 and Waspaloy. These current day "workhorse" alloys have tensile strengths of about 1100 MPa (170 ksi) at 650° C (1200° F), see figure 5 and also figure 4. Waspaloy contains 3 wt. % Ti and 1.2 wt. % Al as the alloying elements which result in the precipitation of about 20 vol % strengthening gamma prime (γ') phase. Increases in Ti plus Al levels in order to increase the γ' content were the obvious approaches for achieving higher strength levels. However, stronger alloys were becoming much more difficult to economically forge and heat treat into reliable components.

Powder metallurgy was the processing breakthrough which opened the door into a new arena of turbine disk superalloys. Specifically, the powder alloys shown in figure 5 have Ti + Al levels of 7 to 10 wt. % with resulting γ' contents of 40 to 50 vol %. More importantly, as illustrated by a comparison of the inset photomicrographs on figure 5, the alloys have much finer grain sizes, no macrosegregation and significantly reduced microsegregation. The γ' in these alloys is much more effective as a strengthener because it is fine and uniformly dispersed throughout the microstructure instead of partially residing in massive primary γ' nodules.

By taking extraordinary care and "paying the price," it has been demonstrated that the very high strength superalloy René 95 can be produced by a cast and wrought approach. However, not only is the powder processed version of the alloy more economical, there is even a slight improvement in both yield and ultimate tensile strength levels over the entire temperature range of interest for turbine disks, see figure 6 (ref. 19).

However, much more importantly than high strength levels, powder processing results in more reproducible mechanical properties, particularly cyclic fatigue behavior. The microstructural uniformity of powder metallurgy superalloys is well accepted as benefitting intrinsic fatigue properties relative to cast and wrought alloys. Furthermore, finer cuts of powder for a given alloy have been demonstrated as an approach for additional improvements in fatigue behavior. As shown in figure 7, the cyclic fatigue life of P/M Astroloy at 600° C (1110° F) can be improved by an order of magnitude by reducing the size of the powders, and the maximum possible defect, from 400 to 150 μm (ref. 20).

Powder Processes

The most commonly used powder manufacturing process is inert gas atomization. As illustrated in figure 8(a), argon, the inert gas used by commercial producers, breaks down a stream of liquid metal into small droplets which solidify fairly rapidly (ref. 21). Centrifugal atomization, figure 8(b), has been evaluated and developed in recent years (ref. 21). One variation is commonly referred to as Rapid Solidification Rate (RSR) processing by Pratt & Whitney Aircraft Corporation. Helium is used as the quenching gas in their process. Still another commercially available process is vacuum atomization, see figure 8(c) (ref. 22). A soluble gas (hydrogen) is used in this process.

The inert gas atomization process typically yields the widest powder particle size distribution, whereas both the centrifugal and vacuum atomization processes yield somewhat smaller particle sizes and narrower distributions. With recent emphasis on using finer powder cuts, extensive effort has been made to fine tune all of these processes in order to increase the yield of finer powders. In spite of some claims to the contrary, it is now generally accepted that for a given powder size, all processes appear to yield comparable microsegregation spacings and, hence, had similar solidification rates.

Powder Consolidation

A typical sequence of consolidation steps is illustrated in figure 9 (ref. 22). Powders are sieved through various mesh sizes in order to eliminate inclusions and classify the powders into a range of sizes. All subsequent powder handling is done under very clean conditions using evacuated or inert gas filled equipment and containers. Powder lots are blended and then encapsulated in high quality steel, nickel, glass, or ceramic containers. Filled containers are usually degassed at intermediate temperatures (~300° C), sealed, preheated, and then hot isostatically pressed (HIP'ed) or extruded. Typical HIP conditions are 1100° to 1260° C (2000° to 2300° F), 100 to 200 MPa (15 to 30 ksi) for several hours with argon as the pressurizing medium.

In recent years post-HIP hot working has been receiving significant attention. Extrusion, warm die forging or high temperature isothermal forging have been evaluated. Extrusion of pre-HIP'ed compacts results in good control of the final grain size because of the extensive amount of particle deformation achieved during extrusion. Isothermal forging, known to some as "Gatorizing," is performed at slow strain rates and results in superplastically deformed shapes.

Recent Advances

Many advances have been made in powder technology in just the last decade. One of the most dramatic of these improvements has been in "nearer" net shape forging capability. Experience in shape retention, die design, and sonic inspection procedures have combined to significantly reduce the amount of powder required to produce turbine disks. For example, the amount of powder required for all "Gatorized" F100 components has been reduced from 620 to 450 kg, as illustrated in figure 10 (ref. 9). Actual powder savings are augmented by savings in energy required for hipping, forging, heat treating, and machining, plus a significant reduction in machining time and chips.

Finally, awareness of the necessity for cleanliness throughout the powder making, handling, and consolidation cycle has significantly reduced many concerns of the last decade. Infancy problems such as oxygen contamination, leaking cans, thermally induced porosity (TIP), striations, prior particle boundaries (PPB's), and large ceramic or reactive inclusions are now reasonably well controlled.

FUTURE DIRECTIONS

We have first attempted to briefly review some of the factors which influenced the emerging P/M superalloy technology. Then we have reviewed the current status of the technology. To complete our goal for this introduction to the seminar we will now comment on some of the newer developments in P/M technology and in those technologies which are or will compete with it, hopefully to allow a rational look toward the maturity of P/M superalloys.

Powder Technology

Because of the concerns for defect controlled LCF behavior in the advanced alloys, there has been a concerted effort to produce "clean" powder products at acceptable costs. The first approach, previously cited, was to restrict the size of the maximum possible flaw by using finer powder cuts. Subsequently a study was initiated to evaluate crucible materials and alternate melting techniques on ingot cleanliness (ref. 23). That study suggested that electroslag remelting is capable of producing cleaner ingot than standard vacuum induction melting practice. Electron Beam Cold Hearth Remelting (EBCHR) is being evaluated as a remelt technique because it has been shown to have potential for achieving ingots with very low oxide contents (ref. 24).

It is apparent that producing low oxide ingot is only one step in producing "clean" powder. It is necessary to convert the clean ingot to powder without introducing ceramics and other detrimental material. The EBCHR technique coupled with future ceramic-less atomization processes offers one approach to converting ingot to powder without the use of ceramics. One alternate ceramic-less approach is that of Plasma Rotating Electrode Process (ref. 25) in which a rotating consumable electrode of superalloy is plasma melted, as shown in figure 11. Other centrifugal atomization techniques coupled with arc or plasma melting offer the potential for clean powder (ref. 26).

Another potential source of powder contamination is from the container used to encapsulate the powder for consolidation. The Consolidation by Atmospheric Pressure (CAP)[5] process addresses the cleanliness problem by using glass for encapsulating the powder (ref. 27). Because the glass is transparent and joined without spatter, it is easier to keep clean and inspect than the metal cans or opaque ceramics. This process offers a potential for reduced cost by using atmospheric pressure for consolidation, thus eliminating the need for high temperature autoclaves necessary for hot isostatic pressing.

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[5]CAP is a tradename of the Universal Cyclops Company.

It has been reported that while most strength properties are equivalent for as-HIP, extruded + isoforge, or HIP + isoforge products, the average LCF life of the forged products is superior to as-HIP (ref. 28). Thus, for LCF limited applications there is a tendency to favor hot worked products to as-HIP ones. More subtle advantages of forging consolidated powder are: (1) the forging process itself might act as a quality control process or technique by cracking material with defects, and (2) forgings from billet multiples are less likely to contain "can" related defects. The latter is due to the fact that forging multiples are typically cut from simple cylindrical shapes and the HIP containers required little welding. They are easily cleaned and inspected. Finally, the locations most easily contaminated are the bottom and top portions of the HIPed cylinder. These portions are usually discarded or used for test material.

Alternative Alloy/Processes

While P/M superalloys have progressed over the past 15 years, so have competing alloys and/or processes. For example, from 1968 to 1977 the ultimate tensile strength of Waspaloy at 535° C was increased about 6 percent. That strength level of 1241 MPa is improved 12.5 percent over the typical Waspaloy of 1960 (ref. 28). Similar improvements have occurred with Inconel 718. Direct-aged (DA) Inconel 718 has an ultimate tensile strength of about 1216 MPa at 650° C compared to 1105 MPa for "conventional" Inconel 718 (refs. 28 and 29). It can be seen in figure 12 that DA 718 has greater strength than P/M - LC Astroloy and at lower temperatures becomes competitive with IN 100. In addition it has an advantage of inherently lower material cost, due to its 20 percent iron content and no cobalt.

A new process is now being developed which, like powder, will reduce macrosegregation. The process, Vacuum Arc Double Electrode Remelt (VADER)[6], is being developed at the Special Metals Company (refs. 30 and 31). A schematic diagram of the process and a typical macrostructure are shown in figure 13. It has been demonstrated that the VADER process produces ceramic-less superalloy billets free of macrosegregation that are easily inspected and which can be readily forged to desired components. As such a process moves toward production, it clearly will be an interesting alternate approach for making forging billets.

Other Considerations

As suggested earlier, the major factor (for the nearer term) determining the amount of P/M superalloys required will be aircraft sales. As the United States continues to up-grade its defense capabilities, we assume that military sales will continue to remain strong. In commercial aviation, as the national economic recovery continues we expect sales will improve. For example, Boeing reported 141 new orders in 1983 compared to 108 in 1982 (ref. 15). For the longer term it has been estimated that by the end of the century over 5000 new commercial aircraft will be required for the world fleet (ref. 32). Almost as many new commuter aircraft may also be required. A 3 percent annual growth rate has been projected for aerospace industries through 1988 (ref. 33).

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[6]VADER is a tradename of the Speical Metals Company.

For the want of a sound basis for forecasting, we assume the relative cost of the basic metals should be stable. It is recognized that periodic disruptions of metal markets are in fact common.

As the U.S. government continues to operate with unprecedented fiscal deficits, we, like many others, fear that interest rates are likely to increase over the next few years. The extent of the increase is, however, open to great conjecture.

Fuel costs are expected to be stable and perhaps slightly lower for a few years, then again rising toward the 1980 prices by 1990 (ref. 34). This of course assumes no major market interruptions.

We believe that the P/M superalloy industry is making good progress toward producing cleaner powder as evidenced by GE's plan to reintroduce P/M René 95 components in its F101 engine family this year.[7] However, it is expected that the costs associated with cleaner powder are likely to increase. We also believe that the industry is still on the steep portion of the "near-net-shape" learning curve and the overall cost of P/M superalloy parts is likely to decrease slightly.

The competitive pressures of VADER, improved processes for ingot-based superalloys, alternative alloys, and technologies we are yet to imagine will also tend to force P/M products to remain competitive.

Future Expectations

We have summarized our expectations in table IV. In all honesty, as a couple of metallurgists, we urge that these be taken as "crystal-balling." We note that many noted economists are equally reluctant to attempt public forecasts with certainty.

There continues to be significant interest in using P/M superalloys in new applications. We expect to see the application of P/M superalloys expand in terms of the number of components and engines that apply them. These applications will tend to be more for wrought powder billets in alloys like IN 100 and René 95, particularly for larger components. New as-HIP, near-net-shape components will tend to be small relatively simple shapes, possible multiple parts such as T700 shapes, (ref. 35) such that powder cans are easily fabricated, cleaned, and inspected. In general, all the applications will be where there is a need for high strength alloys. While concerns for LCF will (rightfully) continue, the successful operation of P/M superalloys in F100, JT8, JT9 and T700 engines should convince even the doubter that there is nothing inherently wrong with P/M superalloys.

In 1982, Andrews made a projection for the superalloy market (ref. 11). This is shown in figure 14(a). He believed the market should continue up toward the end of the decade. Because it appears that engines which will use P/M superalloys should be increasing production soon, we expect that the P/MP

[7]Private communication - D. Chang, General Electric, January 1984.

market has bottomed and will likely be increasing in 1985 and beyond. The question mark we show in figure 14(b) reflects, in part, our uncertainty as to when and how great an effect VADER may have and how soon truly clean powder will be on hand. Of course we have to rely on other's estimates of future aircraft sales.

CONCLUDING REMARKS

In this paper we have reviewed the history of P/M superalloy technology with emphasis on events which were unforeseen at its birth 16 years ago. As is common for both new technical ventures and children, there were great expectations for the future. While those expectations now appear to have been overly optimistic, P/M superalloy technology is a viable entity as it passes through its adolescence, which like human teenagers, is a bit rocky. For the future P/M technology should grow, but like all enterprises must watch and respond to its competition. We look forward to hearing more details on the state-of-the-art and emerging developments from the speakers to follow in this seminar.

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TABLE I. - PRODUCTION GAS TURBINE PROPULSION ENGINES WITH PM SUPERALLOYS*

GE	P&W
T 700	F 100
F 404	TF 30
F 101	JT 8D
CFM 56	JT 9D

*Not necessarily all models of all engines.

TABLE II. - SUPERALLOY COMPOSITIONS

Alloy	Composition, wt. %										
	Co	Cr	Ti	Al	Mo	W	Cb	C	Hf	Fe	Ni
Waspaloy	13.5	19.5	3.0	1.3	4.3	----	----	0.08	----	----	Bal
INCONEL 718	----	19	.9	.5	3	----	5.1	.04	----	18.5	
L/C Astroloy	17	15	3.5	4	5.3	----	----	.04	----	----	
IN 100	15	10	4.7	5.5	3.0	----	----	.07	----	----	
René 95	8	14	2.5	3.5	3.5	3.5	3.5	.06	----	----	
MERL 76 (improved IN 100)	18	13	4.3	5.0	3.2	----	1.6	.02	0.7	----	

TABLE III. - FACTORS WHICH INCREASE USE OF PM SUPERALLOYS

Increasing fuel cost
Improved powder cleanliness
Lower metal/alloy cost
Lower interest rates
Lower powder processing cost

TABLE IV. - ISSUES INFLUENCING FORECAST

Issue	"Crystal ball" prediction
Metal/alloy cost	Stable
Interest rates	?, possibly increasing
Fuel costs	Increasing
Powder process costs	Decreasing slightly
Powder cleanliness	Reduced concern/problem
Engine orders	Increasing

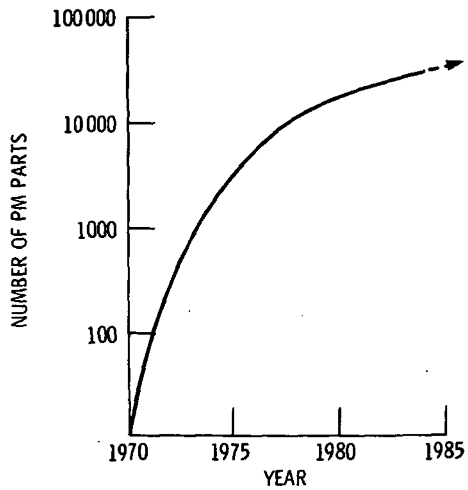


Figure 1. - Over 30 000 forged powder metallurgy superalloy parts manufactured for P&WA F 100 engines.

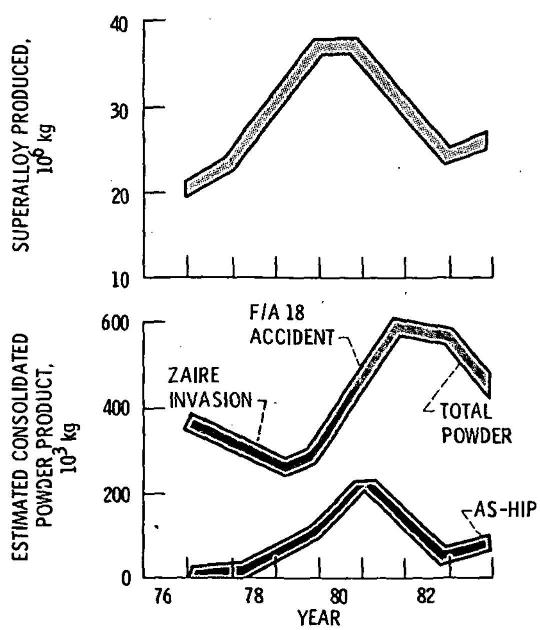


Figure 2. - Superalloy production.

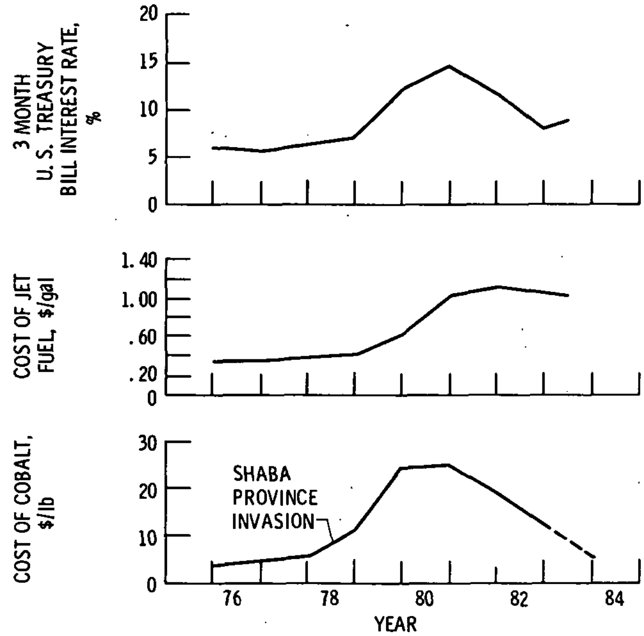


Figure 3. - Economic factors influencing PM superalloy use.

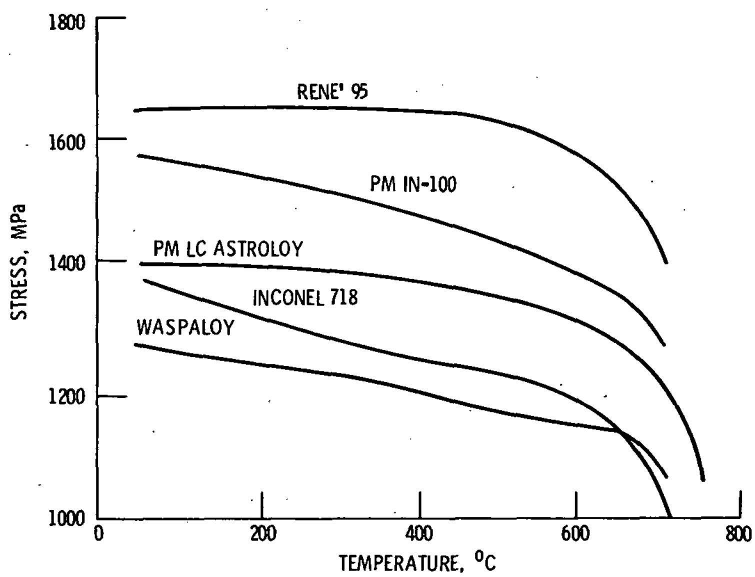


Figure 4. - Ultimate tensile strengths of disk alloys. (Courtesy of Garrett Turbine Engine Co.)

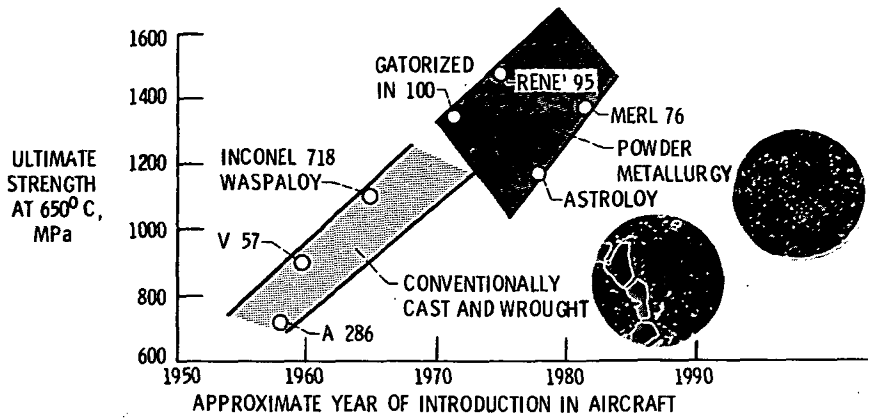


Figure 5. - Strength trends in turbine disk materials. CS-84-580

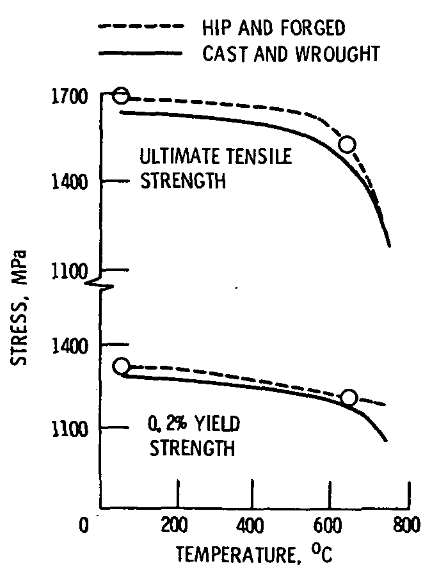


Figure 6. - Tensile properties of Rene' 95. (From Bartos, et al.)

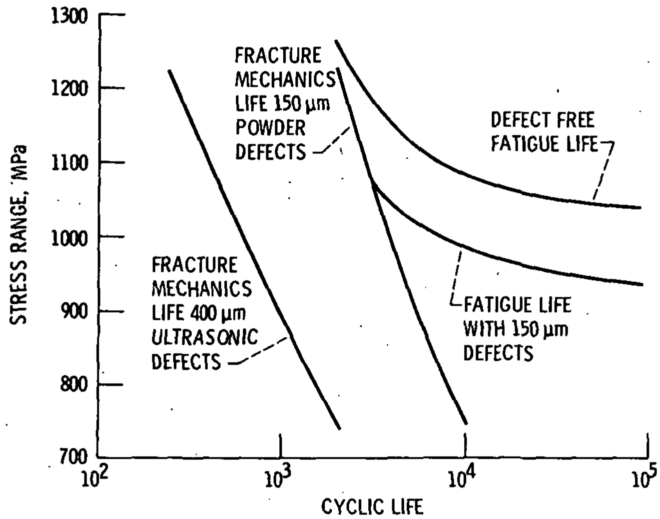
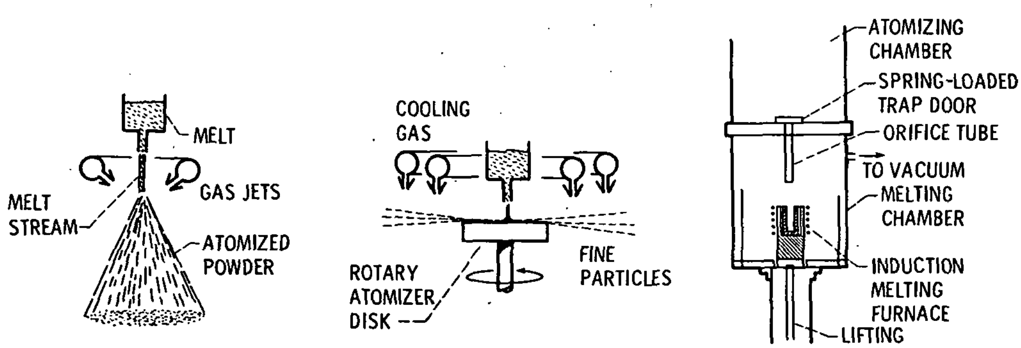


Figure 7. - Cyclic fatigue behavior of P/M astroloy at 600° C. (From Jeal.)



(a) Melt gas atomization.

(b) Centrifugal atomization.

(c) Vacuum atomization.

Figure 8. - Selected powder manufacturing processes. (a, b From Cohen, et al. and c, Eggar, et al.)

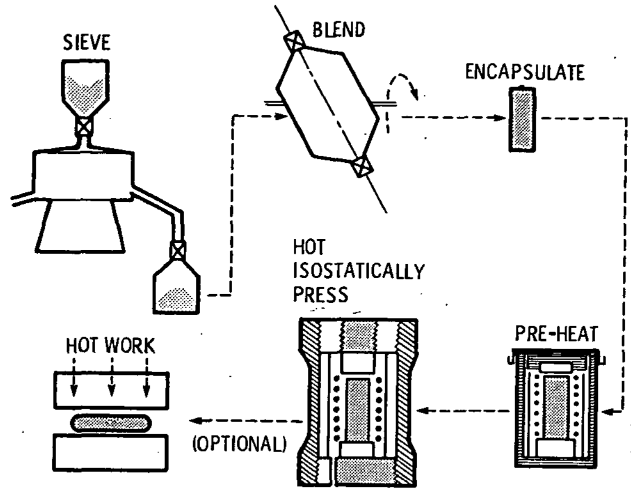


Figure 9. - Typical powder consolidation sequence. (Adapted from Eggar and Siddall.)

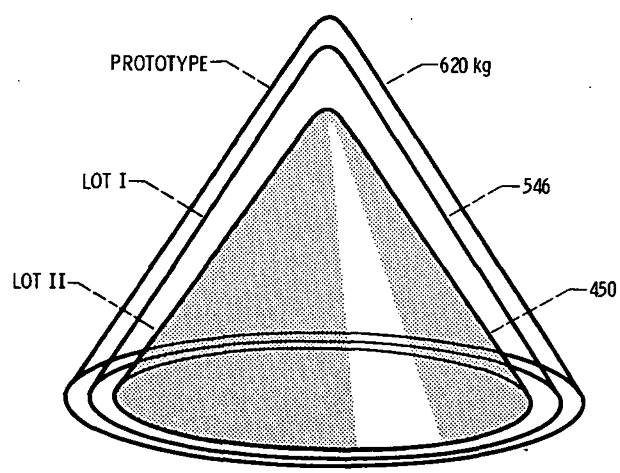


Figure 10. - Improved forging decreased F 100 powder use.

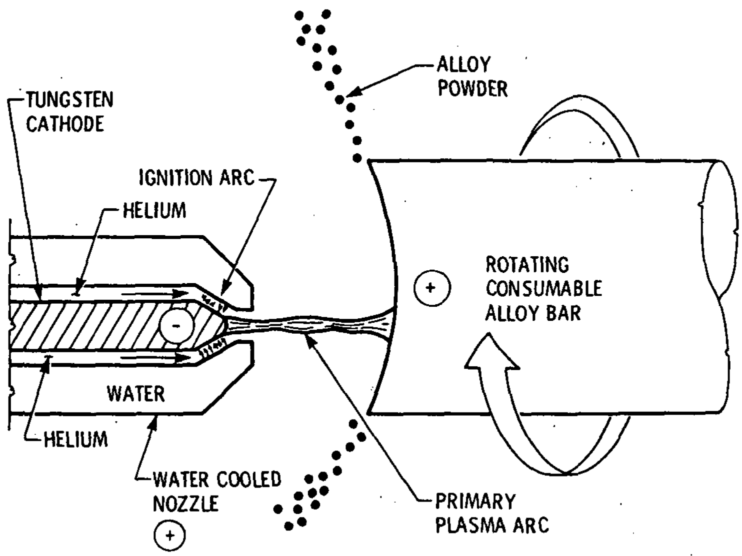


Figure 11. - Principle of PREP.

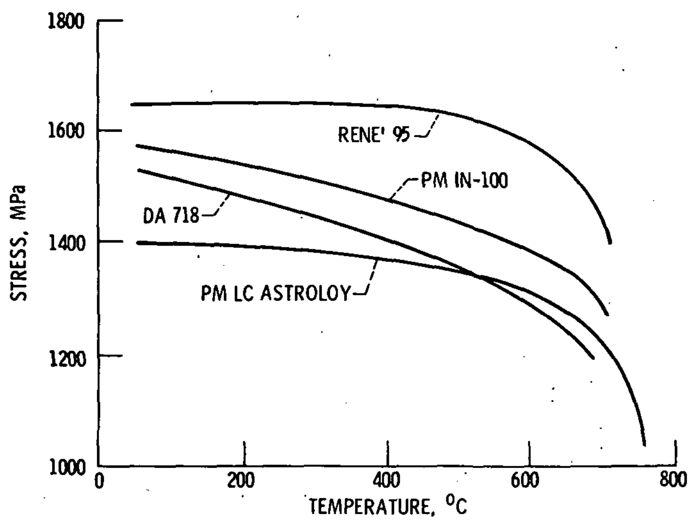


Figure 12. - Ultimate strength of DA 718 and PM superalloys.

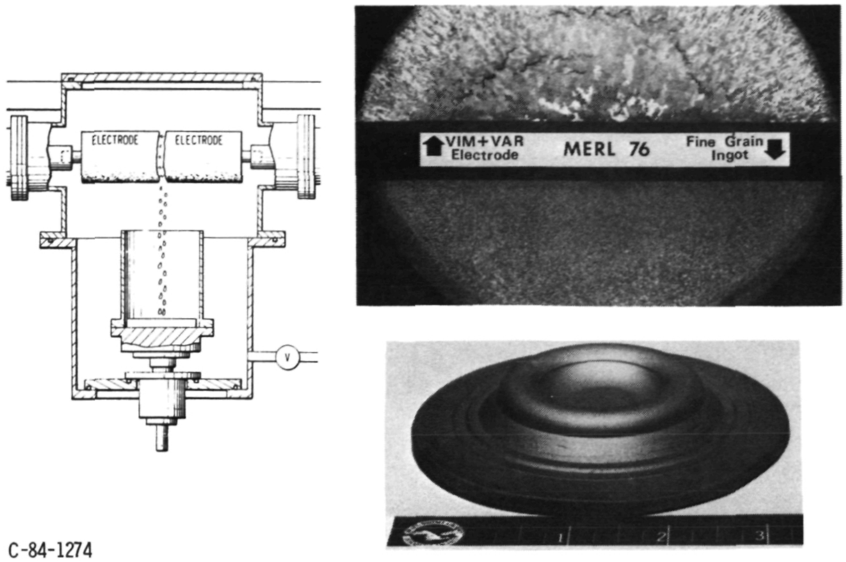


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Figure 13. - Drip casting fine grain ingot process.

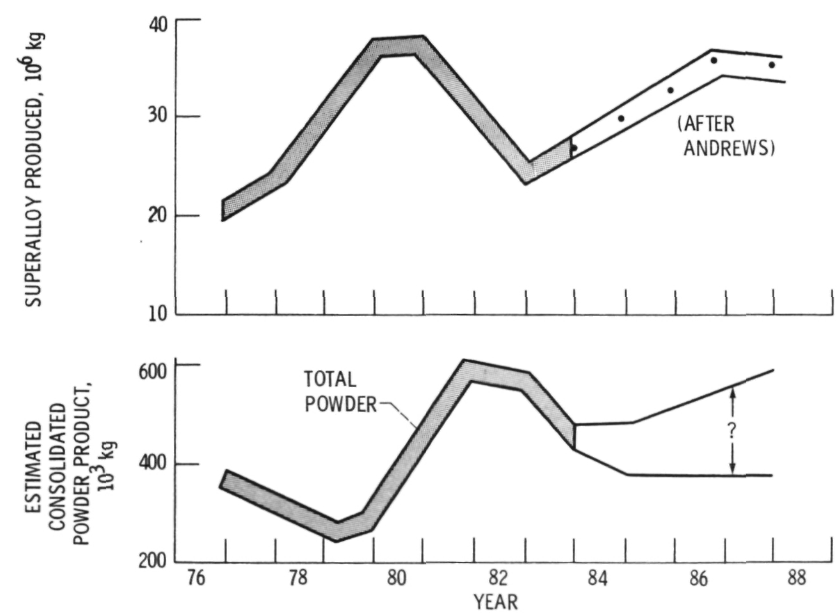

Figure 14. - Superalloy production.

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15. Supplementary Notes

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16. Abstract

As powder metallurgy (P/M) superalloy technology passes through its adolescent years, it is appropriate that we review the growth of the technology. In its childhood in the early 1970's P/M superalloy technology offered the potential of combinations of both higher performance and lower cost compared to ingot metallurgy. As the technology entered its teen years, a combination of unrelated, unforeseen events occurred. They appeared to have strongly influenced and perhaps retarded the technology's growth to the current state-of-the-art which is to be presented in detail elsewhere in this seminar. This paper will review the history of P/M superalloy technology, comment on the state-of-the-art, and speculate on the technology's future potential growth and maturity.

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