EFFECT OF PROCESSING VARIABLES ON POWDER-METALLURGY RENE' 95

J. F. Barker, Mgr., Wrought Alloys
E. H. VanDerMolen, Research Metallurgist

General Electric Company
Cincinnati, Ohio 45215

Abstract

A Rene' 95 powder-metallurgy processing study was conducted to determine a cost effective method for producing Rene' 95 disks and also gain an understanding of the effects of powder-processing variables on properties and producibility. Variables studied included powder manufacturing method (argon atomization, rotating electrode, and H_2/vacuum atomization), particle-size distribution, consolidation techniques (extrusion vs. HIP), forging reductions and temperatures, and heat-treatment schedules. Forging multiples ranged from four pounds for the laboratory portion of the investigation to over four hundred pounds for the engine disks.

For the parameters studied, decreases in powder particle size resulted in increases in 1200F stress-rupture lives of both extruded and HIP consolidated powders. Tensile properties of extruded compacts were superior to HIP properties and were unaffected by prior particle size while HIP compact tensile properties were inversely proportional to powder size. Subsequent forging of the compacts greatly minimized differences caused by the original powder size distribution and resulted in comparable tensile strengths for both consolidation methods. Stress-rupture lives and ductilities, however, were superior for the HIP forgings. Forging at lower temperature (1975F vs. 2075F) and at higher forging reductions improved tensile properties. Forgeability of the consolidated powders was good for virtually all conditions. In summary, the best powder metallurgy forging properties were achieved using powders having a fine particle size distribution that were consolidated at 2090F (below γ' solvus) and forged at 1975F.

Introduction

Jet-engine compressor and turbine rotor disks are the most critical and highly stressed major components in today's advanced engines. They are produced from complex highly alloyed precipitation strengthened superalloys that, because of their alloy content, are difficult to produce and consequently are very expensive. The powder metallurgy process as a method for producing these parts offers significant advantages over conventional cast plus wrought methods used until now. These advantages may be categorized as: 1) Lower Costs because of improved metal utilization, decreased forging operations and better forgeability and 2) Improved Properties attributed to the inherent homogeneity of powders.

The powder metallurgy processes that may be used to produce these components cover a wide spectrum, but two of these have found the most favor. One is extrusion of powders followed by forging and the other is hot-isostatic pressing (HIP) plus forging. The work reported here is centered about these two generalized processes. Powder metallurgy variables utilizing these processes were investigated to determine their effect upon properties and producibility of a superalloy disk material, Rene' 95, with the intention of establishing a cost effective method for producing such disks.

The variables studied included powder manufacturing methods (argon atomization, rotating electrode, and H_2/vacuum atomization), particle size distributions, consolidation techniques, forging reductions and temperatures, and heat-treatment schedules. Forging multiples ranged from four pounds for the subscale laboratory portion of the program to approximately 400 pounds for full-size jet-engine disks.

Materials and Experimental Procedure

Subscale Study

A subscale study utilizing disk type forgings weighing about 4 pounds each was conducted to investigate the effect of powder metallurgy variables on properties and microstructure. Descriptions of the material and experimental procedure used are as follows:

Powder Manufacture: Three Rene' 95 lots of powders produced by argon atomization, the Rotating Electrode Process (REP) and H_2/vac. atomization were investigated. All three lots were produced from a single vacuum induction heat that was cast into remelt bars and distributed to the appropriate vendors. The composition of the Rene' 95 master heat is given in Table I. The argon atomized and the REP powders were screened to -60 mesh while the H_2/vac. atomized powder was screened to -20 mesh. Plots of the powder size distributions for the three subscale powder lots are given in Figure 1 together with the average powder size distribution for the powder lots used in the full-scale disk study. Differences in powder shape and surface smoothness for the three types of powder are illustrated by the scanning electron micrographs in Figure 2.

Consolidation: Powders were consolidated by two methods: extrusion and hot-isostatic pressing. The extrusions were made at 2000F using an extrusion ratio of ten to one. The extruded bars were 2 inch diameter, including the stainless steel can. The HIP compacts were made by heating powders contained in evacuated and sealed cans (3 in. ID and 15 in. high) to 2090F, transferring them rapidly to an unheated autoclave, and applying 15,000 psi pressure. The cans were insulated in such a fashion that little or no heat loss occurred. All compacts were fully densified as indicated by density measurements and metallographic examination. Typical microstructures of both extruded and HIP'd compacts are shown in Figure 3.

Forging: Pancake forgings approximately 4 inch diameter were made from the extruded bars by press forging 3 inch high bar multiples at 1975F and 2075F. Forging reductions of 60 and 75 per cent in height were employed for both forging temperatures. Pancakes receiving 75 per cent reduction were forged in two passes with a 15 minute reheat between passes. The HIP compact multiples, 3 inch high, were press forged in a manner similar to the extruded multiples with the exception that the forging reductions were 30 and 60 per cent at 1975 and 2075F. Thus, the 60 per cent forging reduction was common for both the extrusion and HIP multiples. All of the mults were soaked one hour at the forging temperature prior to forging. The pancakes produced from the extrusion mults were air cooled following forging while the HIP pancakes were oil quenched following forging.

Heat Treatment and Evaluation: Material from both the extrusion and HIP forgings was evaluated using a standard Rene' 95 heat treatment of 2000F/1 hr./oil quench plus a 1400F/16 hr. age. To eliminate the effect of heat treat section size, all heat treating was done on specimen blanks approximately 1/2" x 1/2" x 2". The forgings produced from the extrusions were evaluated using several different intermediate and final aging treatments in addition to the 2000F solution treatment while the HIP forgings were also evaluated using a 1400F/16 hr. direct age (no solution treatment). Evaluations were made on both as-consolidated and forged compacts and included optical microscopy, room temperature and 1200F tensile tests, and 1200F stress-rupture tests. Selected replica and scanning electron microscopy examinations augmented the evaluations.

Full-Scale Disks

Powder Manufacture: Full-size turbine disk forgings were produced from minus 60 mesh argon atomized Rene' 95 powder via consolidation of hot-isostatic pressed preforms and press forging. These parts were utilized for mechanical property evaluations and engine tests. Powders similar to the subscale program powders but produced in larger quantities by a different vendor were used. The chemical analyses and screen analyses of typical powders are given in Table I and Figure 1, respectively, together with the subscale analyses. The powder in each disk represented a blend of two to three different powder lots.

Consolidation: The powders were hot isostatically compacted to the 16" OD x 8.5" high forging preform shape pictured in the top of Figure 4. This process differed from that described for subscale disks in that different mold materials and compaction parameters were used. In this process the powders were contained in glass molds slightly larger than the preforms shown (to compensate for shrinkage during densification) and evacuated and sealed. These were then heated to 2200F in a preheat furnace, transferred to a hot autoclave and held under 750 psi pressure of N_2 at 2300F for 2 hours. At this temperature and pressure, the glass container in the plastic state collapsed about the powders to provide a uniform distribution of pressure throughout the preforms. A density of 99+ per cent of theoretical was obtained. Upon removal and cooling the difference in thermal contraction between the Rene' 95 and the glass caused the glass mold to spall off. Because of the pressure limitations of the larger autoclave, a higher compaction temperature (2300F) than used for the subscale work was required to obtain full density.

Forging: The HIP preforms were lightly machined on the OD prior to forging to remove the surface skin layer which in earlier work was shown to initiate peripheral cracks. The preforms were then wrapped with a fiber-glass type insulating material, canned in mild steel, and press forged in contour dies on an 18,000 ton press using the two pass forging schedules shown below:

Pass	Metal Temp.	% Reduction at Bore/Pass	Total Reduction at Bore
1	2025F	29	29
2	2000F	21	41

Heat Treatment and Evaluation: Photographs of finish-forged parts are shown at the bottom of Figure 4. Following forging, the disks were heat treated per the Rene' 95 forging specification as follows:

Preage - 1650F/24 hrs./AC
Solution - 2000F/1 hr./Salt Quench
Age - 1400F/16 hrs./AC

After ultrasonic inspection, two forgings were selected for mechanical property, density and metallographic evaluations. The mechanical property evaluations consisted of tensile, stress rupture, creep, and sustained peak low-cycle fatigue (SPLCF) tests in the room temperature to 1300F temperature range.

Results and Discussion

Subscale Study

Metallography: The microstructures of consolidated powders, shown in Figure 3, indicate that the extruded powders are fine grained and relatively uniform regardless of the method of powder manufacture and original powder particle size distribution. On the other hand, the grain size of the HIP compacts was directly proportional to the particle size distribution of the original powders. Although recrystallization occurred during extrusion at 2000F, fine grain sizes resulted in the extruded compacts because grain growth was limited by the presence of γ' (γ' solvus is about 2100F) and rapid cooling. Except for the relatively large carbides which are normally present in REP powder, the recrystallization process has eliminated obvious optical metallography differences among the extrusions. Conversely, the low amounts of strain energy added during HIP prevented extensive recrystallization; thus many of the grains are the same size as in the original powder particles. This lack of grain growth results in identification of some original particle boundaries, particularly in the REP powder compact. Prior particle boundaries in Rene' 95 do not contain an excessively large amount of carbides and thus can only be detected below the γ' solvus where grain growth is restricted. When heated above the γ' solvus, all powder compacts, whether consolidated by extrusion or HIP, look similar and have an equiaxed grain size.

The effect of 60 per cent forging reduction at 1975F on the microstructures of extruded and HIP compacts is shown in Figure 5. The extruded and forged microstructures are all similar and exhibit a very fine recrystallized grain size (ASTM 12). Dynamic recrystallization occurred during forging of the extruded microstructure which maintained the fine-grained equiaxed structure. The microstructures of HIP compacts after forging show unrecrystallized warm-worked grains surrounded by a "necklace" of fine recrystallized grains. The amount of recrystallized regions obtained is a function of starting structure, forging temperature, and forging strain rate.

The effect of forging temperature on microstructure is seen in Figure 6. In the case of the extrusions, the higher forging temperature resulted in a similar but somewhat larger grained structure. During recrystallization, moving grain boundaries swept most or all of the γ' present at that temperature into agglomerated "chunks" which soon became large enough to prevent further grain growth. Therefore, the recrystallized grain size was primarily a function of the amount of γ' present at the recrystallization temperature. Grain growth in the recrystallized or necklace region of the HIP forgings was also limited by agglomerated γ' chunks. The forging rate was slow enough (5-10"/minute) that forging at 2075F allowed enough dynamic substructure recovery to occur to reduce the amount of recrystallized areas.

Mechanical Properties: Results of 1200F tensile and stress-rupture tests are plotted in Figure 7 for the three powder lots in the as-consolidated plus heat treated and forged 60 per cent plus heat-treated conditions. The tensile data for the consolidated plus heat-treated compacts correlated well with microstructure. The strengths and ductilities of the HIP compacts decreased with increasing grain size which in turn was related to the original powder particle size. The properties for the extruded plus aged compacts were more uniform and higher than similar data for HIP compacts which again corresponded to the fine grained and more uniform microstructure of the extruded compacts. The 1200F stress-rupture lives, regardless of the consolidation method used, were inversely proportional to the original powder particle size. However, the lives of the extruded compacts were greater than those of the HIP compacts which might be attributed to the higher deformation strain in the extruded compacts. Tensile properties after 60 per cent upset forging were virtually equivalent for all powder types and consolidation methods while stress-rupture properties were superior for the HIP consolidated powders. This superiority in stress-rupture lives corresponded with differences in microstructure between the two processes. That is, the superior properties were achieved with the warm-worked "necklace" structure as opposed to the fine-grained fully recrystallized structure. In this regard, powder metallurgy Rene' 95 forgings are similar to conventional cast plus wrought Rene' 95 forgings.

Tensile and stress-rupture tests illustrating the effect of forging temperature and per cent reduction on properties are presented in Table II for forgings produced from both extruded and HIP compacted argon atomized powders. These data indicate an increase in the per cent reduction at 1975F significantly increases rupture life with some improvement also noted in the room temperature yield strength. An increase in the per cent reduction at 2075F also seems to increase rupture life but decreases tensile strengths. This loss in strength is probably due to grain growth and recovery which took place during the fifteen minute interpass anneal at 2075F, which is only 35F $\pm$ 5F below the γ' solvus. Forging at 1975F resulted in slightly higher strengths coupled with lower ductilities compared to 2075F forging.

The results of tests conducted to evaluate post solution aging treatment for the purpose of achieving a better balance of tensile and rupture properties than obtained with the standard 1400F/16 hr. age are presented in Table III. In particular, rupture elongations of five per cent were sought while maintaining tensile properties and a 50 hour minimum rupture life at 1200F and 150 ksi. Solution treated forgings (2000F/ 1 hr./oil quench) were used in this study that were produced from argon atomized powders and consolidated by extrusion. The data indicate that the 1400F 64 hour aging treatment and the short-time single step aging treatments at 1500 and 1600F improved ductilities over that obtained with the standard age but that stress-rupture lives were decreased. Even so, all were well above the 50 hour minimum life. In addition, these same post solution aging treatment produced small increases in both room temperature and 1200F tensile strengths. Two step aging treatments employing an intermediate age followed by a lower temperature final age lowered rupture lives without offering significant improvements in rupture elongation even though tensile strengths were improved slightly. Metallographic examinations (SEM) indicated differences in the amount and morphology of a grain boundary phase, presumably $M_{23}C_6$, and in fine γ' size between specimens that probably influenced rupture properties. Definite conclusions, however, cannot yet be made.

The results of tests conducted to investigate the effect of a direct age following forging versus the more conventional solution plus aging treatment are presented in Table IV. HIP forgings produced from argon atomized powder and immediately oil quenched after forging were used. These data indicate that the direct aging treatment resulted in improved 1200F tensile and rupture ductilities, equivalent tensile strengths, but lower rupture lives than the standard heat-treated material. The rupture lives, however, were well above the 50 hour minimum requirement. Microstructural features correlating with these data have not yet been identified; however, it is suspected that grain boundary precipitation is strongly affecting ductility properties.

Full Scale Disks

Ultrasonic Inspection: The disks were non-destructively examined for defects using longitudinal and shear modes of emersion ultrasonic inspection with a 3/4 inch diameter long focused transducer drive at 5 Mhz. No indications larger than 1/4 the calibration reference (20 mil dia. by 0.5" long hole) were found which is well within acceptable limits and in general superior to conventional forgings.

Metallographic Examination: A macroetched cross-sectional slice from the disk forging is shown in Figure 8 together with a similar slice from a conventional forging. Note the very uniform structure of the powder metallurgy disk. Photomicrographs from the bore and rim regions of the powder disk are also shown in the same figure in comparison with photomicrographs of conventional disks. These illustrate the partially recrystallized warm-worked structure that is typical of Rene' 95 forgings. The structures are similar with the exception that the powder metallurgy structure is finer and more uniform and does not contain large carbides.

Mechanical Properties: Smooth and notch tensile properties for the powder metallurgy disks are given in Tables V and VI together with available data for cast plus wrought conventional forgings. These data indicate the powder disk forgings compare very favorably with conventional Rene' 95 forgings. The axial (short transverse) properties are particularly attractive in view of the fact that such properties in conventional forgings are generally 10 to 15 per cent lower in ultimate strengths than tangential or radial properties and 60 per cent to 75 per cent lower in ductilities.

Creep and stress-rupture properties are plotted in Figure 9 in comparison with conventional forging data. The creep lives of powder metallurgy forgings are approximately 1 to 2 Larson-Miller parameter numbers greater than conventional forgings while the stress-rupture properties are comparable. Stress-rupture elongations, not plotted, averaged 7 per cent over the 1100 to 1300F range.

Notched sustained peak low-cycle fatigue (SPLCF) properties for the powder disk forgings are plotted in Figure 10 together with average curves for conventional forgings. This property is an important design consideration for the disk in the dovetail turbine blade attachment region at the rim. These data show the powder metallurgy forgings to be slightly superior to conventional forgings in this respect.

Summary and Conclusions

The results of this investigation indicated that powder metallurgy Rene' 95 can be scaled up very successfully from small 4 pound laboratory size forgings to large production parts having properties comparable or superior to those of conventional forgings. All of the variables investigated in the subscale portion of this study (powder manufacturing method, powder particle size distribution, consolidation method, forging parameters, and heat treatment variations) affected the microstructure and resultant mechanical properties. It is expected that several different combinations of these processing variables could be used to obtain the desired structure and properties. A description of the major trends resulting from both the subscale and full-scale investigations is summarized below.

Powder Manufacturing Method and Particle Size

The most significant difference noted between the three powder manufacturing processes investigated was the resultant powder particle size distribution which affected the grain size and properties in the HIP compacts. That is, coarser particle size distributions resulted in larger grained compacts having lower tensile and stress-rupture properties than did similar compacts made from finer powders. Compaction by extrusion or subsequent working of the compacts significantly minimized differences caused by the original powder particle size distribution. Comparable results might be expected from powders produced by all three methods (argon atomization, rotating electrode process, and H_2/vacuum atomization) if the powder manufacturing parameters were adjusted to produce the same particle size distribution.

Consolidation Method

Regardless of the powder particle size employed, the mechanical properties of the non-forged extruded compacts were superior to those of the non-forged HIP compacts. This appeared to be primarily a function of the fine grain size of the extrusions. Because of the heavy deformation occurring in the extrusion process, the size of the original powder particles did not significantly affect the final grain size. Wide variations in extruded grain size and properties could result by extruding under different sets of extrusion temperatures, ratios and rates. Since very little deformation occurs in the HIP compaction process there are very few options available for controlling grain size other than increasing it by higher temperature compaction. Because there is much more shape flexibility for the HIP process than there is for extrusions, HIP compaction has attractive potential for producing forging preform shapes that cannot be made by extrusion. Forging preforms produced by extrusion are not as desirable in that the best properties are in the longitudinal orientation and as such require heavy upsets in forging to achieve the necessary radial properties. The HIP process has additional potential as a method for producing final part shapes, not requiring forging, that could be very cost effective. The use of very fine size powders coupled with compaction below the γ' solvus may be a way for achieving mechanical properties approaching those of forgings.

Forging Parameters

Forging of the extruded and the HIP compacts tended to level out property differences noted between the non-forged consolidated compacts. For the most part, forging at lower temperatures, 1975F as opposed to 2075F, and at higher forging reductions improved tensile properties. It was significant to note that with only 30 per cent forging reduction, the HIP forgings exhibited properties comparable to extruded compacts and only slightly lower than extrusions receiving 60 per cent forging reduction. Forgings produced from HIP compacts also tended to have slightly higher stress-rupture ductilities than did similar forgings made from extrusions. This was attributed to the warm-worked necklace structure of the HIP forgings. The stress-rupture properties of the full-scale HIP forgings which contained very well defined warm-worked grains were even higher. The use of an anneal at or slightly above the γ' solvus on extruded compacts prior to forging would permit grain growth and would be expected to result in structures and properties in forgings comparable to those of forged HIP compacts.

Heat Treatment

Single step aging treatments ranging from long times at 1400F (64 hrs.) to very short times at higher temperatures (1 hr. at 1600F and 4 hrs. at 1500F) resulted in slightly higher tensile properties and correspondingly lower stress-rupture lives than obtained with the standard 1400F/16 hr. age. Stress-rupture ductilities were, however, increased over those obtained with the standard aging cycle. It appears, therefore, that for some applications using a short-time age at 1500 or 1600F may provide the best balance of properties. It should be pointed out, however, that stress-rupture ductility data from the full-scale disks were improved over those of the subscale disks and were fully adequate for the intended application. This better rupture behavior for the full-scale disks was attributed to the heavier section size of these forgings which led to lower strength levels and correspondingly higher ductilities.

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TABLE I

CHEMICAL ANALYSES OF RENE' 95 POWDERS USED IN SUBSCALE STUDY AND FOR FULL-SCALE DISKS

	Chemical Analyses (w/o)		
Elements	Subscale Master Ingot	Average of Full-Scale Disks	Powder Spec. Range
Carbon	0.070	0.074	0.04-0.09
Manganese	0.01*	0.05*	0.15 max.
Silicon	0.01	0.10*	0.20 max.
Sulfur	0.005	0.006	0.015 max.
Phosphorous	0.007	0.004	0.015 max.
Chromium	13.63	13.66	12.00-14.00
Cobalt	7.85	8.12	7.00-9.00
Molybdenum	3.50	3.46	3.30-3.70
Columbium	3.46	3.45	3.30-3.70
Zirconium	0.05	0.044	0.03-0.07
Titanium	2.48	2.54	2.30-2.70
Aluminum	3.43	3.50	3.30-3.70
Iron	-	0.11	0.50 max.
Boron	0.009	0.009	0.006-0.015
Tungsten	3.50	3.42	3.30-3.70
Oxygen	0.0032	0.0072	0.015 max.
Nitrogen	-	0.0028	0.005 max.
Nickel	Bal.	Bal.	Bal.

* Less than.

TABLE II

EFFECT OF FORGING TEMPERATURE AND FORGING REDUCTION

Material: Argon atomized powders
Extrusion: 10 to 1 at 2000F
HIP: 2090F - 15 ksi

				Tensile Properties					1200F/150 k Ruptu	
Consolidation Method	Forge Temp. (F)	Total % Red.	Number of Passes	Test Temp. (F)	0.2% YD (ksi)	UTS (ksi)	El. (%)	RA (%)	Life (hrs.)	E (%
HIP	1975	30	1	72	188	252	16.8	23.4	180	3
				1200	184	213	7.2	9.8		
HIP	1975	60	2	72	196	257	15.1	15.3	659	2
				1200	180	212	7.4	10.5		
HIP	2075	30	1	72	176	240	15.3	18.6	173	5
				1200	168	218	9.3	10.0		
HIP	2075	60	2	72	176	239	12.0	13.9	715	3
				1200	179	208	8.7	11.9		
EXT	1975	60	1	72	194	247	12.0	15.0	184	3
				1200	182	230	9.0	11.0		
EXT	1975	75	2	72	199	252	15.0	16.0	686	2
				1200	184	222	9.0	11.0		
EXT	2075	60	1	72	191	252	15.0	17.0	295	2.
				1200	182	226	9.0	10.0		
EXT	2075	75	2	72	184	245	16.0	21.0	192	3.
				1200	172	222	12.0	14.0		

TABLE III

EFFECT OF POST-SOLUTION AGING TREATMENT

Material: Argon atomized powders
Thermo-mechanical Treatment: Extruded at 2000F plus upset forged 75% at 1975F
Heat Treatment: 2000F/1 hour/oil quench plus final one or two step aging treatment indicated below

Post-Solution Aging Treatment	Tensile Properties: Test Temp. (F)	0.2% YD (ksi)	UTS (ksi)	El. (%)	RA (%)	1200F/150 ksi Stress Rupture: Life (hrs.)	El. (%)	RA (%)
1400F/16 hrs.	72	199	252	15	16	686	2.8	4.5
	1200	184	222	9	11			
1400F/64 hrs.	72	208	258	13	15	100	9.0	10.6
	1200	188	226	12	15			
1500F/4 hrs.	72	202	254	13	19	121	5.6	6.5
	1200	187	225	10	14			
1600F/1 hr.	72	200	251	16	22	179	6.8	6.0
	1200	182	222	12	14			
1500F/4 hrs. +	72	211	261	13	15	42	3.8	4.7
1400F/16 hrs.	1200	192	224	10	12			
1400F/16 hrs. +	72	211	252	10	13	220	3.8	4.6
1300F/16 hrs.	1200	187	230	10	12			
1600F/1 hr. +	72	213	262	17	20	92	2.8	3.9
1300F/16 hrs.	1200	194	222	9	13			

TABLE IV

DIRECT AGE VERSUS RESOLUTION TREATMENT PLUS AGE

Material: Argon atomized powders
Consolidation: HIP (2090F/15 ksi)
Forging: 1975F; oil quenched from press

Forging Reduction	Heat Treatment	Tensile Properties: Test Temp. (F)	0.2% YD (ksi)	UTS (ksi)	El. (%)	RA (%)	Stress Rupture Pr: Life (hrs.)	El. (%)
30	Standard*	R.T.	188	252	16.8	23.4	180	3.0
		1200	184	213	7.2	9.8		
30	Direct Age**	R.T.	204	261	12.7	12.7	100	7.0
		1200	180	207	12.9	18.6		
60	Standard*	R.T.	196	257	15.1	15.3	659	2.8
		1200	180	212	7.4	10.4		
60	Direct Age**	R.T.	199	260	18.5	25.7	155	9.4
		1200	184	220	12.0	17.2		

* 2000F/1 hr./oil quench plus 1400F/16 hrs.

** 1400F/16 hrs.

TABLE V

TENSILE PROPERTIES OF FULL-SCALE
RENE' 95 POWDER DISK (1)

Test Temp.	Location	Orientation	UTS (ksi)	0.2% YS (ksi)	El. (%)	RA (%)	Section Thickness(in)
R.T.	Bore	Tang.	224	173	11	14	4.5
R.T.	Bore	Rad.	228	168	11	13	4.5
R.T.	Bore	Axial	210	167	7	8	4.5
R.T.	Average	Cast + Wrought	215	168	15	17	4.5
R.T.	Rim	Tang.	225	172	11	11	2.5
R.T.	Rim	Rad.	236	179	13	14	2.5
R.T.	Average	Cast + Wrought	224	174	15	17	2.5
900	Bore	Tang.	217	162	13	15	4.5
900	Bore	Rad.	206	156	9	11	4.5
900	Bore	Axial	204	158	7	10	4.5
900	Average	Cast + Wrought	208	162	12	14	4.5
900	Rim	Tang.	221	169	11	14	2.5
900	Rim	Rad.	223	166	12	15	2.5
900	Average	Cast + Wrought	216	167	12	14	2.5
1200	Bore	Tang.	208	166	10	15	4.5
1200	Bore	Rad.	199	154	15	18	4.5
1200	Bore	Axial	191	158	5	7	4.5
1200	Average	Cast + Wrought	194	156	14	16	4.5
1200	Rim	Tang.	204	166	12	16	2.5
1200	Rim	Rad.	203	166	15	20	2.5
1200	Average	Cast + Wrought	203	161	14	16	2.5
1300	Rim	Tang.	188	168	9	15	2.5
1300	Average	Cast + Wrought	189	158	15	16	2.5

(1) Averaged data from two disks.

TABLE VI

NOTCH TENSILE PROPERTIES OF FULL-SCALE
RENE' 95 POWDER DISK

Temp.(F)	Material	UTS(ksi) $K_t=1$	UTS(ksi) $K_t=3.5$	N/S Ratio
R.T.	Powder Met.	230	253	1.1
R.T.	Cast + Wrought	-	-	-
900	Powder Met.	222	247	1.1
900	Cast + Wrought	214	240	1.1
1200	Powder Metl.	203	257	1.3
1200	Cast + Wrought	-	-	-

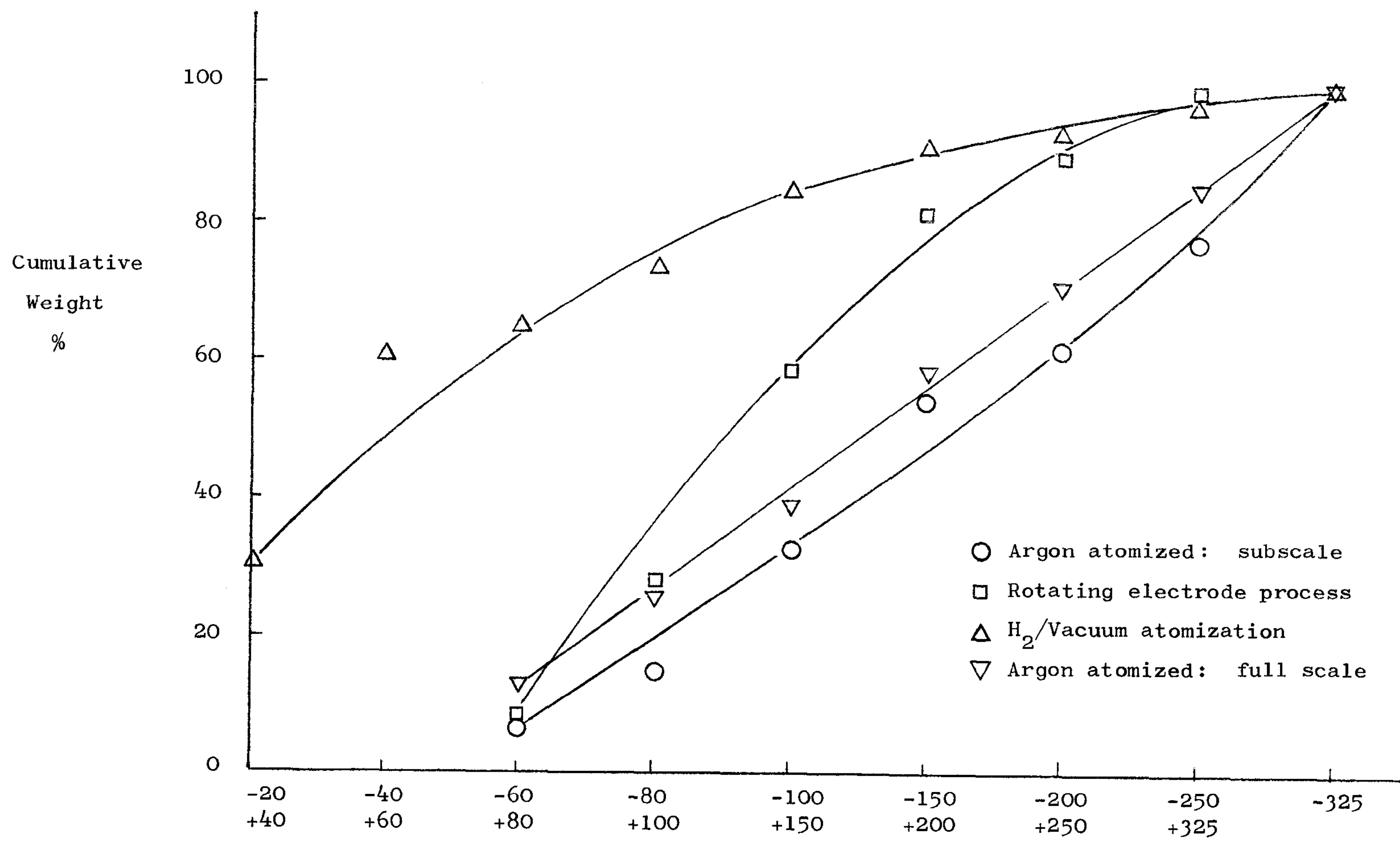
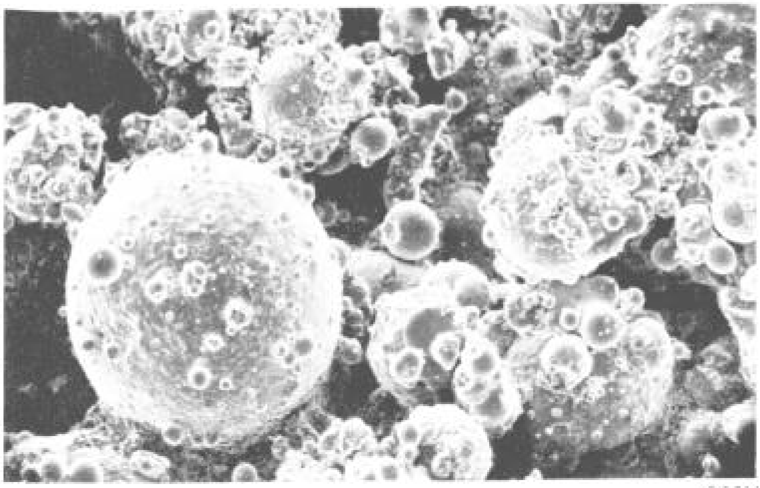
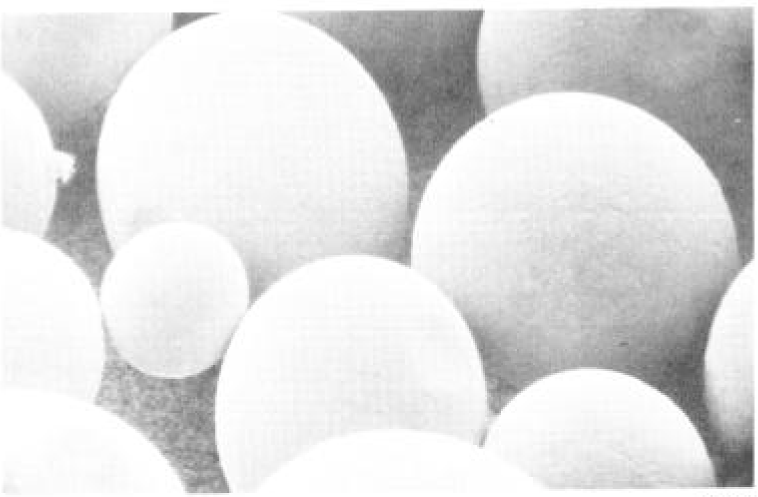


Figure 1: Particle size distribution for three subscale powder lots and average of full-scale pow



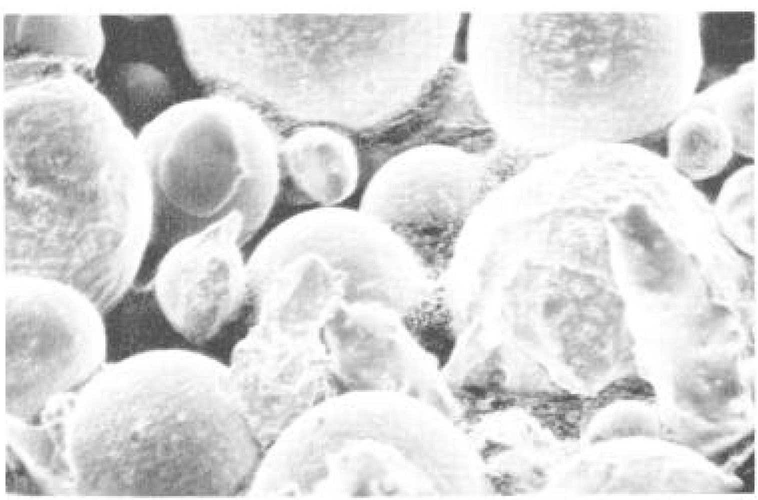
200X

Argon Atomization
(-60 mesh)



200X

Rotating Electrode
Process (-60 mesh)



200X

H_2/Vacuum
Atomization (-20 mesh)

Figure 2. Scanning Electron Micrographs of Powders Made by Three Manufacturing Techniques.

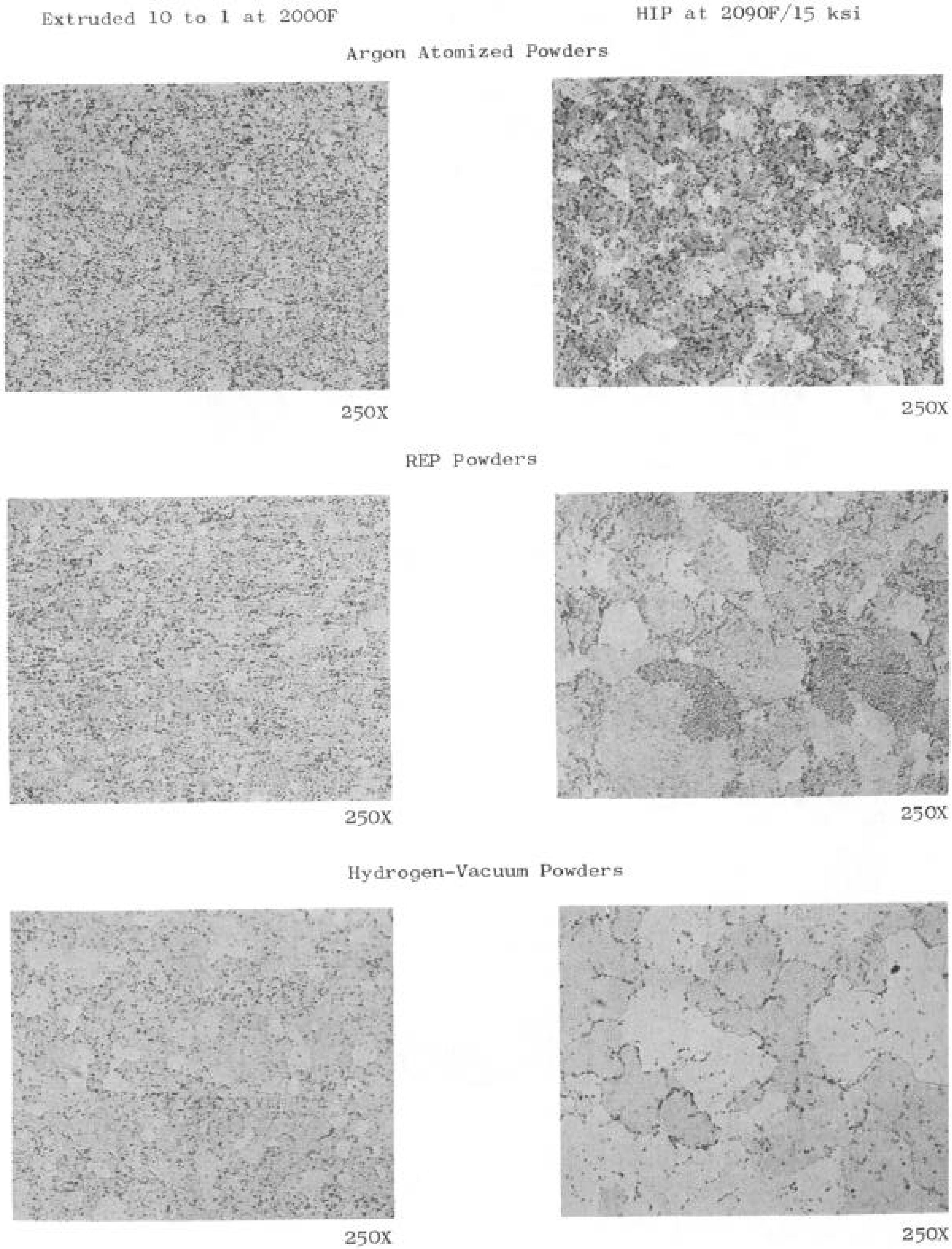
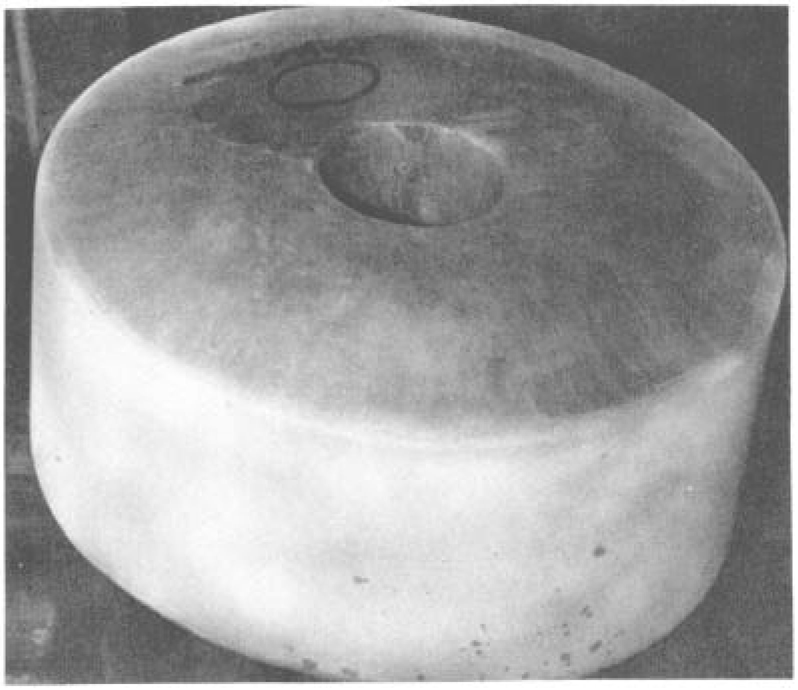


Figure 3. As-Consolidated Microstructures.



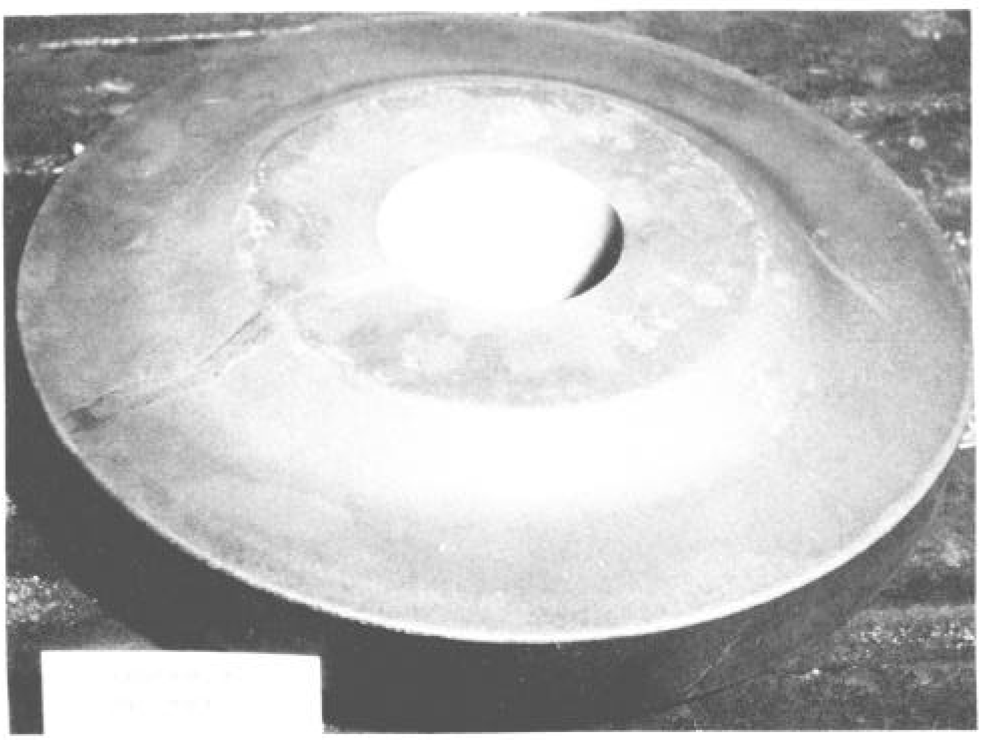


Figure 4: Rene' 95 Full-Scale Forging Preform and Jet Engine Disk Forging.
Top: Forging Preform: (15-1/2" OD X 8-1/2" thick)
Bottom: Finish Forged Disk: (20" OD X 4" thick at bore)

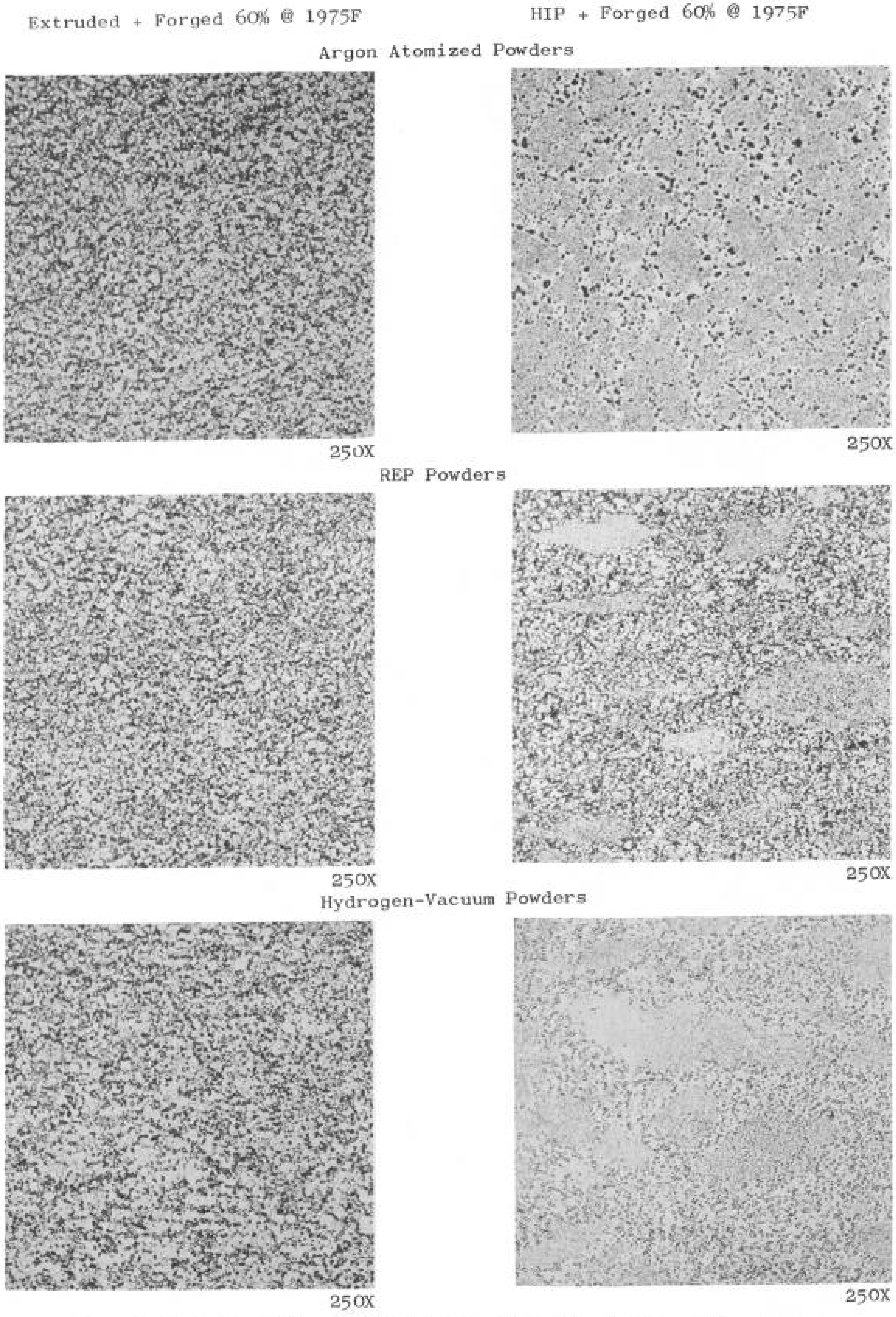
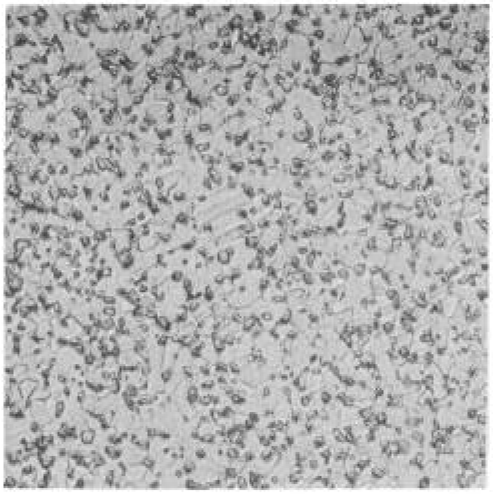


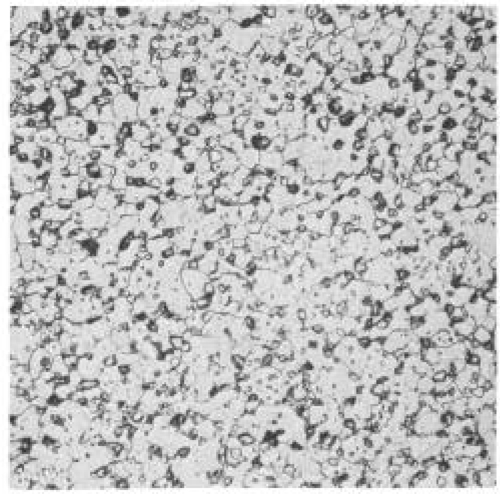
Figure 5. Effect of Powder Manufacturing Technique on Consolidated and Forged Microstructures.

Extruded + Forged 60%



500X

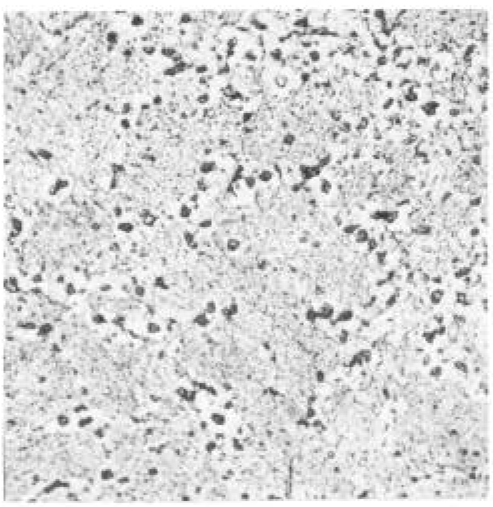
1975F forging



500X

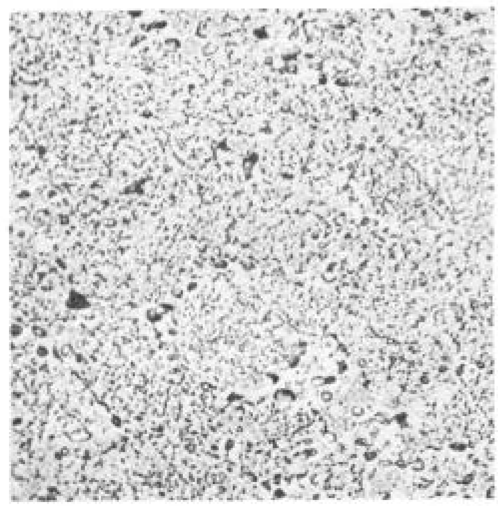
2075F forging

HIP + Forged 60%



500X

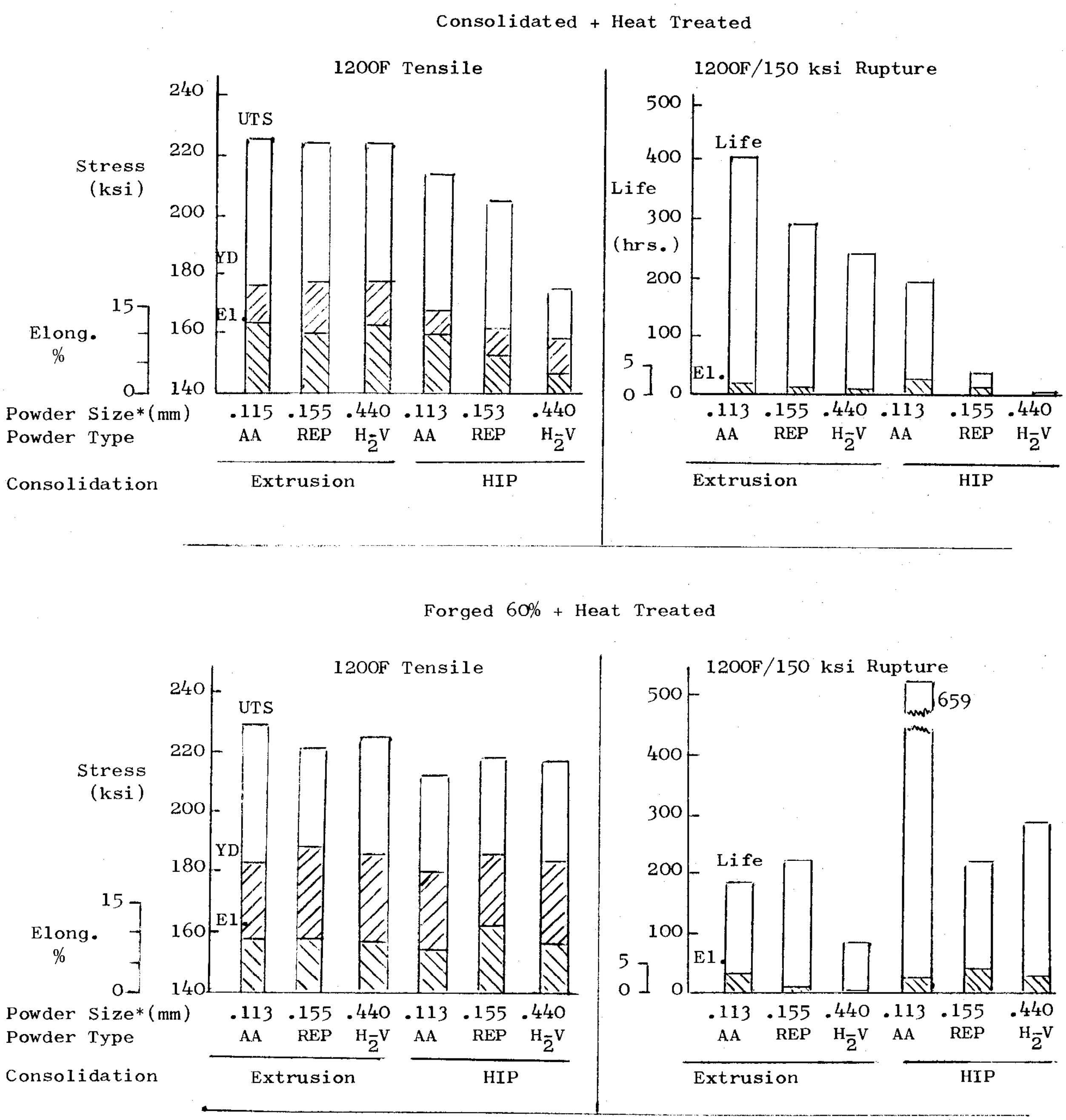
1975F forging



500X

2075F forging

Figure 6: Effect of Forging Temperature on HIP Compacts and Extrusions using Argon Atomized Powders.



* Size of particle of average weight.

Figure 7. Effect of Powder Manufacturing Technique and Consolidation Method on As-Consolidated and Forged Properties

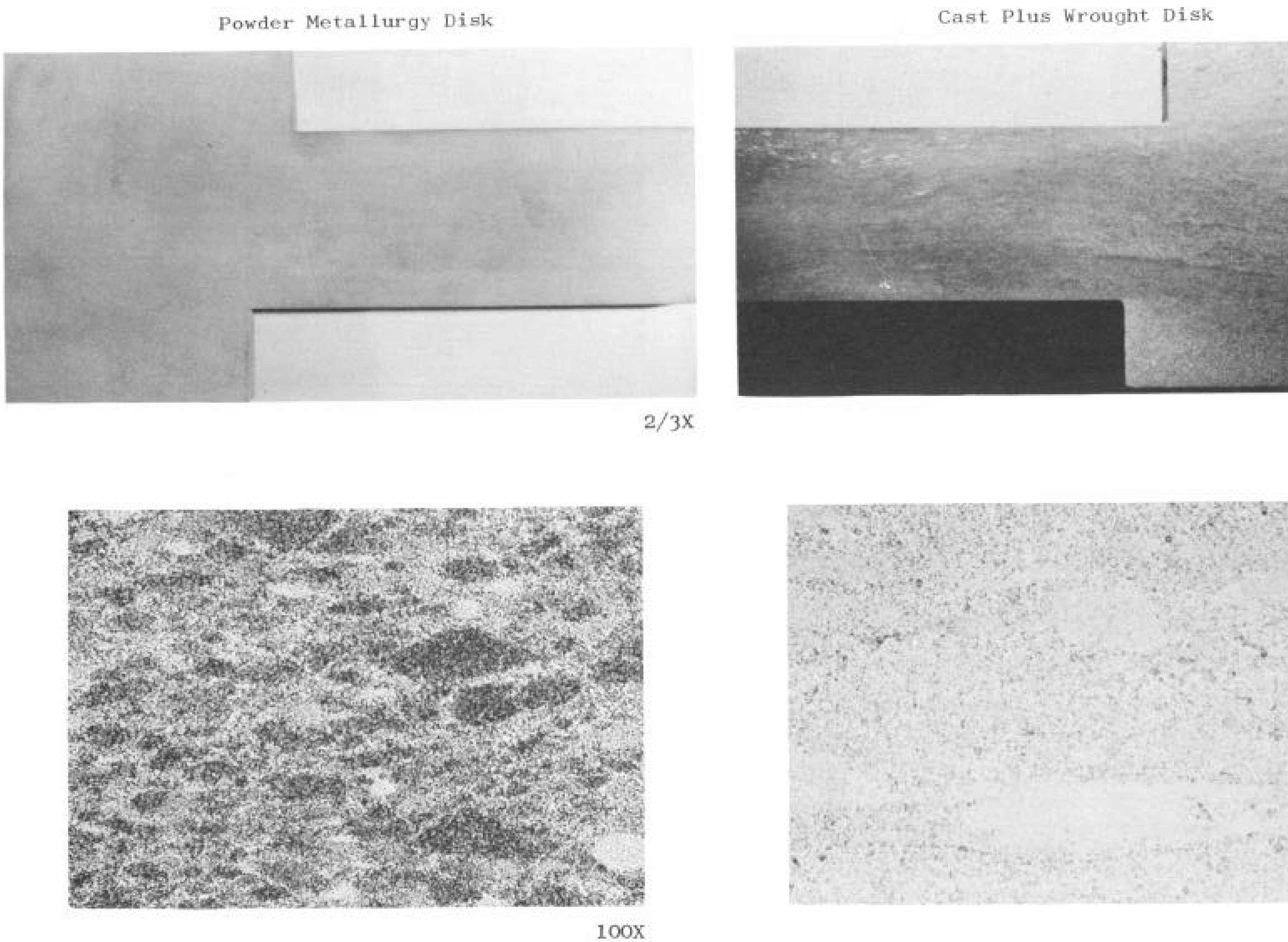


Figure 8: Comparative Macro and Microstructures of Powder Metallurgy and Conventional Cast Plus Wrought Rene' 95 Disks.

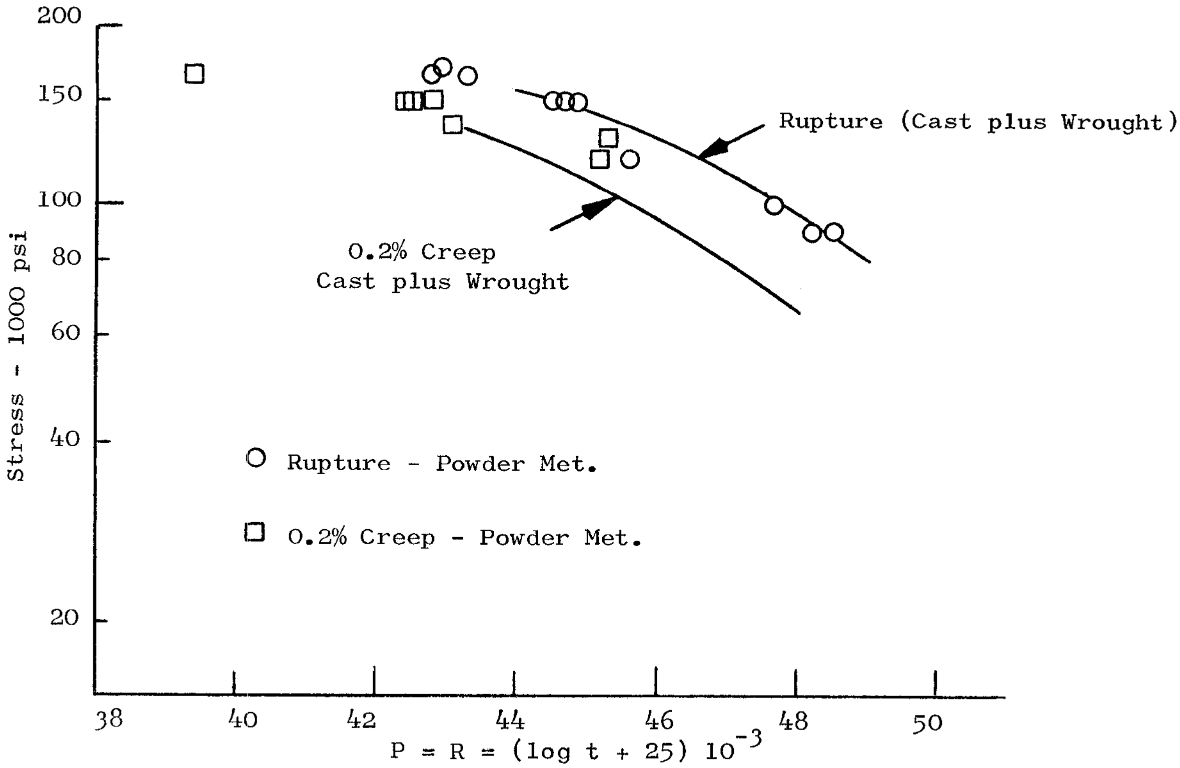


Figure 9: Creep Rupture Properties of Full Scale (2.5 inch thick rim) Rene' 95 Disks.

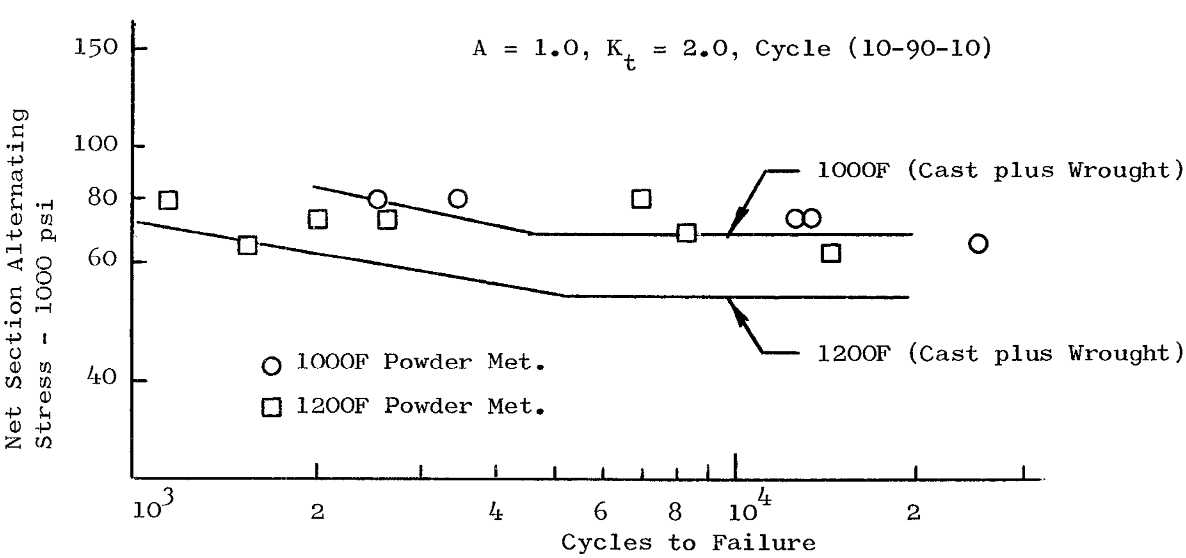


Figure 10: Sustained Peak Low-Cycle Fatigue (SPLCF) Properties of Full Scale (2.5 inch thick rim) Rene' 95 Disks.