P/M ALLOY 718 TUBING PRODUCED

BY COLD RADIAL FORGING

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Abstract

A unique advantage of P/M processing is in producing near-net shape or even final shape products. A good example is the Grotnes cold radial forging of P/M 718 tube hollows as a promising method of manufacturing turbine rings and shafts up to 15 ft. length. The segmented dies and a tapered ring in the jaws of the shrinker squeeze the P/M 718 tube hollow radially over a mandrel and provide precise control over the ID, wall thickness and concentricity. In comparison, an extruded tube needs additional work to obtain similar dimensional control. In this study, tube sections were incrementally reduced from 9 pct to 45 pct from machined 4 3/4 in. OD, 7/16 in. wall, 15 in. long hollows (now produced directly by the use of glass tube molds in the CAP^r process). Both after the standard solution and aging treatment and as radial cold forged and aged, excellent strength and ductility were obtained in tensile tests at ambient and at 650°C and in stress rupture tests at 650°C. The latter treatment provides even higher strength properties with good yield to tensile ratio and adequate ductility for most applications. In both cases, the large reduction in grain size from ASTM5.5 to 8.5 with increasing forging reduction and the pancaking in the longitudinal direction occurred. Also, the properties compared favorably with Pilger mill rolled product from the same P/M tube hollow material. Although, the Grotnes metal forming equipment cannot provide the long lengths of tubing that are possible with Pilger mill rolling, the operation should be studied to provide longer starting stock for Pilgering rather than extrusion, and with the added benefit of better dimensional control for Pilgering.

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Introduction

The use of powder metallurgy (P/M) technology in the production of Alloy 718 is a relatively recent event, and the paper by Radavich and Meyers[1] reveals the structural behavior of P/M 718 when subjected to thermomechanical processing. The same phases are found in P/M 718 as in the conventionally produced wrought counterpart; however, both precipitate and second phase particles are much finer and more uniformly dispersed in P/M 718. The recrystallized structure of P/M 718 maintains a finer grain size at a given solution temperature, presumably at least partially due to the small discrete particles in pinning grain boundaries. Mechanical properties of P/M 718 rolled bar are equivalent to those of wrought 718 rolled bar and can be varied as a function of solution treatment temperature. These facts indicate that the use of P/M technology for production of Alloy 718 provides a high quality product which offers the advantages of a finer and more uniform microstructure and the ability to process at higher temperatures, as well as considerable flexibility in mechanical properties.

A unique advantage of P/M processing is in producing near-net shape or even final shape products. Various P/M forging procedures achieve high properties by processing parts to high or full density. Specialty tubing and piping are a particular application where product quality and relative cost should be investigated. This paper provides a metallurgical evaluation of P/M Alloy 718 tubing that was produced by the Grotnes cold radial forging process.[2] The operation, diagramed in Figure 1, is done on three zones of a die which, in sequence, reduces the cross-section of the tube hollow over the mandrel via the action of the manipulator jaws. The machine is a feed-through type with several round shrinking dies actuated by tapered wedges that are moved by hydraulic cylinders pressing rather than hammering the hollow radially over the hardened mandrel. The use of a combination of dies with spacers allows the machine to have a wide range of part diameters. The three zones of the die are the sinking zone, forging zone and sizing zone which provide precise control over the ID, wall thickness and concentricity. In comparison, an extruded tube needs additional work to obtain similar dimensional control. Thus, the process

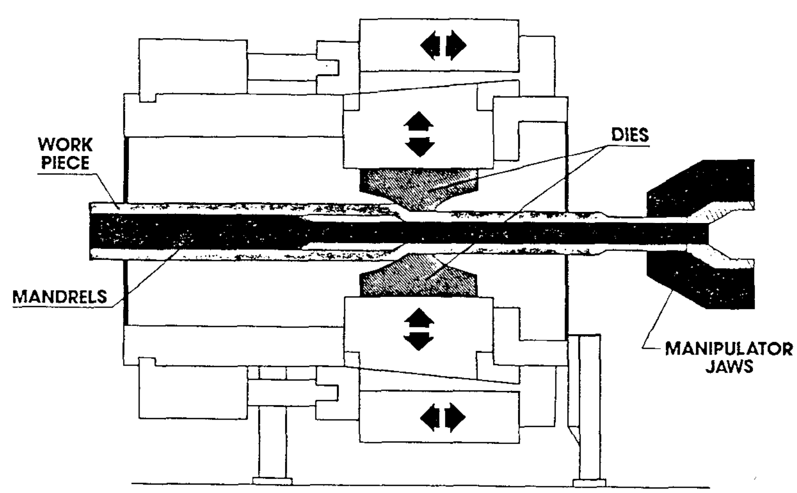

Figure 1 - Diagram of Grotnes cold radial forging process.

will produce precision hollow shafts up to 15 feet length which would be of primary interest for jet engines and stationary turbines.

Material and Procedure

The powder was produced by argon atomization, screened to-150 mesh and consolidated by atmospheric pressure technology, the CAP process,[1] from a VIM heat that analyzed on a wt pct basis:

C	Mn	Si	Cr	Mo	Nb	Fe
0.036	0.09	0.06	18.63	2.95	5.23	19.23
Ni	**Al**	**Ti**	**B**	**O(ppm)**	**N(ppm)**	
bal	0.52	0.85	0.006	144	150	

P/M 718 billets that were 5.0 in. diameter and 30 in. long were cut in half and machined to 4 3/4 in. OD, 3 7/8 in. ID and 7/16 in. wall. After annealing for 1 hour at 1010°C (1850°F) and air cooling, the billet microstructure consisted of a uniform ASTM5 grain size. For comparison, another billet from this heat was machined to 4 3/4 in. and 3/4 in. wall and direct cold reduced to 3.0 in. x 0.470 in. x 40 in. length on a commercial Pilger mill in two stages reducing the cross-section by 37 pct and 39 pct.

One P/M 718 tube hollow was forged over the first mandrel only while the other one was also forged over the first mandrel, then annealed, and forged over the second mandrel. At this point, both were split in-half (longitudinally) with one-half of each annealed (A) and other half left in the as-forged (F) condition. The ribbed appearance of the OD of the tube produced by the segmented dies when forged on the first mandrel is shown in Figure 2a. The smooth surface of the ID over more heavily reduced two parts, or major part of the length of the tube, is shown in Figure 2b.

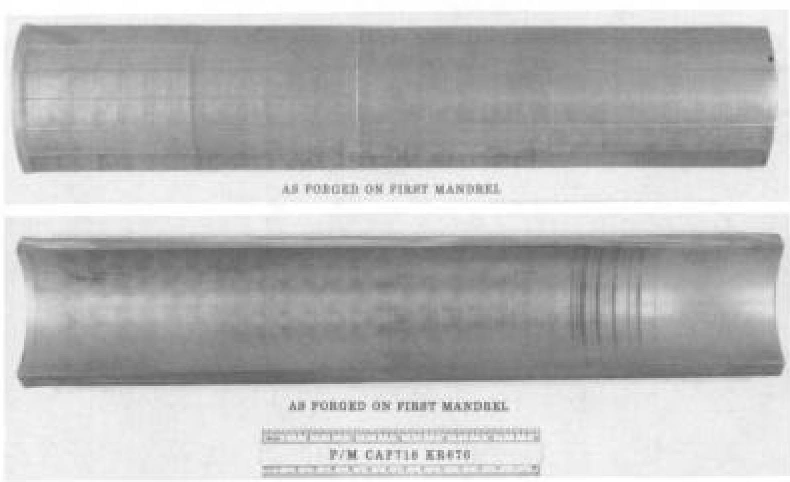

Figure 2 - View of outside diameter and inside diameter of P/M 718 tube forged on first mandrel incrementally to provide 9 pct, 14 pct and 22 pct reduction in cross section. Note longitudinal ribs produced by segmented dies which will be removed by machining the outside surface. The interior surface is very smooth but bears an impression of mandrel and segmented die ring.

The identification of the four pieces from the two tubes and the percentage cross-section reduction (to starting cross-section) over a specified length of the tube (piece) was recorded as 9 pct over 3 1/2 in. from one end, 14.6 pct over 3 3/8 in. of the middle portion, and 22.6 pct over 4 1/2 in. towards the other end of the tube hollow forged only on the first mandrel. The specimens are identified with prefix 1 referring to forging over the first mandrel only, A or F referring to Annealed or as-Forged respectively and 9 indicating the percent reduction, for example: 1A9 or 1F9. For the other tube hollow that was forged over the second mandrel, the values were 28.4 pct over 4 7/8 in. from one end, 36.2 pct over 5 in. of the middle portion and 45 pct over 4 3/8 in. towards the other end of the tube. These specimens are identified with prefix 2 in this paper, for example: 2A28 or 2F28.

A rectangular specimen was cut from each of the three parts of the tube forged over the first mandrel and three parts of the second tube forged over both the first and second mandrels. The density of each specimen was measured by the water displacement method, that is its weight in air and then in water and with the determinations inserted in a standard formula. Pieces for machining into stress rupture and tensile test specimens were cut in the longitudinal direction from each incremental reduced section of the tubing.

TABLE I

Density Measurements on P/M CAP 718 Tubing Produced by Grotnes Radial Cold Forging

Spec. Ident.	Thickness, inch	Density, g/cc
1F9	0.410	8.1975
1F14	0.388	8.1941
1F22	0.357	8.2116
2F28	0.335	8.2209
2F36	0.302	8.2383
2F45	0.255	8.2716

Density values determined by water displacement technique. Published density of cast and wrought 718 = 8.199 g/cc, or 0.296 lb./in.^{3}.

TABLE II

Tensile Test Results on Annealed P/M CAP 718 Tubing

Spec. Ident.	Thickness (inch)	Ultimate Stress, psi	0.2% Yield Stress, psi	Elong. pct.	Red. of Area, pct.
		After Cold Forging and After Annealing by Grotnes			
1A9	0.410	121,300	51,900	55.5	46.2
1A14	0.388	124,800	51,900	54.5	51.3
1A22	0.357	128,400	55,100	51.2	50.9
2A36	0.302	136,100	62,100	48.3	53.5
2A45	0.255	137,600	64,100	45.8	56.2

Results

Table I presents the density values determined by the water displacement technique on the as-forged specimens. If the values are compared with the published value of 8.199 g/cm^3 for wrought 718, it is apparent that practically full density was achieved with reduction of 9 pct and 14 pct while full density was definitely obtained with reductions above 22 pct. Table II shows, that after annealing for 1 hr at 1010°C (1850°F), the incrementally reduced sections of the two tubes possess room temperature tensile test properties that would insure good workability. The yield to tensile ratios are superior to those obtained on annealed rounds of conventional cast and wrought 718.

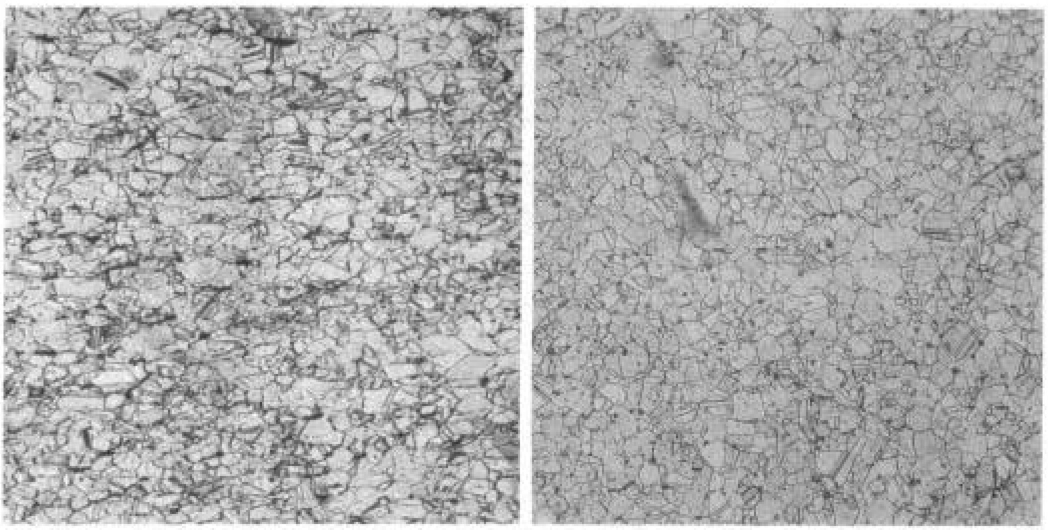

Figure 3 - Structure in longitudinal and transverse direction of radial forged P/M 718 tube hollow cold reduced 36 pct to 0.302 in. ASTM 7 grain size. X100.

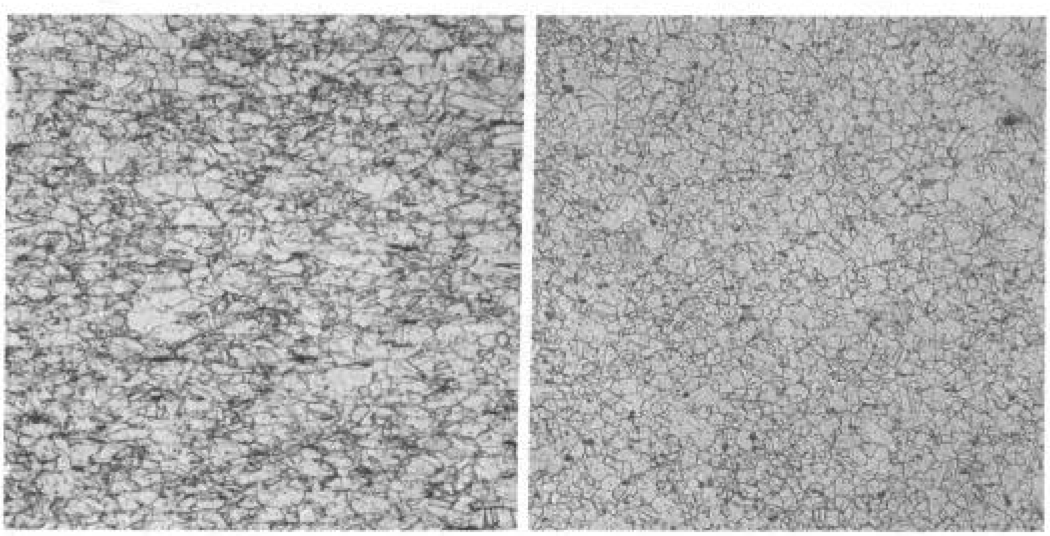

Figure 4 - Structure in longitudinal and transverse direction of radial forged P/M 718 tube hollow cold reduced 45 pct to 0.255 in. ASTM 8.5 grain size. X100.

TABLE III

Mechanical Properties of P/M CAP 718 Tubing Produced by Grotnes Radial Cold Forging

Spec. Ident.	Thickness* (inch)	Type Test	Test Temp, °F	Ultimate Stress, psi	0.2% Yield Stress, psi	Elong. pct.	Red. of Area, pct.	Rupture Life, hr.
			Standard Solution and Aging Treatment**					
1A9	0.410	Tensile	Room	195,200	168,500	18.6	30.7	
		Tensile	Room	195,900	167,400	20.1	33.0	
		Tensile	1200	162,700	141,800	14.3	23.7	
		S/R	1200	110,000		8.5	13.7	54.0
1A14	0.388	Tensile	Room	197,300	171,800	18.0	35.5	
		Tensile	Room	197,600	171,800	17.8	35.7	
		Tensile	1200	165,100	144,600	16.3	31.0	
		S/R	1200	110,000		8.9	15.9	46.8
1A22	0.357	Tensile	Room	201,900	175,000	20.8	37.4	
		Tensile	Room	200,100	174,700	16.9	35.4	
		Tensile	1200	166,200	145,300	15.2	24.7	
		S/R	1200	110,000		10.0	13.9	56.8
2A28	0.335	Tensile	Room	202,500	174,900	20.6	41.2	
		Tensile	Room	202,600	176,600	18.6	36.4	
		Tensile	1200	167,900	146,700	15.4	22.2	
		S/R	1200	110,000		7.1	16.5	97.9
2A36	0.302	Tensile	Room	204,900	178,300	18.9	40.5	
		Tensile	Room	205,600	178,500	18.6	39.7	
		Tensile	1200	170,600	148,000	20.2	31.7	
		S/R	1200	110,000		8.5	12.8	74.5
2A45	0.255	Tensile	Room	207,600	178,600	20.5	42.6	
		Tensile	Room	205,100	173,200	20.3	42.3	
		Tensile	1200	172,800	151,500	17.2	27.9	
		S/R	1200	110,000		8.1	15.7	65.8

* Original thickness = 0.4375 inch (7/16 inch); tube hollow was machined to 4-3/4 inch O.D. and 3-7/8 inch I.D. Final O.D. = 4 inch and final length = 16 inch (original length = 15 inch).

** Solution annealed at 1875°F for 1 hour, water quenched, plus aging for 8 hours at 1325°F, furnace cool to 1150°F and holding for 8 hours at 1150°F, then air cooled.

Representative micrographs of the cross-sections taken in both the longitudinal and transverse directions of the tube sections cold reduced 36 and 45 pct are set forth as Figure 3 and4. There is a diminishing amount of microporosity as the forging reduction increases from 9 to 45 pct. The microporosity is evident as black dots and irregular areas which are magnified by the residue of the strong etchant (HCl) employed to outline the grain size. The large reduction in grain size from ASTM5.5 to 8.5 with increasing forging reduction is an important feature as well as the pancaking of the grains noted principally in the longitudinal views.

Table III presents the tensile and stress rupture results for each forging increment of the tubing. These specimens were given the conventional solution and two stage aging treatment established for conventionally cast and wrought 718. The solution temperature was 1025°C (1875°F) instead of 936°C (1825°F) which was the case for the CAP 718 tubing produced by Pilger Mill rolling. The ambient tensile test results are good even for the lowest reduction in cross-section and for all of the two-stage reductions, excellent strength and ductility values are evident throughout. AMS 5662B and 5663B for bars, forgings, and rings and AMS 5589 for seamless tubing allow minimum 185,000 psi ultimate, 150,000 psi yield, 12 pct elongation, and 15 pct reduction of area. The tensile test results at 650°C (1200°F) are also well above the requirements of these specs which are 145,000 psi ultimate, 125,000 psi yield with 12 pct elongation and 15

TABLE IV

Mechanical Properties of P/M CAP 718 Tubing Produced by Grotnes Radial Cold Forging

Spec. Ident.	Thickness* (inch)	Type Test	Test Temp, °F	Ultimate Stress, psi	0.2% Yield Stress, psi	Elong. pct.	Red. of Area, pct.	Rupture Life, hr.
		As Radially Cold Forged and Standard Aging Treatment**						
1F9	0.410	Tensile	Room	201,900	186,000	9.8	22.8	
		Tensile	Room	200,600	183,900	10.5	23.0	
		Tensile	1200	165,600	152,500	11.4	24.9	
		S/R	1200	110,000		5.2	11.0	76.8
1F14	0.388	Tensile	Room	205,800	192,500	9.7	21.9	
		Tensile	Room	206,600	193,000	9.5	23.4	
		Tensile	1200	172,100	158,400	11.5	18.7	
		S/R	1200	110,000		2.8	7.6	66.4
1F22	0.357	Tensile	Room	216,600	206,400	6.8	21.0	
		Tensile	Room	204,600	192,000	8.8	25.0	
		Tensile	1200	178,200	164,800	8.6	19.3	
		S/R	1200	110,000		2.0	3.8	109.3
2F28	0.335	Tensile	Room	224,000	213,900	10.0	18.0	
		Tensile	Room	225,700	216,800	9.5	28.5	
		Tensile	1200	187,600	172,100	13.1	32.6	
		S/R	1200	110,000		4.0	6.7	113.5
2F36	0.302	Tensile	Room	234,500	225,100	9.7	29.1	
		Tensile	Room	234,400	225,000	8.3	30.1	
		Tensile	1200	194,500	178,500	10.8	35.2	
		S/R	1200	110,000		5.5	14.4	111.7
2F45	0.255	Tensile	Room	236,800	227,000	11.2	33.6	
		Tensile	Room	239,200	227,800	8.7	29.2	
		Tensile	1200	202,100	182,100	11.1	35.9	
		S/R	1200	110,000		7.1	8.0	101.4

* Original thickness = 0.4375 inch (7/16 inch); tube hollow was machined to 4-3/4 inch O.D. and 3-7/8 inch I.D. Final O.D. was 4 inch and final length 16 inch (original length = 15 inch).

** The above as forged specimens were aged at 1325°F for 8 hours then furnace cooled to 1150°F and held for 8 hours and air cooled (no prior solution treatment).

pct reduction of area. Finally, the stress rupture requirements of 23 hours and 4% elongation under a stress of 100,000 psi at 650°C are exceeded, in every case, even at a higher stress of 110,000 psi. In comparison, the ultimate tensile strength of Standard Process 718 at room temperature is nominally 185,000 psi for ASTM4-6 grain size[3] so it is evident that the P/M forged tube has adequate properties for turbine shafts and rings.

In the case of conventionally cast and wrought 718, there has been interest and evaluation of direct aged 718. This product has been produced by heavy forging of billets, 60 to 75 pct in the 1025-982°C (1875-1800°F) range, and then giving them only the standard two-stage aging treatment (with no preceding solution treatment). As an experimental procedure, specimens were also obtained from the tube sections that were in the the as radially cold forged condition and these were given only the standard two-stage aging treatment. The data presented in Table IV show, for the higher reductions produced by forging on the second mandrel, that even higher strength properties (than the conventional treatment, per Table III), with good yield to tensile ratio and adequate ductility values for most applications are possible. Direct Age 718 processing maximizes tensile strength and LCF properties and the ultimate tensile strength is typically 210,000 psi for ASTM10 grain size.[3] Again, it is evident that direct aging of P/M 718 forged tubing provides excellent UTS to qualify such product for a high-pressure turbine application.

TABLE V

Comparison of Mechanical Properties of P/M CAP 718 Cold Reduced to Tubing via Grotnes Radial Forging (Product A) vs. Pilger Mill Rolling (Product B)

Ambient Tensile Properties	Grotnes	Pilger
Ultimate Strength, psi	206,400	216,000
0.2% Yield Strength, psi	178,300	187,000
Elongation, %	20.4	20.3
Reduction of Area, %	42.5	38.7
Tensile Properties at 1200°F	**Grotnes**	**Pilger**
Ultimate Strength, psi	172,800	175,500
0.2% Yield Strength, psi	151,500	156,000
Elongation, %	17.2	13.7
Reduction of Area, %	27.9	19.8
Stressed 110,000 psi at 1200°F	**Grotnes**	**Pilger**
Rupture Life, hours	65.8	53.3

Properties obtained after solution anneal and double aging treatment. Solution temperature was 1875°F for 1 hour for Product A and 1825°F for 1 hour for Product B.

Discussion

It is interesting to compare the results of Grotnes two-stage cold rotary forged to 45 pct reduction in cross-section with P/M 718 directly cold reduced to tubing in a Pilger mill in two stages reducing the cross-section by 37 pct and 39 pct. The results presented in Table V show that the less heavily worked product from the Grotnes process produces comparable properties to the Pilger mill rolled product. The minor variations in properties are likely a result of the difference in solution temperatures. The high ductility values for the percent reduction are noteworthy and also reflective of powder quality in view of the known effect on ductility of oxygen in the powder. It should be recognized that the Grotnes metalforming equipment will not be able to provide longer lengths of tubing that are possible with Pilger mill rolling, but it could be used to provide longer starting stock for Pilgering rather than extrusion, and with the added benefit of better dimensional control. Thus, a way to lengthen a short P/M hollow preform to a size that will provide a commercial length of tubing via Pilgering that will meet the requirements for sour-gas wells and CPI should be possible. And the distinct advantage of this two-stage process would be that the operation would be done without hot working to disrupt the fine grain size of the original P/M product.

A comparison can also be made between the mechanical properties of the cold forged tube properties listed in Table V and cold rolled plate derived from a 1 in. thick slice cut from the end of a billet of the same heat that was solution annealed at 1010°C, cold rolled 50 pct, then reannealed and cold rolled another 50 pct. After the standard solution and aging treatment, the respective tensile properties were 220,700 psi, 188,500 psi, 18.6 pct and 28.5 pct at room temperature, and 176,400 psi, 153,500 psi, 12.0 pct and 19.2 pct at 650°C, and with a rupture life of 66.5 hr when stressed at 110,000 psi. Again, it is apparent that the less heavily worked cold forged tube produces comparable results to cold rolled plate product from the same CAP718 billet.

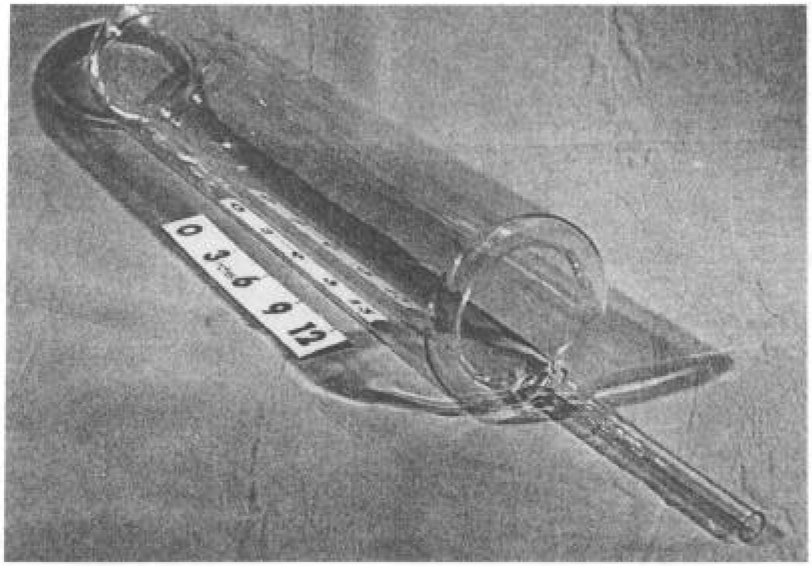

Figure 5 - Glass mold to produce tube hollows of P/M 718 and 625 via CAP technology.

Spray forming of Alloy 718 tube preforms via the Osprey Process has been shown to be a worthwhile procedure. The properties are improved by the densification resulting from a HIP treatment and are further improved by forging.[4,5] Although a strict comparison should not be made for various reasons, our results on cold radial forging of CAP718 hollows, derived from argon atomizing, compare very well with high nitrogen content 718 spray

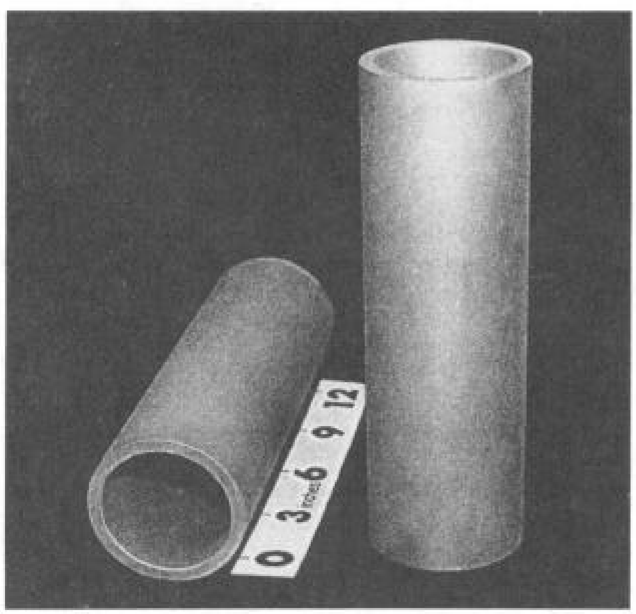

Figure 6 - P/M 718 tube hollows produced by CAP technology.

formed tube product, from nitrogen atomizing, that was then HIP and forged and superior to the results on spray formed tube, from argon atomizing, that had been given these densifying treatments.

Since this study was done to show the feasibility of the process, glass mold fabrication for the CAP process has been perfected which will produce tube hollows directly. An example of a glass mold which has been used to produce tube hollows of P/M 718 and 625 via CAP technology is shown in Figure 5 and a couple of P/M 718 hollow preforms produced directly from glass molds are shown in Figure 6. Tube length and wall thickness can now be varied and such preforms are well suited for cold radial forging to an end-product such as a turbine shaft or an intermediate product to be reduced to longer length, thin wall piping on a Pilger mill. P/M processing of Alloy 718 and 625 is advantageous because it not only produces a finer grain size but also minimizes segregation tendency that occurs in ingot or casting solidification. In addition to the use of a CAP preform, alternate starting materials would be hollow-HIP preform, hollow ESR ingot or trepanned billet. The features of the Grotnes hollow shaft manufacturing process include less consumption of critical materials, less input material (50-75 pct reduction) and reduced OD machining and elimination of up to 95 pct of ID machining.

Conclusion

This initial survey of the Grotnes cold radial forging process reveals that it will produce excellent mechanical properties and refined grain size in P/M CAP 718 tube hollows, and further work on its application for the production of turbine shafts and rings, and intermediate product for Pilger mill rolling to longer lengths of thin wall piping is recommended.

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