COMPARISON OF ASTROLOY POWDER CONSOLIDATION PROCESSES

FORGING AND TESTING OF ASTROLOY POWDER BILLET

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Abstract

A heat of Astroloy powder was produced and consolidated into billet by three different techniques:

1. Hot isostatic pressing at two different temperatures
2. Extrusion using an 8:1 ratio
3. Forge compaction

The resulting eight powder billets were then upset forged along with two VAR billets in three operations. The pancakes so produced were heat treated at temperatures which gave partial and full gamma prime solutioning. Tensile, combination stress rupture, creep, and LCF tests were performed from each billet. These test results are reported along with optical and electron micrographs of each billet.

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Introduction

Since high purity superalloy powders became available commercially, virtually every consolidation process has been investigated to determine the best method to consolidate these powders to full density. Three methods appear to have commercial importance: extrusion, hot isostatic pressing and forge-consolidation. The purpose of this work was to determine the effects of the consolidation process on the properties of a conventionally forged high strength nickel-base superalloy. The properties obtained were compared with those obtained from VAR billets that had been processed with the powder consolidations. Astroloy was chosen as the alloy for this work because of its availability in wrought form and because of the availability of base line data for this alloy.

Two different heat treatments were used on the consolidations and the materials were tested under the conditions applicable to the particular heat treatment.

Procedure

Starting Material

The powder used for all of this work was from Federal-Mogul Heat R-71186. The master heat of Astroloy which was used to produce the powder was Teledyne Allvac Heat 4376.

The cast-wrought material was supplied by Special Metals in the form of 4" round VAR billet and was identified as Heat 8-2000.

Analyses of the two heats are shown below:

	Teledyne Allvac Heat No. 4376	Federal-Mogul* Heat No. R-71186	Special Metals Heat No. 8-2000
C	.077	.074	.07
Mn	.01	<.01	<.01
Si	.05	.10	<.10
Cr	15.10	14.81	15.0
Ni	Bal.	54.63	Bal.
Co	17.23	17.52	18.7
Fe	.08	.18	.25
Mo	5.10	5.11	4.80
Ti	3.56	3.35	3.46
Al	4.08	4.07	4.30
B	.026	.022	.030
Zr	.01	< .01	< .05
S	.003	.003	.003
Cu	.02	.06	< .10
P	--	.003	--

* Hot isopressed powder

Hot Isopressed Billet

The powder for the two hot isopressed billets was canned, evacuated, and sealed at Federal-Mogul. One container was isopressed at 15 KSI and 2250°F (S/N 2), and the other at 15 KSI and 2350°F (S/N 1). After can removal by machining, compact #1 was

4-3/8" round by 7-3/4" long, and weighed 33 pounds. Compact #2 was 4-1/2" round by 7-15/16", and weighed 36 pounds. A 1/2" slice was cut from the end of each compact and the remainder of each was then cut in half and identified with A and B such that A was nearest to the slice. This yielded four HIP billets for forging, 1A, 1B, 2A, and 2B. The dimensions, weights, and densities (by Archimedes' method) are listed in Table I.

Extruded Powder Billet

Federal-Mogul loaded 300 pounds of powder into a stainless steel container, 11" diameter x 18" long, evacuated, sealed, heated to 2100°F, and extruded using a 6.5:1 extrusion ratio to produce, after machining, 3-3/8" round bar. The section, shipped to Wyman-Gordon for this work, was 3-3/8" round x 12-3/8" long, and weighed 32 pounds. A 1/2" slice was again cut from the extruded bar, and the remaining bar cut into two pieces which were labeled 3A and 3B. The remaining billet weights, dimensions, and density are also listed in Table I.

Cast Wrought Billet

One piece of VAR and forged U-700 bar, 4" round x 10" long, was purchased from Special Metals. After cutting a 1/2" slice from the end of this bar, it was cut into two billets and identified 4A and 4B. Dimensions and weights are listed in Table I.

Forge Compacted Billet

Three cans 4-1/4" round (O.D.) x 7-7/8" overall height were loaded with powder in a glove box under argon. The cans were then evacuated to 10^{-5} Torr, heated to 1000°F, and sealed. Approximately 13 pounds of powder were loaded into each container. The cans were identified as 5A, 5B, and 5C. The third can (5C) was produced so that material would be available for testing in the "as-compacted" condition.

The cans were heated to 2100°F for 4 hours and then compacted in the dies incorporating two punches and a floating chamber. After compaction, 5A, 5B, and 5C were loaded into a 2260°F furnace, sintered for two hours, and then air cooled.

A density check at this point gave the following results:

	gm/cc	lb/in^3
5A	7.94	.287
5B	7.94	.287
5C	7.91	.286

The compacts were then machined all over and chamfered to remove the surface skin in preparation for forging.

The billet weights, dimensions, and densities at this stage of processing are listed in Table I.

#1 Upset Forging

The ten billets were loaded into a furnace operating at 1650°F for two hours. They were then transferred to an adjacent furnace at 2050°F and held approximately one hour and 50 minutes before forging was started. The dies were approximately 750/600°F.

TABLE I

SIZE, WEIGHT, AND DENSITY OF FORGING BILLETS, U-700

Serial Number	Compact Method	Diameter (Inches)	Height (Inches)	Weight (Pounds)	Density Lbs/in^3
1A	HIP-2350°F-15KSI	4.32	3.57	15.2	.290
1B	HIP-2350°F-15KSI	4.32	3.46	14.6	.290
2A	HIP-2250°F-15KSI	4.45	3.66	16.5	.290
2B	HIP-2250°F-15KSI	4.45	3.54	15.8	.290
3A	Extruded - 8:1 Ratio	3.37	5.77	14.9	.289
3B	Extruded - 8:1 Ratio	3.37	5.72	14.8	.289
4A	Forged VAR	4.38	3.68	15.4	.288
4B	Forged VAR	4.38	3.58	14.9	.288
5A	Forge Compact - 2100°F/100KSI	3.86	3.00	10.1	.289
5B	Forge Compact - 2100°F/100KSI	3.92	3.16	11.0	.289

Billets 1A and B, 2A and B, and 4A and B were upset to 2.5" high, which required approximately 350T. Billets 3A and B were upset to 3.5" (approximately 200T), and 5A and B were upset to 2-1/8" (approximately 300T). There was no apparent rupturing during the forge operation. After air cooling from forging, the parts were sand blasted. The surface condition on all of the upsets was excellent. Subsequent etching in acid $FeCl_3$ followed by red dye inspection revealed a few small pores on a portion of the outside of 5B. These were ground off prior to the second upset.

The results of density determinations on all of the pancakes are listed in Table II. Following regular practice for VAR material, S/N 4A and B were annealed at 2125°F for one-half hour at heat prior to upset #2.

Upset #2

All of the billets were coated, wrapped, and canned to minimize heat loss during forging. The parts were then loaded in a furnace which was controlling at 2050°F. After heating for 4 hours, a second upset operation was performed on each part. Die temperatures were approximately 720°F/600°F. Details of the resultant sizes and reductions are listed in Table III.

S/N 3A and 3B were still longer and smaller in diameter than the other upsets due to their original billet size. An additional upset was given to these two parts so that all of the material would be about the same thickness when performing the final forge operation. These two billets were free of cracking after the #2 upset and they were sand blasted, coated, and wrapped for the third upset without any additional conditioning.

Upset #3 - 3A and 3B

The parts were heated for three hours at 2050°F, and then upset forged on flat dies. Die temperatures were approximately 420/550°F. Subsequent etching and red dye inspection revealed the presence of minor cracking around the periphery on both parts. Pertinent dimensions and forging pressures are listed below:

Serial Number	Diameter (Inches)	Height (Inches)	Pressing Force-Tons	% Reduction in Height
3A	7.12	1.35	570	40.7
3B	7.18	1.35	550	40.5

Machining and Annealing

The peripheral bulge was lathe machined from the upsets to remove the small bursts present on all of the parts. The corners were then machined to a 1/4" radius. Following machining, the forgings were weighed, coated to reduce oxidation, and all except 4A and 4B were annealed. Serial numbers 1A, 1B, 2A, 2B, 5A, and 5B were annealed for 24 hours at 2250°F. Because prior experience had shown that excessive grain growth can occur at this temperature in extruded powder billet, 3A and 3B were annealed at 2175°F for 24 hours. After annealing, the parts were again blasted and weighed. Weights and weight losses from machining and from annealing are listed in Table IV. Weight losses range from 8 to 16% after machining, and from .4 to 1% after annealing. The reason for the greater weight loss during annealing at the lower temperature is not known.

TABLE II

SIZE, REDUCTION, AND DENSITIES OF PANCAKES AFTER #1 UPSET

Serial Number	Diameter (Inches)	Height (Inches)	% Reduction	Density Lbs/in^3
1A	5.48	2.32	35.0	.290
1B	5.38	2.31	33.2	.290
2A	5.70	2.32	36.6	.290
2B	5.48	2.31	34.7	.290
3A	4.57	3.32	42.5	.289
3B	4.58	3.32	42.0	.289
4A	5.53	2.32	37.0	.288
4B	5.47	2.31	35.5	.288
5A	4.84	1.96	34.7	.289
5B	5.04	1.96	38.0	.289

TABLE III

DIMENSIONS AND FORGE PRESSURES - #2 UPSET

Serial Number	Diameter (Inches)	Height (Inches)	Press Forge Tons	% Reduction in Height
1A	7.87	1.07	750	54.0
1B	7.36	1.19	600	48.5
2A	7.80	1.18	600	49.2
2B	7.60	1.19	600	48.5
3A	5.57	2.26	400	32.0
3B	5.53	2.27	400	31.7
4A	7.56	1.20	600	48.3
4B	7.46	1.18	600	48.9
5A	6.16	1.19	350	39.3
5B	6.36	1.18	350	38.8

TABLE IV

WEIGHT LOSSES OF UPSETS AFTER MACHINING AND AFTER HIGH TEMPERATURE ANNEAL

ALL PARTS (EXCEPT 4A AND 4B) WERE ANNEALED FOR 24 HOURS

Serial Number	Last Forge Operation	Weight Before Machining (G)	Weight After Machining (G)	Machining Weight Loss (G)	% Loss	Anneal Temperature	Weight After Annealing	Annealing Weight Loss
1A	Upset #2	6875.7	6205.0	670.7	9.8	2250°F	6175.4	29.6
1B	Upset #2	6661.6	5740.6	921.0	13.8	2250°F	5712.1	28.5
2A	Upset #2	7486.2	6645.8	840.4	11.2	2250°F	6610.8	35.0
2B	Upset #2	7153.7	6241.9	911.8	12.7	2250°F	6213.1	28.8
3A	Upset #3	6764.9	5962.1	802.8	11.9	2175°F	5899.0	63.1
3B	Upset #3	6728.0	5844.6	883.4	13.0	2175°F	5797.8	46.8
4A	Upset #2	6947.8	5914.3	1033.5	14.9	-	-	-
4B	Upset #2	6746.5	6179.6	566.9	8.4	-	-	-
5A	Upset #2	4573.8	3957.4	616.4	13.5	2250°F	3942.4	15.0
5B	Upset #2	4960.8	4154.6	806.2	16.3	2250°F	4132.1	22.5

Upset #3 (And #4 for 3A and 3B)

After the annealing cycle, the parts were blasted, coated, and wrapped with insulant prior to forging. The parts were preheated at 1750°F for 2-1/2 hours, and transferred to a 2050°F furnace for 30 minutes prior to final forging. Forging force was 1500 tons for all parts.

The upsets were sand blasted after forging. The resulting part dimensions and reductions are shown in Table V.

Heat Treatment of Upsets

Prior to heat treatment, all of the upsets were blasted and then ground to remove any minor cracking present. A segment with a chord length of about 4 - 4-1/2" was then cut from the edge of the five upsets identified by A. This was held for examination of the "as-forged" microstructure. The balance of each of the "A" upsets was then heat treated as indicated below:

Solution	2060°F	4 hours	oil quench
Age	1600°F	8 hours	air cool
	1800°F	4 hours	air cool
	1200°F	24 hours	air cool
	1400°F	8 hours	air cool

The "B" upsets were heat treated as follows:

Solution	1975°F	4 hours	oil quench
Age	1200°F	24 hours	air cool
	1400°F	8 hours	air cool

Testing

Machining of Test Bars

Following heat treatment of the upsets, test coupons were abrasively cut according to the sketch in Figure 1.

All of the specimens were then prepared on a Sheffield crush grinder.

Room and hot tensiles were standard .250" diameter specimens. The hot tensiles were held at the test temperature for 30 minutes prior to testing.

The stress-rupture tests were combination tests with a plain bar and V-notch diameter of .178". The notch had a root radius of .005" and a 60° included notch angle. The creep specimens were .250" diameter in the gage section with a gage length of 1.364".

Low cycle fatigue specimens had a gage section approximately 1" long and .357" in diameter. The 60° notch in the center of the gage section was .250" in diameter with a .037" root radius giving a K_t of 2.0.

TABLE V

PART DIMENSIONS AFTER FINAL FORGING

Serial Number	Operation	Diameter (Inches)	Final Thickness (Inches)	Start Thickness (Inches)	% Reduction	Surface Condition
1A	Upset #3	8.86	.760	1.07	30.0	Light Ruptures in one area
1B	Upset #3	8.54	.730	1.19	38.6	Light ruptures 360°
2A	Upset #3	9.43	.730	1.18	38.1	Few light ruptures
2B	Upset #3	8.73	.760	1.19	36.1	Light ruptures 360°
3A	Upset #4	8.88	.760	1.35	43.7	Clean
3B	Upset #4	8.43	.750	1.35	44.4	O.D. ruptures 360° to 1/8"
4A	Upset #3	8.97	.730	1.70	39.2	Clean
4B	Upset #3	8.80	.740	1.18	37.3	Clean
5A	Upset #3	7.36	.720	1.19	39.5	Clean
5B	Upset #3	7.63	.640	1.18	45.8	Few light ruptures

Tensile Testing

The room temperature and hot tensiles were tested on production tensile machines using stress-strain recording with appropriate extensometers. The elevated temperature tests were held at temperature for 1/2 hour prior to testing. Strain rates were .005/inch up to the yield point.

Stress Ruptures

The combination stress-rupture tests were performed according to standard production practice in calibrated test frames. Specimens were loaded and allowed to reach the testing temperature prior to application of the test load. Tests were run at the test temperature and load to failure.

Creep Tests

The creep tests were performed at Joliet Metallurgical Laboratories according to standard procedures. Specimen deformation vs. time was recorded every two hours during secondary creep.

Low Cycle Fatigue

The LCF testing was performed at Teledyne Materials Research on an MTS electro-hydraulic testing machine. Test frequency was approximately 30 Hertz with a nominal mean tensile stress of 40,000 psi and an alternating stress superimposed of $\pm$50,000 psi. Specimen heating was by an induction generator; specimen temperature was 1175°F and controlled by a couple at the specimen notch.

Results and Discussion

Microstructure

The microstructures of all materials in the as-received, as-forged and in both heat treated conditions are shown in Figures 2 through 6. Although upset #1 was consolidated well above the published melting point for Astroloy, no obvious areas of incipient melting were detected.

The extruded product (upset #3) had the finest grain size of all the upsets. The as-received billet had a finer grain size and this material received a lower in-process anneal prior to the final forging step. The VAR product (upset #4) had the coarsest grain size of all the upsets. Although there is no evidence of prior particle identity in any of the powder products, the powder particles appear to have an effect on retarding grain growth for equivalent heat treatments. The microstructures of upsets #1, #2, and #5 are similar, although there are some differences in grain size and in the presence of coarse grains.

Tensile Tests

Room temperature and elevated temperature tensile tests for the A and B upsets are shown in Tables VI and VII respectively. In all of the room temperature tensile tests, the powder upsets had properties as good as or better than those of the cast-wrought material (upset #4). The best room temperature tensile properties were found in the extruded material in both the A and B upsets. This is probably due to the finer grain size of the extruded material.

TABLE VI

ROOM TEMPERATURE AND 1400°F TENSILE TEST RESULTS FOR "A" UPSETS

Test Number	Test Temp. (°F)	Yield Strength 0.2% Offset ksi	Ultimate Strength ksi	Elongation % in 4D	Reduction of Area %
1A-7	70	152.0	212.0	18.0	23.7
1A-8	70	150.0	211.4	18.0	25.1
2A-7	70	156.0	214.0	22.0	30.5
2A-8	70	158.0	218.0	20.0	27.8
3A-7	70	162.0	224.2	21.0	37.0
3A-8	70	162.0	228.0	21.0	34.4
4A-7	70	150.0	206.0	20.0	21.7
4A-8	70	148.0	206.0	20.0	22.3
5A-7	70	156.6	218.0	20.0	26.6
5A-8	70	157.0	218.2	20.0	30.8
1A-3	1400	132.0	152.4	25.0	27.2
1A-4	1400	134.0	156.8	14.0	18.1
2A-3	1400	138.0	164.0	30.0	46.1
2A-4	1400	130.8	150.8	28.5	35.7
3A-3	1400	134.0	156.4	20.0	23.7
3A-4	1400	138.0	160.0	20.0	24.5
4A-3	1400	139.0	152.0	28.0	37.6
4A-4	1400	125.6	146.8	24.0	29.9
5A-3	1400	134.0	156.0	23.0	29.2
5A-4	1400	133.2	156.0	23.0	29.2

TABLE VII

ROOM TEMPERATURE AND 1200°F TENSILE TEST RESULTS FOR "B" UPSETS

Test Number	Test Temp. (°F)	Yield Strength 0.2% Offset ksi	Ultimate Strength ksi	Elongation % in 4D	Reduction of Area %
1B-7	70	157.0	212.0	23.0	28.6
1B-8	70	154.8	209.0	22.0	25.1
2B-7	70	158.0	213.4	23.0	31.1
2B-8	70	158.1	213.9	21.0	27.3
3B-7	70	171.6	229.2	22.5	28.6
3B-8	70	170.0	227.6	23.0	33.2
4B-7	70	154.0	206.4	21.0	25.1
4B-8	70	152.0	206.0	21.0	25.1
5B-7	70	160.0	215.6	23.0	29.9
5B-8	70	160.0	216.0	23.5	30.5
1B-3	1200	146.0	197.0	18.0	20.9
1B-4	1200	144.0	195.0	19.0	23.7
2B-3	1200	146.2	201.4	13.0	17.4
2B-4	1200	149.8	206.4	18.0	19.6
3B-3	1200	158.0	208.8	25.0	25.1
3B-4	1200	155.8	209.2	20.5	20.9
4B-3	1200	144.0	194.8	20.0	20.9
4B-4	1200	142.2	193.4	21.5	23.7
5B-3	1200	147.6	198.2	20.0	23.1
5B-4	1200	146.0	197.2	23.5	25.1

In the 1400°F A upsets, there was considerable overlap in test results from the various upsets. The most noticeable difference in tests was the high elongation and reduction in area of the #2 upset.

In the case of the B upsets tested at 1200°F, the powder upsets again had strength properties equal to or higher than the cast-wrought upsets with the highest strengths occurring again in the extruded powder.

<u>Stress-Rupture Tests</u>

Stress-rupture test results are shown in Tables VIII and IX respectively. The cast-wrought stress-rupture tests were generally equivalent to most of the powder upsets in specimen life. The one exception to this was upset #3 (extruded material) which had a test life which appeared to be significantly lower than those of any of the other tests. There appears to be a grain size effect in going from 1300°F to 1400°F because the extruded product showed good 1300°F creep properties when compared to the other upsets. Upset #4 had stress-rupture elongations which were at least 50% higher than the powder upsets and upset #1 had elongations which were about half those in the other powder parts.

The 1200°F stress-rupture results did not reveal any marked differences between upsets.

<u>Creep Tests</u>

Creep test results are shown in Tables X and XI respectively. The creep test results in the A upsets indicated a somewhat longer time to reach 0.1% deformation in upset #3 as compared with the average times for the other upsets, perhaps due to the finer grain size. The creep life of cast-wrought material appeared to be on the lower side of the range as compared with the powder upset. In the case of the B upsets, the situation was somewhat reversed with the cast-wrought giving the longest life to 0.1% deformation.

The creep test results for the B upsets are more difficult to explain, although the normal specification requirement of 125 hours to 0.2% plastic deformation was achieved in all cases. The fact that the structure is still in a partially cold work state and exact specimen location in the upset may be important.

<u>Low Cycle Fatigue Tests</u>

The low cycle fatigue results (Table XII) show the extruded powder of upset #3A to be definitely superior to the other A upsets which appear to be generally in the same population. We feel, again, that this is due to the finer grain size. The poorest performance (average of two tests) was found in the upset #1. There is considerable scatter in the B upset results, but extruded material does tend to give better fatigue life.

Summary

From the results of the work done, we can conclude that the properties obtained from forged P/M Astroloy compacted by three different methods equals or exceeds those obtained from VAR Astroloy processed in the same manner. Test results show that for 1300°F and below properties, the material forged from extruded powder billet tended to show superior properties, particularly in low cycle fatigue. For 1400°F stress-rupture properties, the material forged from the hot isostatic pressed billets and forge-compactions showed better properties under the same processing conditions. These differences in properties are believed to be due to differences in the grain sizes in the heat treated forgings.

TABLE VIII

COMBINATION STRESS RUPTURE RESULTS FOR "A" UPSETS

TEST CONDITIONS: 1400°F; 85 KSI LOAD

Test Number	Specimen Life (Hours)	Elong. %	Location of Break
1A-5	40.5	12.3	Plain Bar
1A-6	31.1	10.9	Plain Bar
2A-5	44.9	21.4	Plain Bar
2A-6	37.8	20.7	Plain Bar
3A-5	23.1	17.2	Plain Bar
3A-6	18.1	21.4	Plain Bar
4A-5	37.3	33.3	Plain Bar
4A-6	40.6	33.3	Plain Bar
5A-5	52.9	19.3	Plain Bar
5A-6	37.1	19.3	Plain Bar

TABLE IX

COMBINATION STRESS RUPTURE RESULTS FOR "B" UPSETS

TEST CONDITIONS: 1300°F; 110 KSI LOAD

Test Number	Specimen Life (Hours)	Elong. %	Location of Break
1B-5	110.1	27.8	Plain Bar
1B-6	124.9	24.2	Plain Bar
2B-5	127.5	27.1	Plain Bar
2B-6	(138.7)	(9.6)	Plain Bar
3B-5	112.7	20.0	Plain Bar
3B-6	125.3	21.4	Plain Bar
4B-5	91.5	30.5	Plain Bar
4B-6	87.1	17.2	Plain Bar
5B-5	(130.4)	(15.1)	Plain Bar
5B-6	116.1	27.8	Plain Bar

( ) Test discontinued before break

TABLE X

CREEP TEST RESULTS OF "A" UPSETS

TEST CONDITIONS: 1300°F; 74 KSI

Test Number	Primary Creep Duration Hours	Primary Creep % Deformation	Secondary Creep Duration Hours	Secondary Creep % Deformation	Time to 0.1% Creep (Hours)
1A-1	11.1	.011	120.3	.068	158.0
1A-10	9.4	.013	96.0	.043	174.0
2A-1	10.7	.014	108.4	.053	169.0
2A-10	11.2	.015	126.6	.056	186.0
3A-1	11.3	.021	128.1	.049	192.0
3A-10	14.7	.017	118.0	.043	197.5
4A-1	10.5	.013	108.4	.063	155.5
4A-10	15.6	.026	*	*	154.0
5A-1	17.0	.022	92.4	.049	154.0
5A-10	4.8	.004	86.1	.036	188.0

* Test discontinued before secondary creep was complete

TABLE XI

CREEP TEST RESULTS OF "B" UPSETS

TEST CONDITIONS: 1300°F; 65 KSI

Test Number	Primary Creep Duration Hours	Primary Creep % Deformation	Secondary Creep Duration Hours	Secondary Creep % Deformation	Time in Hours to Reach 0.1%	Time in Hours to Reach 0.2%
1B-1	61.7	.010	958.1	.180	535.0	1060.0
1B-10	152.5	.050	*	*	385.0	860.0
2B-1	161.0	.068	*	*	330.0	880.0
2B-10	52.9	.026	*	*	395.0	860.0
3B-1	20.5	.025	179.5	.086	195.0	364.5
3B-10	30.9	.025	*	*	200.0	425.0
4B-1	69.1	.020	438.7	.104	420.0	830.0
4B-10	28.7	.015	602.2	.136	410.0	815.0
5B-1	99.2	.067	*	*	190.0	490.0
5B-10	22.4	.021	*	*	290.0	632.0

* Test discontinued before completion of secondary creep

TABLE XII

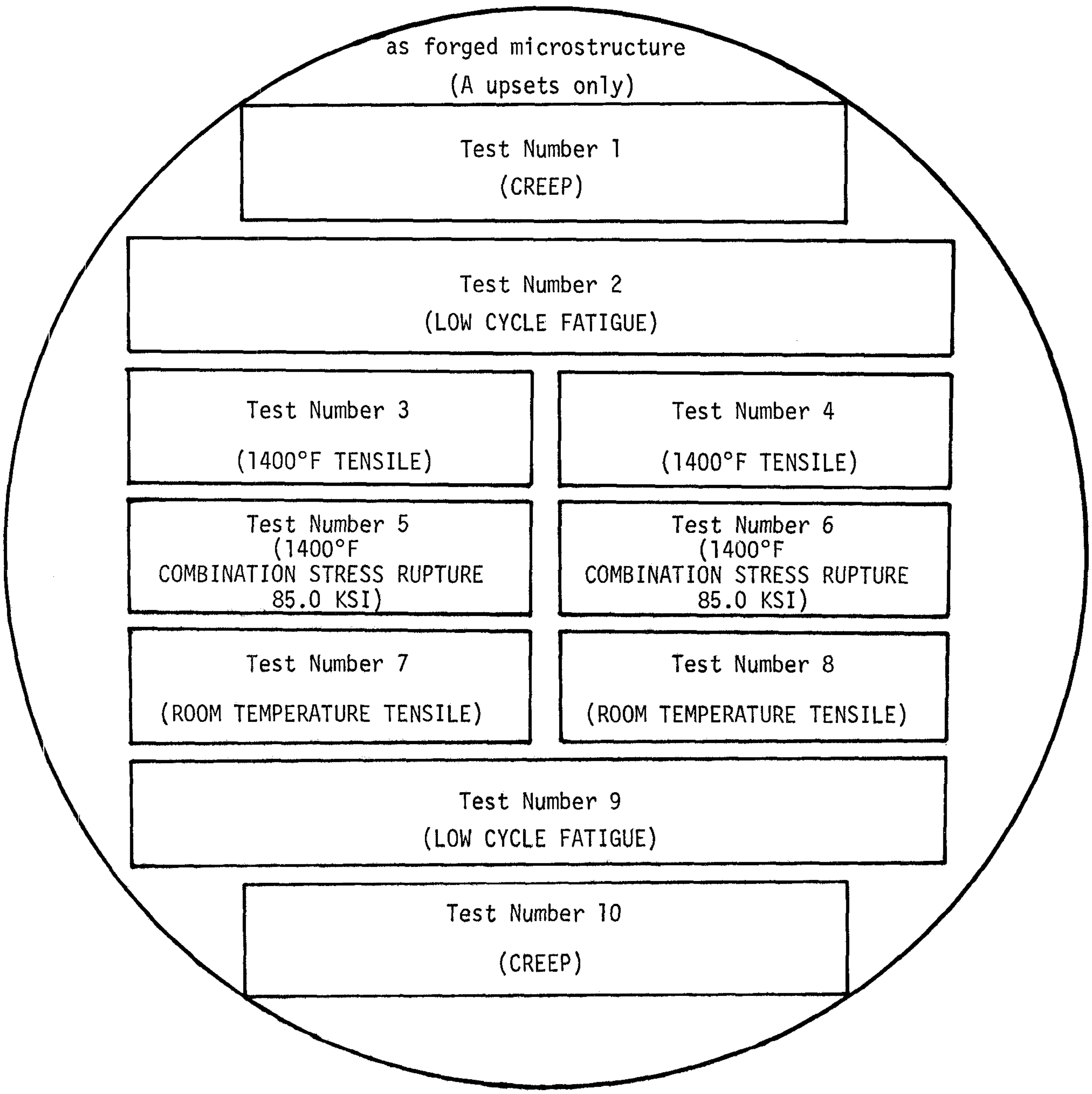
LOW CYCLE FATIGUE TEST RESULTS

TEST CONDITIONS: 1175°F; 40 KSI STEADY TENSILE LOAD
$\pm$50 KSI ALTERNATING (30 HERTZ) LOAD

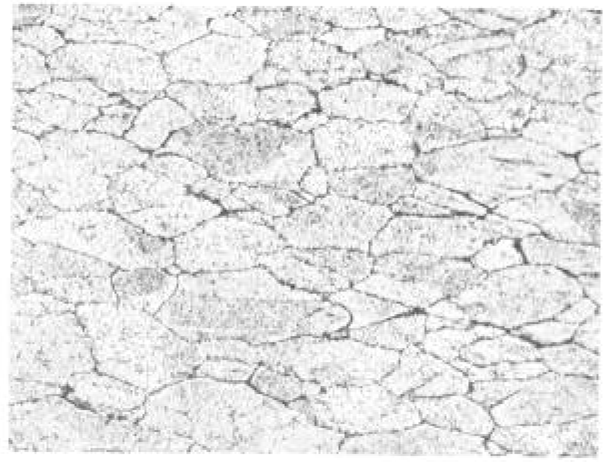
Test Number	Test Life Cycles
1A-2	11,000
1A-9	15,400
2A-2	15,100
2A-9	21,200
3A-2	60,800
3A-9	36,800
4A-2	13,700
4A-9	14,500
5A-2	17,100
5A-9	25,100
1B-2	17,000
1B-9	35,700
2B-2	28,200
2B-9	37,600
3B-2	98,500
3B-9	148,400
4B-2	21,200
4B-9	10,100
5B-2	13,400
5B-9	92,000

FIGURE 1

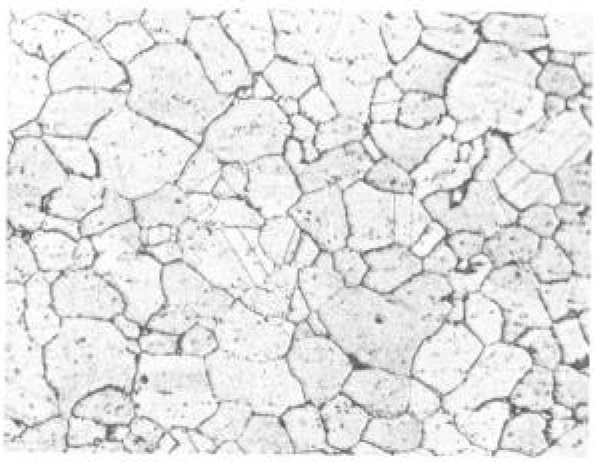
TEST LOCATIONS FOR UPSETS A AND B, SERIAL NUMBERS 1 THROUGH 5



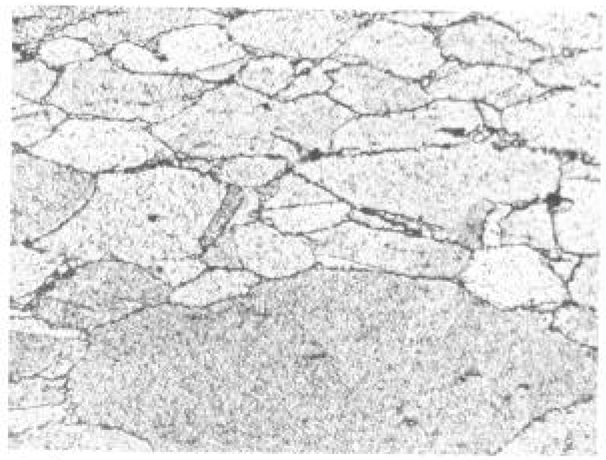
(A) as received X250



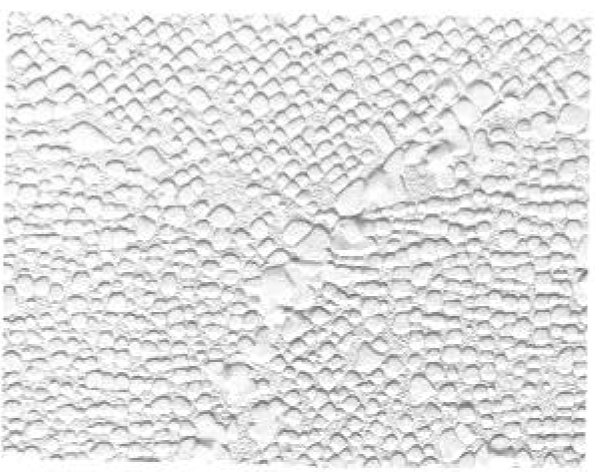
(B) as forged G/S ASTM 7,6 X250



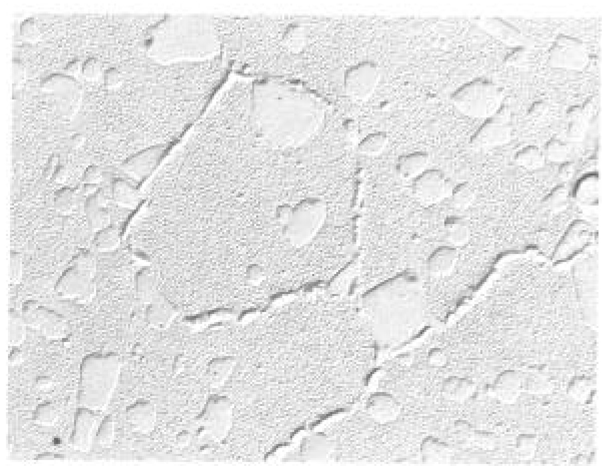
(C) upset A G/S ASTM 7,4 X250



(D) upset B G/S ASTM 7,3 X250

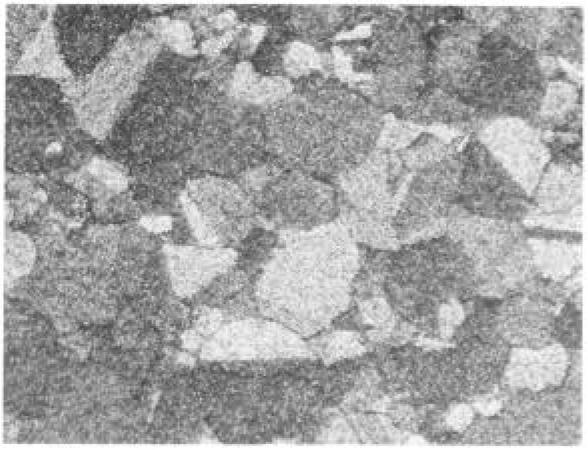


(E) upset A X10,000

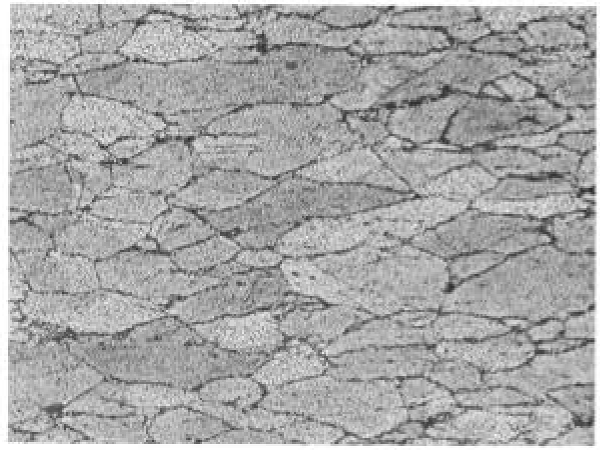


(F) upset B X10,000

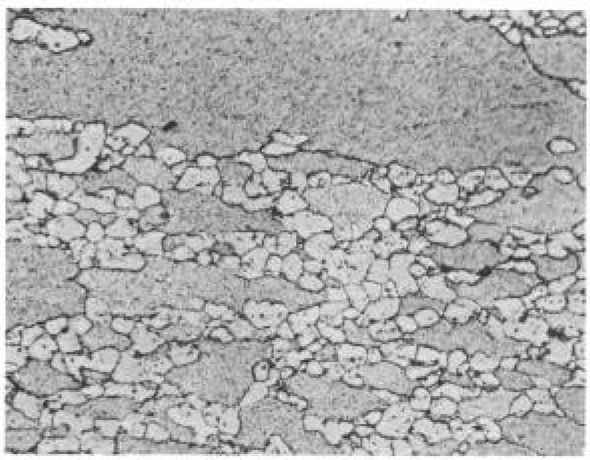
Figure 2 - Microstructures of Upset #1
Billet Hot Isopressed at 2350°F - 15 KSI



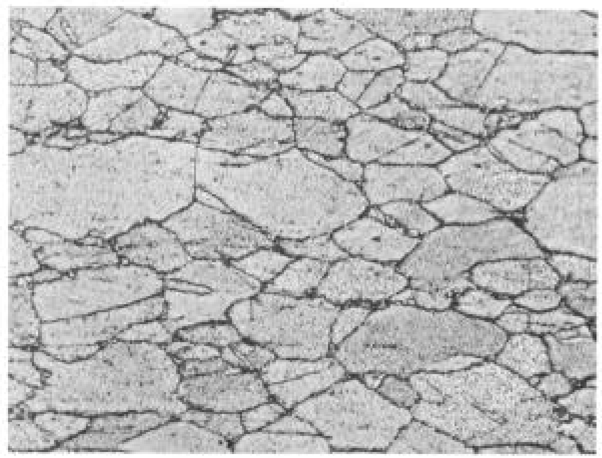
(A) as received X250



(B) as forged G/S ASTM 7,8 X250

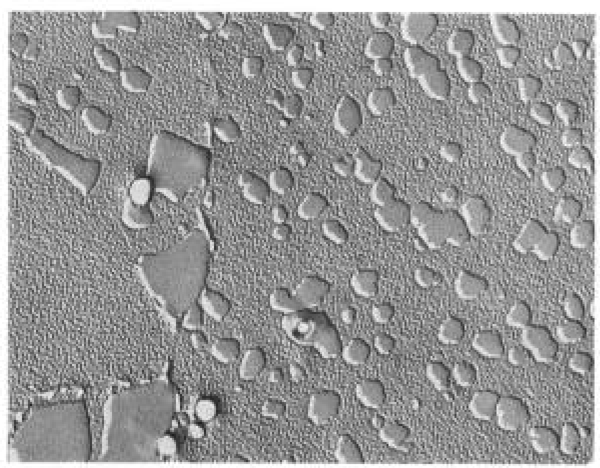


(C) upset A G/S ASTM 8,5 X250



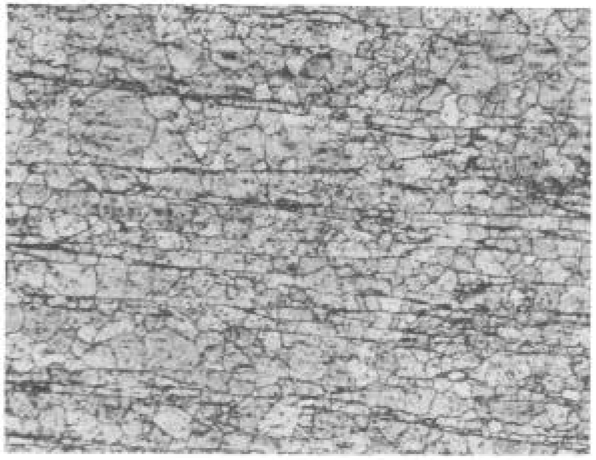
(D) upset B G/S ASTM 8,2 X250

(E) upset A X10,000

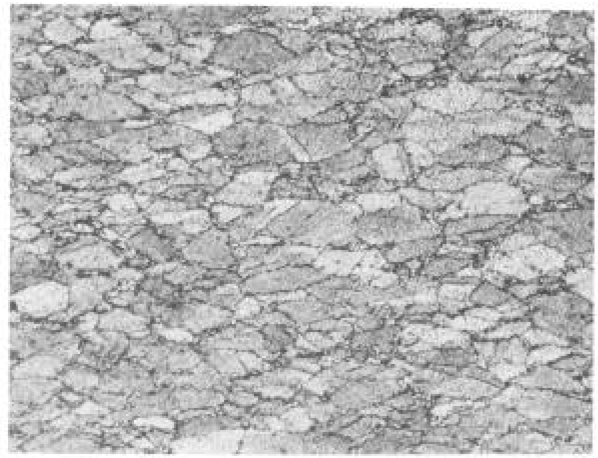


(F) upset B X10,000

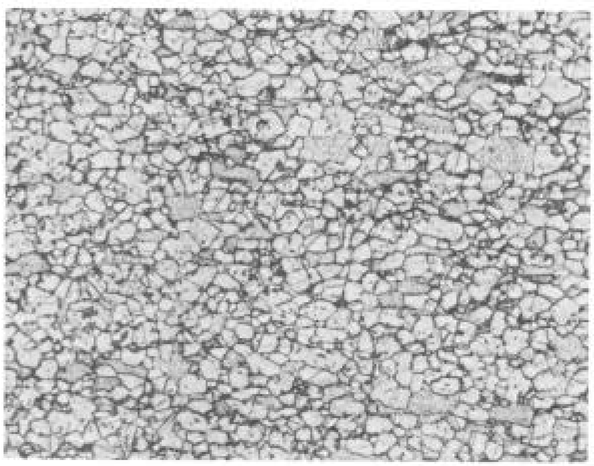
Figure 3 - Microstructures of Upset #2
Billet Hot Isopressed at 2250°F - 15 KSI



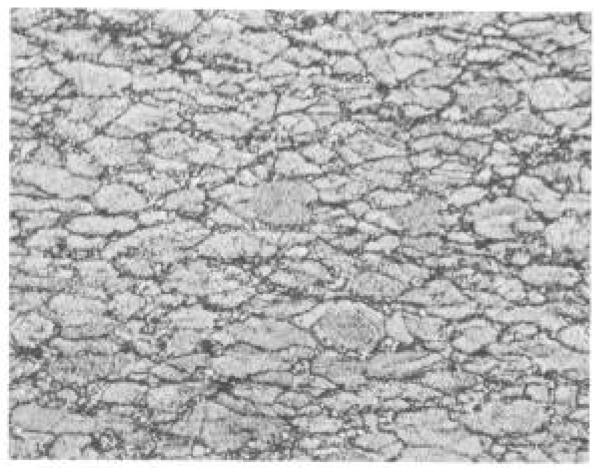
(A) as received X250



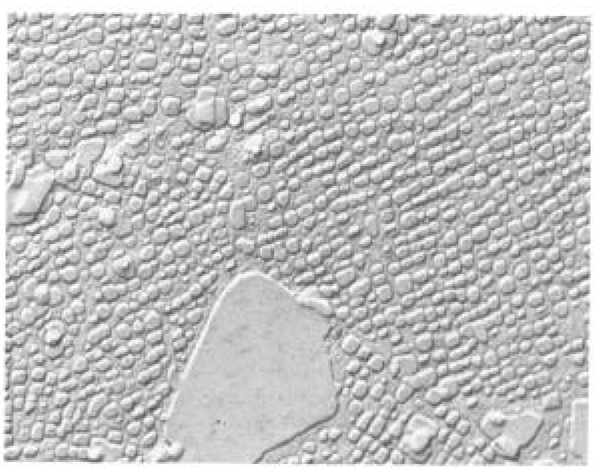
(B) as forged G/S ASTM 10,0 X250



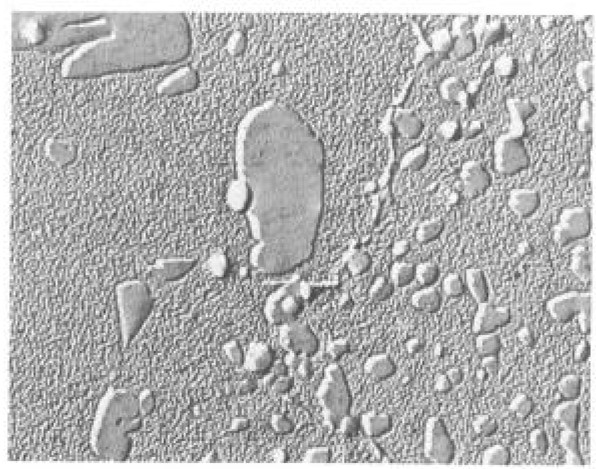
(C) upset A G/S ASTM 10,6 X250



(D) upset B G/S ASTM 10,2 X250

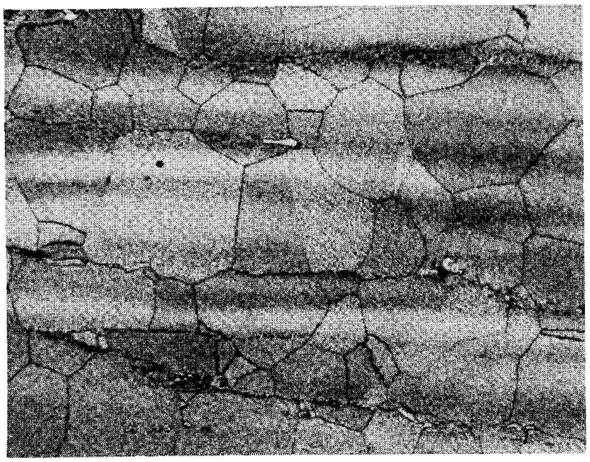


(E) upset A X10,000

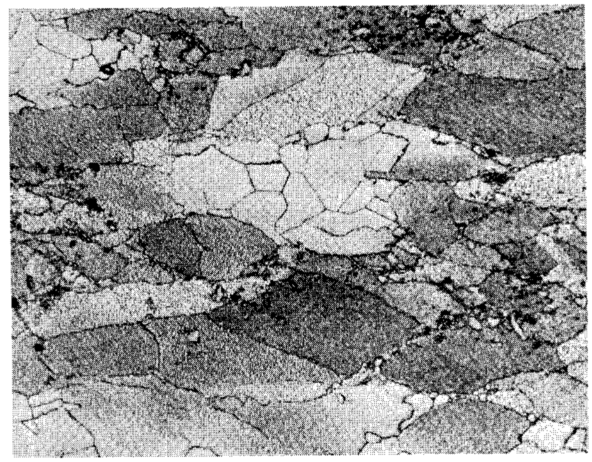


(F) upset B X10,000

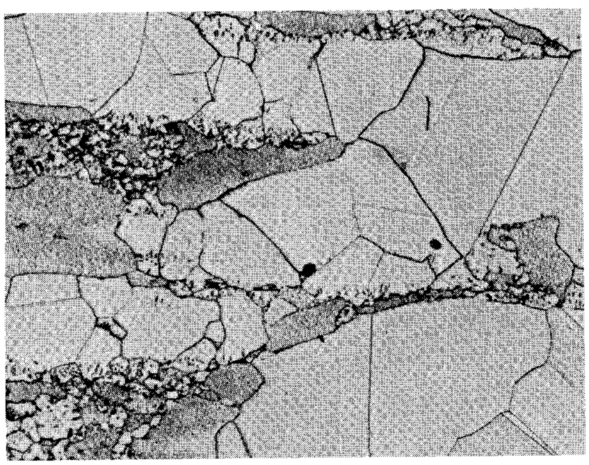
Figure 4 - Microstructures of Upset #3
Extruded Powder Billet



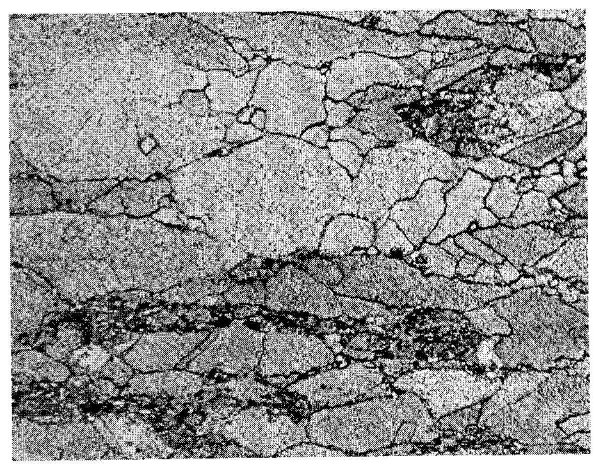
(A) as received X250



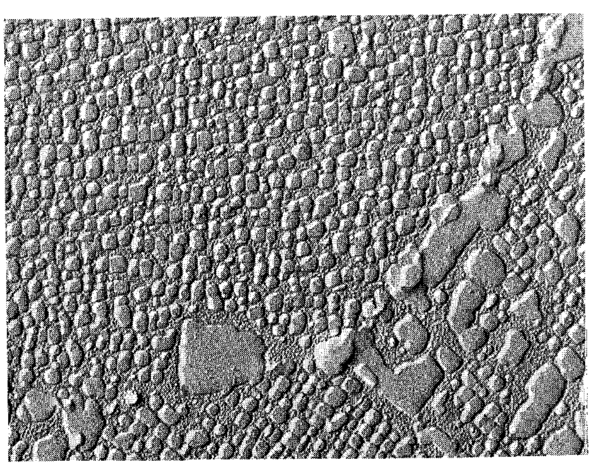
(B) as forged G/S ASTM 7,4 X250



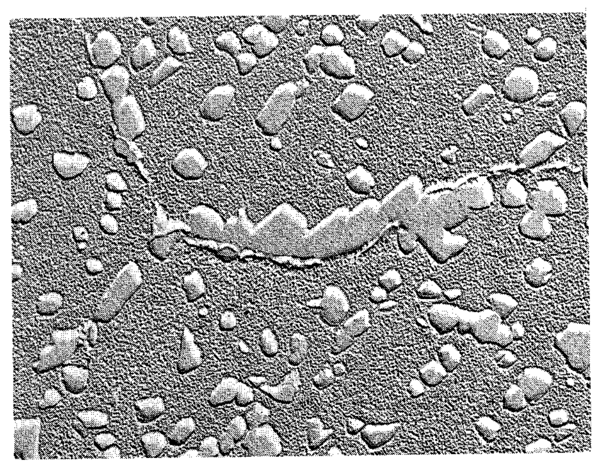
(C) upset A G/S ASTM 6,9 X250



(D) upset B G/S ASTM 7,5 X250

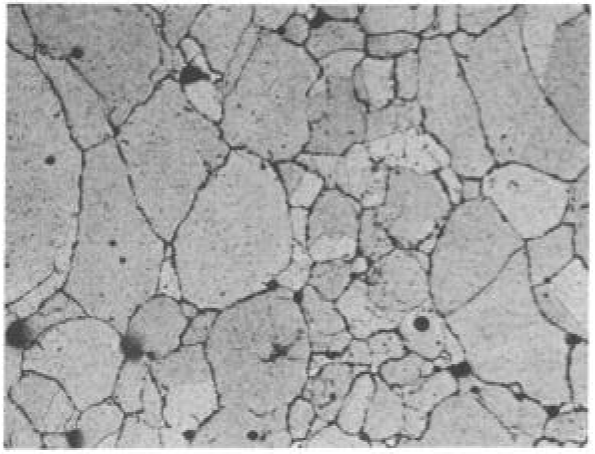


(E) upset A X10,000

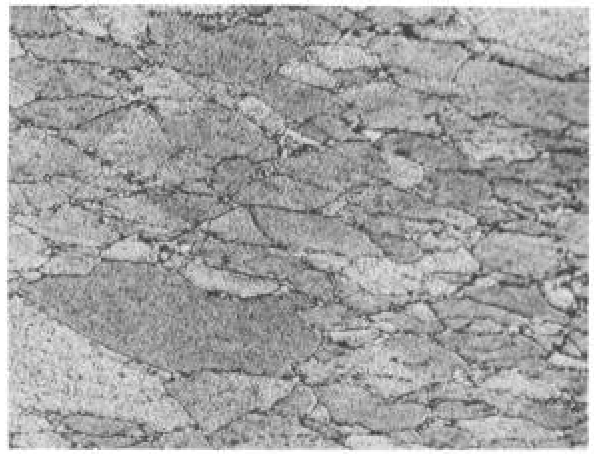


(F) upset B X10,000

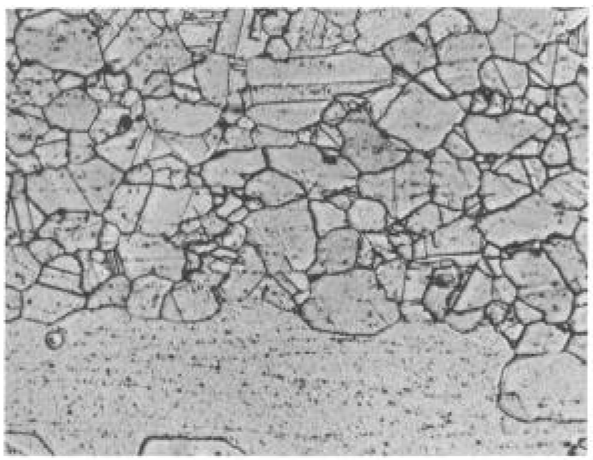
Figure 5 - Microstructures of Upset #4
Cast Wrought Billet



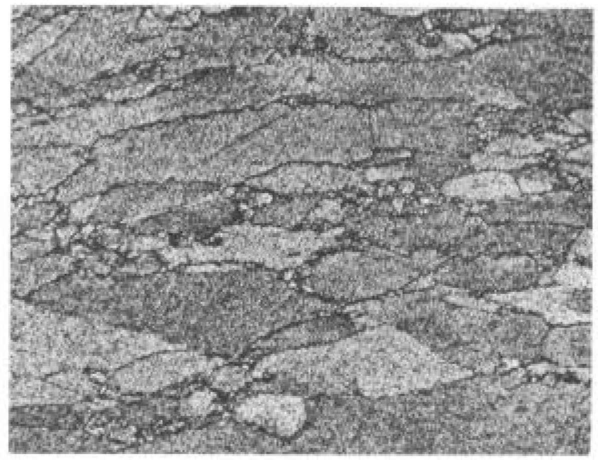
(A) as received X250



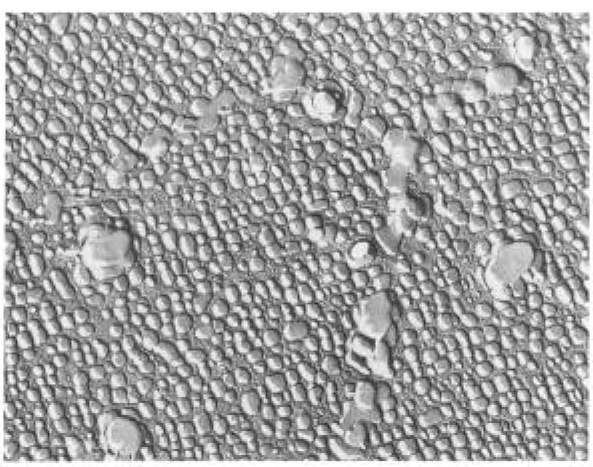
(B) as forged G/S ASTM 7,8 X250



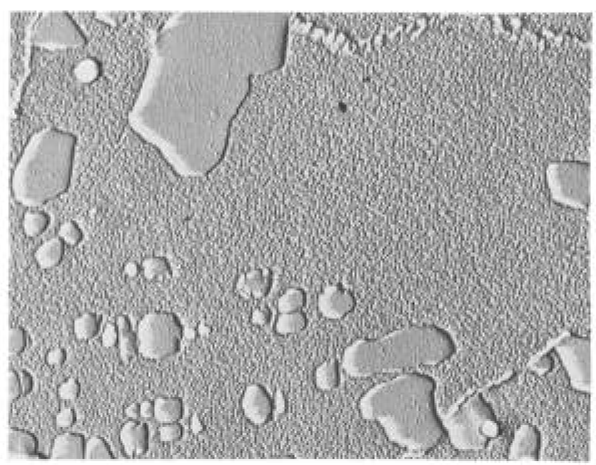
(C) upset A G/S ASTM 8,0 X250



(D) upset B G/S ASTM 8,5 X250



(E) upset A X10,000



(F) upset B X10,000

Figure 6 - Microstructures of Upset #5
Forge Compacted Billet