HIGH QUALITY, HIGH STRENGTH ALLOY 718 BILLET

MATERIAL USING FINE-GRAIN CONVERSION PRACTICE

Murray Kaufman and Charles J. Scholl

General Electric Co. Wyman-Gordon Co.

Abstract

Elimination of the forging process step in the manufacture of conventionally forged products could reduce overall costs appreciably. For this to be possible, the starting material would have to be clean with respect to non-metallic inclusions and carbide aggregation, and have minimal chemical segregation. The ingot to billet conversion process would have to produce a uniformly fine grained structure with carbide stringers, inclusion content and mechanical properties that would meet forged part requirements.

A production ingot of Alloy 718 was homogenized and converted to 15" RCS billet by the melter. It was then further processed to three 8" round billets, 135" long each at Wyman-Gordon using a "fine grain" conversion practice. This practice employs controlled reductions and heating times with a decreasing forge temperature ending at 1800°F for the final cosmetic pass. A 2000 T conversion press and flat draw dies were used.

After a 1750°F solution and two step age the structure, cleanliness and mechanical properties were evaluated on specimens taken from the top of the top billet, the top of the middle billet and the bottom of the bottom billet. Traverse and longitudinal sections were examined macroscopically and metallographically for grain size, grain flow, presence of stringers and inclusions, precipitated phases, etc. Smooth and notched tensile tests were run at R.T. and 1000F in duplicate on specimens in the longitudinal, radial and tangential orientations from each of the three billet locations. Creep rupture tests at 1200F were carried out on similarly oriented test bars. Low cycle fatigue tests, strain controlled, were run at 800F in triplicate for the longitudinal and radial orientations of the three billets.

Cleanliness and grain structure was very good, with only rare patches of coarser grains at the very surface of the top billet. Occasional carbide stringers up to a maximum of 0.0075" long were seen. Some variation of Ni_3Cb precipitate was present, within the normally encountered range in forgings. Tensile strengths and ductilities were good at both temperatures, with notched to smooth U.T.S. ratios always above 1.35. Creep rupture and LCF properties were comparable to those of normal forgings, as well. No significant differences with billet location were found for any of the properties. The longitudinal specimens did tend to exhibit greater

Superalloy 718—Metallurgy and Applications
Edited by E.A. Loria
The Minerals, Metals & Materials Society, 1989

ductility and LCF life than the others.

In summary, cleanliness, structure and properties of these Alloy 718 billets appear to be equivalent to those of conventional forgings.

Introduction

Many parts requiring high strength at low to moderate temperatures are machined from forgings. The conventional production sequence is cast ingot-billet-forging-machined component. Elimination of any of the steps in this sequence may offer substantial savings. In the past, the conversion of the cast ingot to a wrought billet, and the forging of billet segments was necessary to produce the high strengths and quality required. Non-metallic inclusions and carbides had to be broken up and dispersed, voids and porosities closed, chemical homogeneity improved, fine-uniform grains produced, etc. With the introduction of cleaner and better controlled ingot production and improved conversion to billet processing, it may be possible to attain the required properties and quality in the finished billet and therefore avoid the costly forging operation.

The purpose of the present work is to evaluate the quality and mechanical properties of billets of Alloy 718 made by an improved conversion technique. Billets of a size applicable to many parts (8" dia.), were made from a large production size ingot and heat treated. Quality was evaluated by ultrasonic inspection of the billets, metallographic inspection of billet sections plus optical and SEM examination of all test bars. Mechanical properties were determined in the longitudinal, radial and tangential (where possible) directions on material from the top, middle and bottom of the billets. Properties tested were tensile (smooth and notched) at R.T. and elevated temperature, creep rupture, low cycle fatigue and crack growth rate.

Materials and Testing

The alloy 718 material originated as a production 21" round VIM-VAR ingot, Cytemp heat number 6L7902-K11, weighing 7000 pounds. Cytemp homogenized and converted the ingot to 15" RCS billet using their standard conversion practice.

The billet was further converted to 8" round billet at Wyman Gordon Co. using a "fine grain" practice. This practice employs controlled reductions of initially high percentage but with decreasing percentages as the final size is approached. A complimentary controlled time, decreasing temperature reheat schedule is used. The final rounding up passes are performed from 1800F. A 2000T conversion press and flat draw dies were used.

Chemical analysis of ingot and billet material is listed in Table I. Requirements of AMS 5663 are met.

From the three 135" long billets produced, 30" long mults were cut from the top of the top billet (TT), the top of the middle billet (TIT) and the bottom of the bottom billet (BB), relative to the original ingot. The three mults were heat treated at 1750F, 1 hour, water quench plus 1325F, 8 hours, furnace cool at 100F per hour to 1150F and held 8 hours followed by air cooling. The mults were sonic inspected after heat treatment.

Mechanical property and metallographic specimens were cut from each of the three mults in the longitudinal, radial and tangential (where possible) orientations. Tensile specimens had a gage diameter of 0.1785" and gage length of 1". Notch tensile specimens had a stress concentration factor of 3.5, with a root diameter of 0.1785". Creep rupture specimens were 1/4" diameter with a gage length of 1 1/4". LCF specimens had a gage diameter of 0.400" and a uniform gage length of 2.500". (Because of their length, LCF specimens could not be taken in the tangential direction.) A compact tensile type specimen of dimensions 1.200 x 1.250 x 0.500" was used for the crack growth rate tests.

Tensile tests were performed at R.T. and 1000F; creep rupture tests at 1200F, 95,000 psi; LCF strain control, A=1, 0.8% strain range at 800F and crack growth rate at 800F.

Material Structure and Inspection Results

The ultrasonic inspection of the billets (after heat treatment) was done by immersion at $5MH_z$ using a No.2 FBH standard at 80% of screen height. The noise level was 10-20% of screen height. No indications above the noise level were detected.

A photograph of one of the transverse cross-sections is shown in Fig. 1. The circled numbers are the locations at which samples were cut for micro examination. Although the cut-off operation has left straight line saw marks, it can be seen that the macrostructure is moderately uniform. Occasional patches of coarser grains can be seen, (spots 2, 4, 6). An apparent flow line pattern could be seen in the longitudinal macro sections.

Table II is a summary of the microstructural examinations.

Table I. Chemical Composition of Alloy 718 Material

Element	Ingot Cytemp 6L 7902 Weight %	Billet Wyman-Gordon S 3581 Weight %
C	0.038	0.039
P	0.006	0.003
S	0.001	0.0001
Ni	52.80	52.89
Ti	1.02	1.03
Al	0.56	0.52
Mn	0.08	0.11
Fe	18.14	18.20
Co	0.22	0.21
Mo	3.07	3.09
Cr	18.52	18.50
Cu	0.05	0.06
Si	0.10	0.10
Cb	-	5.34
Ta	-	0.05
Cb + Ta	5.41	5.39
B	0.0037	0.0052
Mg	0.0017	0.0038
Ca	<0.0005	0.001
Ag	0.0002	<0.001
Sn	0.0020	<0.005
Bi	<0.00003	<0.00005
Pb	0.0002	<0.001
N	-	0.001
O	-	0.0013

Recrystallized grain sizes were quite fine, averaging ASTM 9-12, with a maximum as large as 6. The unrecrystallized grains (where present) were coarser, averaging ASTM 5-8, except at a single location (TT, surface, spot no. 6) which averaged ASTM 3, with a grain as large as 0. No non-metallic inclusions were noted. MC carbides were generally fine and well dispersed. Carbide stringers were few and not dense. The longest stringer found (0.0075") was near the surface of a metallographic sample taken from a slice of billet BB.

Etched microstructures are shown in Fig. 2. At the center (longitudinal section billet TIT), the grains appear uniform and equiaxed, with a moderately small amount of acicular Ni_3Cb and uniform $\gamma' - \gamma''$ precipitate within the grains (Fig. 2a). Near the surface (longitudinal section, billet TT), the grain size is generally very fine (Fig. 2b) with a rare area of unrecrystallized coarser grains. Precipitation of Ni_3Cb and $\gamma' - \gamma''$ is similar to the center section.

Mechanical Property Test Results

The tensile test data is listed in Tables III and IV for R.T. and 1000F, respectively. All RT properties exceed the requirements of specification AMS 5663. In order to provide a better means of comparison of the results, the strength, ductility and the notch/smooth UTS ratios were plotted as a function of orientation and location (available on request). There did not seem to be any significant differences among the 3 billets at either temperature in strength, ductility or N/S ratio. There is a clear trend for the longitudinal orientation to have higher ductility than the other orientations, as well as a smaller advantage in the N/S ratio (which is ductility-related). Inspection of fracture surfaces revealed no defects.

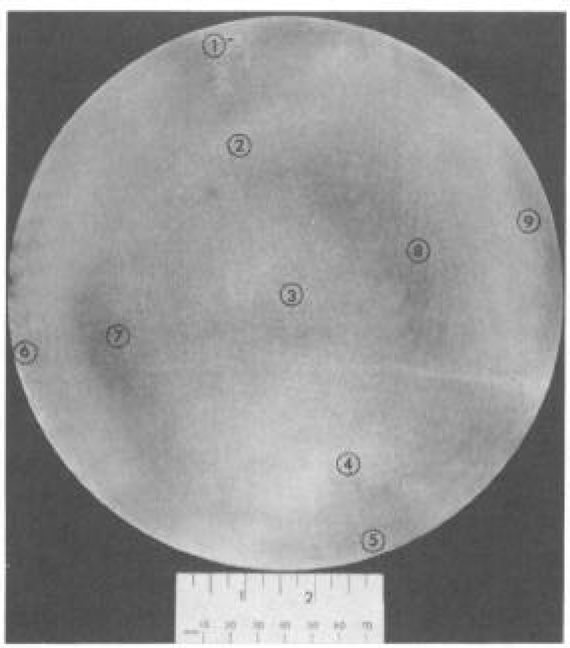


Figure 1. Alloy 718 Transverse Macrostructure and Micro Locations at the Top Billet Section (TT)

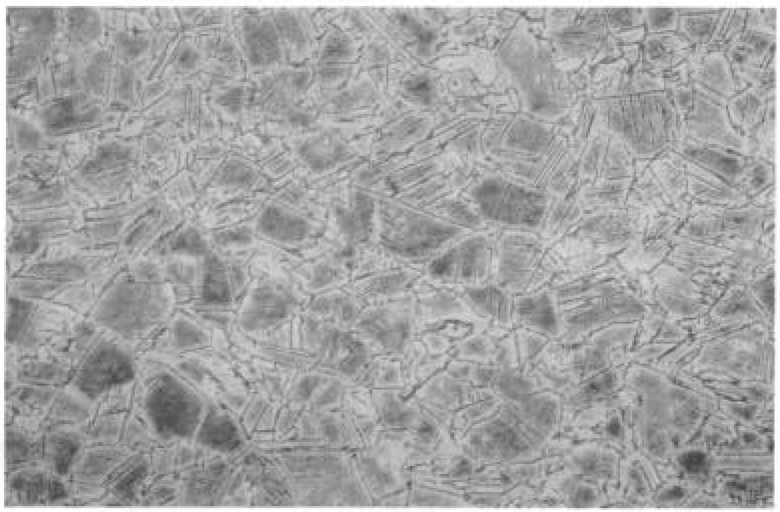
The creep-rupture results are summarized in Table V. Average grain size and Ni_3Nb precipitate at the fracture area is included for selected samples. All test results, extrapolated to the 100,000 psi stress level of AMS 5663, exceed the specification requirement. The lowest test result (TIT, radial, 27R) had a very fine grain size (ASTM 12) and medium-heavy Ni_3Nb precipitate at the fracture. Comparisons of billet and orientation effects indicate there are no significant differences between billets, although the bottom billet does have slightly higher average creep and rupture lives. Generally the longitudinal specimens have the longest lives and the radial (through the billet center) have the lowest. No defects were found on fracture surfaces.

Table II. Grain Structure Summary, Alloy 718

Billet	Spec. Description		Spot	Grain Size				Percent	Total
	Orient.	Location	No.	Recryst.		Unrecryst.		Unre-	Average
				Av'g.	Max	Av'g.	Max.	cryst.	Gr.Size
Top (TT)	Transv.	Center	3	9	8	-	-	0	9
		Mid-radius	2	11	10	6	5	25	10.5
			4	11	10	6	5	30	10.5
			7	12	11	7	6	15	11.7
			8	9	8	-	-	0	9
		Surface	1	12	11	8	6	15	11.7
			5	12	11	8	7	40	11.3
			6	11	10	3	0	50	10
			9	12	11	8	7	40	11.3
	Long.	Center	23	9	8	-	-	0	9
		Mid-radius	22	10	9	7	5	15	9.7
			24	9	7	-	-	0	9
		Surface	21	11	10	5	3	40	10.3
			25	11	10	-	-	0	11
Middle (T1T)	Transv.	Center	3	10	8	-	-	0	10
		Mid-radius	2	10	6	-	-	0	10
			4	11	10	7	6	10	10.8
			7	10	7	-	-	0	10
			8	10	9	-	-	0	10
		Surface	1	12	11	7	6	25	11.5
			5	11	10	7	5	25	10.6
			6	11	9	7	3	10	10.8
			9	12	10	-	-	0	12
	Long.	Center	23	9	8	-	-	0	9
		Mid-radius	22	9	6	-	-	0	9
			24	8	6	-	-	0	8
		Surface	21	11	10	5	3	25	10.6
			25	11	8	-	-	0	11
			26	7	6	-	-	0	7
Bottom (BB)	Transv.	Center	3	9	7	-	-	0	9
		Mid-radius	2	10	9	-	-	0	10
			4	10	9	-	-	0	10
			7	9	8	-	-	0	9
			8	9	8	6	5	15	8.7
		Surface	1	12	9	6	5	10	11.8
			5	10	9	8	7	10	9.8
			6	12	11	7	6	15	11.7
			9	12	11	7	6	10	11.8
	Long.	Center	23	9	7	-	-	0	9
		Mid-radius	22	9	8	-	-	0	9
			24	10	8	-	-	0	10
		Surface	21	11	10	-	-	0	11
			25	9	8	-	-	0	9

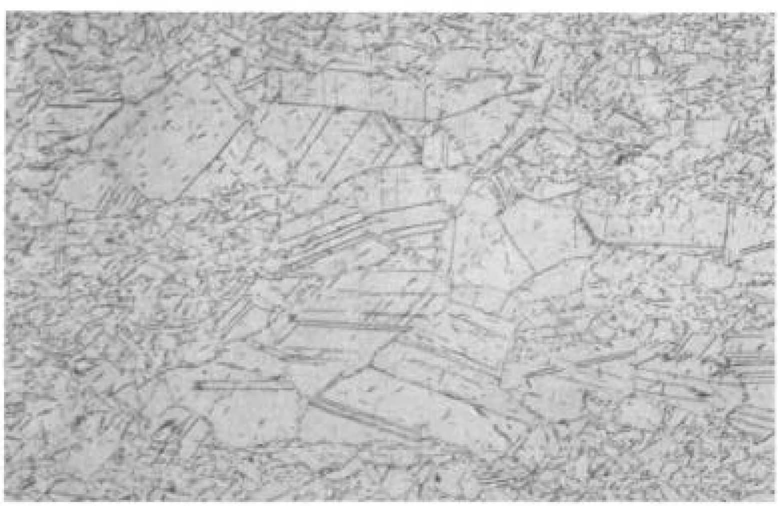
Low cycle fatigue data is listed in Table VI. Many specimens had failures initiating at MC carbide areas. This is not unusual since there are so many of them all over. None covered an area larger than about 2 x 4 mils. A single specimen (billet BB, radial no. 36) had a 3 x 6 mil non-metallic inclusion at the origin, causing the lowest life of all the tests. This inclusion size is below the noise level of the #2 FBH ultrasonic inspection. The overall (log) average life (including the specimen with the inclusion) is 19, 501 cycles, which is representative of good forging values. The longitudinal orientation does indicate higher lives in all three billets, but there is no significant difference from billet to billet.

Crack growth rate results are plotted in Fig. 3. The three orientations for each billet and the three billets are included in the same figure. There is no significant difference in the three billets and orientations. Threshold stress intensity averages about 7 1/2 Ksi $\sqrt{in.}$ and the critical intensity seems to be ~80.



0.001"

a. Billet TIT, center. Uniform grain size, γ'-γ'' and Ni_3Cb



b. Billet TT, surface. Coarsest unrecrystallized grain area, surrounded by normal fine grains Originals 400X

Figure 2. Alloy 718 Billet Microstructures, Longitudinal Sections

Discussion of Results

The structure and soundness of the billets of Alloy 718 made by the fine-grain conversion practice were comparable to those of conventionally processed forgings, and properties fell within the range of conventionally processed Alloy 718. Clean master heat material plus the conversion techniques produced relatively uniform billets, with no significant differences in properties from end-to-end of the billets. Some directional variation still exists; the longitudinal specimens generally showed better ductility related properties, including strain controlled LCF lives. In parts made by slicing from billets, the longitudinal direction of the billet becomes the short transverse direction of the slice. Traditionally in forgings, that is the lowest ductility/property direction. However, even in the radial and tangential orientations, the properties appear to belong to the populations for forgings made per specifications such as AMS 5663.

The fine-grain conversion process does not produce a completely uniform structure. Grain size and Ni_3Nb precipitate varied. The increase to the billet lengths from the relatively short ingot lengths does result in a "grain"

Table III. Alloy 718 Tensile Properties at R.T.

Billet	Test Orient.	Spec Type	Spec. No.	0.2% Y.S. ksi	U.T.S. ksi	Elong. %	R.A. %	Avg. N/S Ratio
Top (TT)	Long.	Smooth	1	168.4	203.2	19.3	34.9	1.428
			2	172.0	205.2	22.1	35.8	
		Notched	7	-	291.2	-	-	
			8	-	292.0	-	-	
	Radial	Smooth	3	171.2	202.0	17.9	26.5	1.357
			4	169.6	202.0	17.9	26.5	
		Notched	9	-	274.4	-	-	
			10	-	274.0	-	-	
	Tang.	Smooth	5	169.2	202.0	16.5	24.6	1.365
			6	173.2	205.6	16.5	23.6	
		Notched	11	-	276.0	-	-	
			12	-	280.4	-	-	
Middle (T1T)	Long.	Smooth	1	168.0	202.0	22.1	35.8	1.443
			2	165.2	204.0	20.7	34.0	
		Notched	7	-	294.8	-	-	
			8	-	291.2	-	-	
	Radial	Smooth	3	178.0	206.4	17.9	25.6	1.415
			4	179.6	207.2	17.9	24.6	
		Notched	9	-	292.0	-	-	
			10	-	293.2	-	-	
	Tang.	Smooth	5	178.0	202.0	16.5	29.4	1.387
			6	172.4	206.0	16.5	25.6	
		Notched	11	-	280.4	-	-	
			12	-	285.6	-	-	
Bottom (BB)	Long.	Smooth	1	173.2	206.0	19.3	35.8	1.418
			2	175.2	204.8	19.3	34.9	
		Notched	7	-	288.4	-	-	
			8	-	294.0	-	-	
	Radial	Smooth	3	174.4	204.4	17.9	32.2	1.418
			4	171.6	202.8	17.9	31.3	
		Notched	9	-	289.6	-	-	
			10	-	288.0	-	-	
	Tang.	Smooth	5	177.7	208.4	19.3	23.8	1.386
			6	173.2	201.2	17.9	29.4	
		Notched	11	-	287.6	-	-	
			12	-	280.0	-	-	

structure, carbide stringering, etc. along the longitudinal axis, which probably cannot be entirely eliminated. Nevertheless, the variations seen here still were within acceptable forging limits, and except for some limited spots were quite good.

Heat treatments were done on the mults. These are quite large compared to material cut for a part or a comparable forging. There may be somewhat of a penalty this way in properties compared to heat treating of the individual (smaller) pieces. For production application, it would be recommended that heat treatments should be done after cutting to individual part size.

While the present results indicate a successful promising process, it should be remembered that only a single ingot was included in the program. Additional heats must be tested to evaluate the reproducibility and consistency of the process.

Table IV. Alloy 718 Tensile Properties at 1000F

Billet	Test Orient.	Spec Type	Spec. No.	0.2% Y.S. ksi	U.T.S. ksi	Elong. %	R.A. %	Avg. N/S Ratio
Top (TT)	Long.	Smooth	13	148.0	172.4	20.0	40.2	1.453
			14	143.2	174.8	20.0	38.5	
		Notched	19	-	254.8	-	-	
			20	-	249.6	-	-	
	Radial	Smooth	15	146.4	170.8	16.5	33.1	1.434
			16	146.4	170.4	17.9	30.2	
		Notched	21	-	246.8	-	-	
			22	-	242.4	-	-	
	Tang.	Smooth	17	148.0	172.8	16.5	31.3	1.443
			18	139.6	173.2	16.5	30.2	
		Notched	23	-	252.8	-	-	
			24	-	246.4	-	-	
Middle (T1T)	Long.	Smooth	13	152.0	176.0	20.0	36.7	1.474
			14	151.6	174.8	19.3	40.2	
		Notched	19	-	255.6	-	-	
			20	-	261.5	-	-	
	Radial	Smooth	15	156.7	176.6	15.1	26.6	1.405
			16	157.6	176.8	15.1	27.5	
		Notched	21	-	245.1	-	-	
			22	-	251.6	-	-	
	Tang.	Smooth	17	148.7	174.0	16.5	27.2	1.466
			18	141.6	171.2	19.3	31.3	
		Notched	23	-	254.8	-	-	
			24	-	251.2	-	-	
Bottom (BB)	Long.	Smooth	13	153.7	178.1	18.6	37.2	1.477
			14	149.2	172.8	20.0	37.6	
		Notched	19	-	260.0	-	-	
			20	-	258.2	-	-	
	Radial	Smooth	15	154.0	174.0	20.0	34.9	1.457
			16	149.2	172.8	17.9	33.1	
		Notched	21	-	249.2	-	-	
			22	-	256.0	-	-	
	Tang.	Smooth	17	150.0	170.8	17.9	33.1	1.482
			18	150.0	171.8	19.3	34.7	
		Notched	23	-	251.6	-	-	
			24	-	256.0	-	-	

Table V. Alloy 718 Creep-Rupture Properties at 1200F, 95 ksi

Billet	Test Orient.	Spec. No.	Time to Creep, hrs. 0.2%	0.5%	1.0%	2.0%	Rupture Life hrs.	Elong. %	Av'g. ASTM G.S.*	Ni3Nb* Precip.
Top (TT)	Long.	25	58	130	156	192	274.7	29.0		
	Radial	27	18	45	71	82	109.2	23.5	5	Heavy
	Radial	28	22	57	78	104	125.1	12.3		
	Tang.	29	43	110	161	197	257.4	14.6		
Middle (T1T)	Long.	25	50	105	135	164	213.9	15.4		
	Long.	26	52	110	146	177	224.4	19.0		
	Radial	27	24	53	75	91	106.7	15.0	11	Medium
	Radial	27R	9	20	31	40	52.0	10.3	12	Med-Hvy
	Radial	28	58	127	171	201	258.6	18.0	9	Light
	Tang.	29	31	74	120	154	209.0	19.2		
	Tang.	30	29	72	108	133	171.2	12.4		
Bottom (BB)	Long.	25	98	200	242	282	372.9	17.7		
	Radial	27	47	98	130	156	203.5	14.5		
	Tang.	29	43	92	145	186	280.6	25.0		

* Measured on test specimen at fracture location

Table VI. Alloy 718 Strain Controlled LCF at 800F, A=1, 0.8% Total Strain Range

Billet	Test Orient.	Spec. No.	Cycles to Initiate Ni	Failure Nf	SEM Examination of Origins §
Top (TT)	Long.	31	31487	34673 *	
		32	29189	30795	Surface: 1 x 1.3 mil carbide
		33	27926	28367 *	
	Radial	34	12671	15029	Surface: 1.6 x 2 mil carbides
		35	17782	19211	0.2 mils subsurface: 1.5 x 2.2 mil carbides
		36	10809	13145	
Middle (T1T)	Long.	31 +	-	44629 *	
		32	28306	28325 *	
		33	23621	23844 *	Surface origin
	Radial	34	7112	8503	4.6 mils subsurface: 1.6 x 3.7 mil carbides
					Surface: 1.8 x 3 mil carbides
		35	13428	13798 *	20 mil subsurface: 0.8 x 1.2 mil carbide
					Second origin at surface
		36	8924	10497	0.5 mils subsurface: 2.4 x 3.2 mil carbides
Bottom (BB)	Long.	31	-	21884 *	
		32	14718	17947 *	
		33	32904	33259 *	Surface origin
	Radial	34	28380	28450 *	Surface origin
		35	22043	22558 *	
		36	6006	7989	Surface: 3 x 6 mil inclusion, Mg, Al, Ca, Ti rich

\+ Tested at 0.7% strain range
§ No carbides or inclusions on any other fracture surface
* Failed at end of, or outside gage length

Acknowledgement

The authors wish to thank Dr. Jong Soo Park for overseeing the testing and the compiling of the data.

Conclusions

1. The Alloy 718 billets processed by the fine-grain conversion process reported in this paper appear to attain the properties, structures, cleanliness, etc. of a commercial forging specification (AMS 5663) for the alloy.

2. No significant differences were seen from end-to-end of the billets. Specimens oriented longitudinally in the billet generally had better ductility and LCF lives than radially or tangentially oriented specimens.

3. Some variation in grain size and Ni_3Nb precipitate existed, but were within the range of acceptable forging structures.

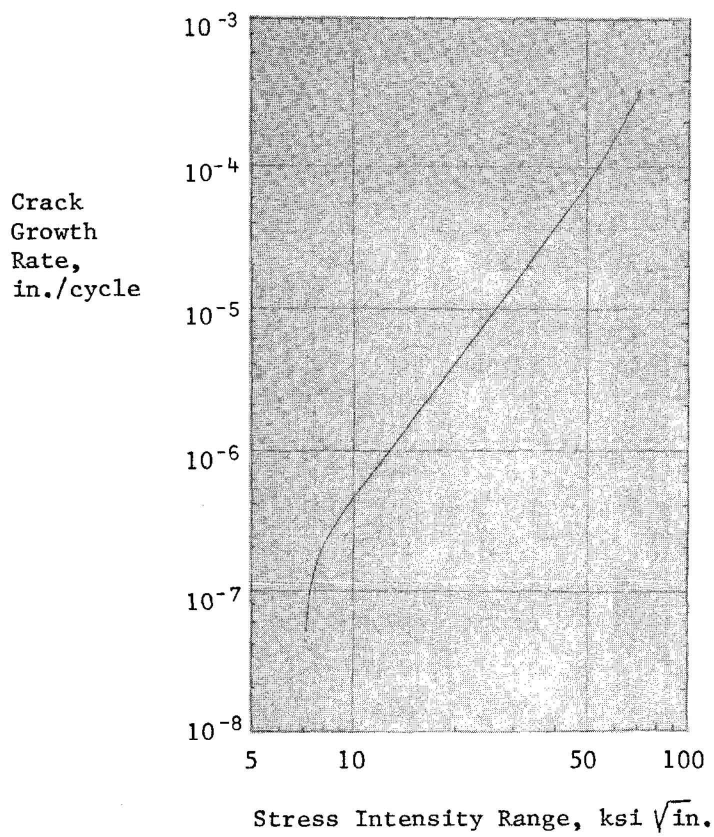


Figure 3. Alloy 718 Crack Growth Rate, 800F, A=1, Average of Two Tests From Each of Three Mults