THE PROPERTIES AND MICROSTRUCTURE OF A LARGE FORGED SUPERALLOY TURBINE WHEEL

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ABSTRACT

A development program was conducted to assess the feasibility of forging large (9000 lbs.) industrial gas turbine wheels from superalloys, and to characterize the resulting properties and microstructure. The alloy chosen for this study was Alloy 706, a Fe-Ni-base superalloy strengthened by precipitation heat treatments. Starting material consisted of an electro-flux melted (EFM) ingot 24 inches in diameter weighing 11,000 pounds. The ingot was forged into a wheel configuration by a major forging vendor. Sections from the wheel were given either a two-step or three-step heat treatment to primarily develop tensile or rupture properties, respectively. Mechanical properties were determined in the hub, mid-radius and rim areas for both heat treatments. Property evaluations consisted of tensile, rupture, fracture toughness and impact tests. Microstructures were examined by standard metallographic techniques as well as by scanning electron and transmission microscopy, selected area electron diffraction analysis and X-ray diffraction.

The conclusion reached was that superalloy wheels of this size are feasible, at least in Alloy 706.

INTRODUCTION

A development program was conducted to assess the feasibility of forging large (9000 lbs.) industrial gas turbine wheels from superalloys. The concern centered on the size of the wheel for the objective was much larger wheels than had ever been produced in a superalloy previously. To meet this need a survey was conducted of alloys that might fill the design requirements and could reasonably be expected to be melted and forged in large sizes. The initial goal was a wheel 72 inches in diameter, 15 inches thick at the hub and 5 inches thick at the rim. The weight was calculated to be 9200 lbs.

The dimensional requirements changed somewhat in the design evolution so a slightly larger wheel than that described was finally produced.

Although many alloys were considered, the field quickly narrowed down to 706 Alloy, a precipitation strengthened Fe-Ni base heat resistant material. Although not new, it is less well known than 718 Alloy which is similar in many respects. The main reasons 706 Alloy was chosen in preference to several other alloys which also met the mechanical property requirements were:

1. Demonstrated good forgeability
2. Moderate deformation strength
3. Ingot size availability
4. Relatively good machinability

A study was initiated to determine the feasibility of forging a wheel of this size and to characterize the resulting properties and microstructure.

PROCESSING PROCEDURES

The ingot used was 24 in. nominal diameter by approximately 90 in. long and weighed 11,700 lbs. It was produced by the electro-flux melt (EFM) process. The composition of the ingot is listed in Table 1. A 1/2 in. thick slab was removed from the top and a 5 in. thick slab from the bottom for macro etch and upset tests, reducing the ingot weight to approximately 11,000 lbs.

The forging procedure started with a direct upset of the ingot. Although a drawing operation (increasing the length) prior to upsetting is desirable, the 24 in. diameter of the ingot precluded that because of the possibility of buckling. No evidence was found that the direct upset was harmful. Later in the cycle (Fig. 1) another upset operation was done so the total hot work put into the material was considerable.

The last two forging steps were done on a 50,000 T press. The final forge operation was carried out at 2,000 F and the earlier steps at slightly higher temperature. In the final operation the full capacity of the press was used to move the material to final dimensions. (Fig. 2)

TABLE 1

COMPOSITION OF 706 ALLOY INGOT

C	Mn	Si	P	S	Cr	Ni	Cb+Ta	Ti	Al	B	Fe
.04	.19	.14	.006	.002	16.30	42.18	2.94	1.70	.24	.004	36.45

Before heat treatment, the wheel was machined and sectioned. One quarter was given a 2 step heat treatment, one quarter a 3 step heat treatment and a half held in the as-forged condition for future work. The heat treatments were those recommended for tensile limiting (2 step cycle) or rupture limiting (3 step cycle) applications by Huntington Alloys, Inc. (1)

The wheel sections were ultrasonically tested using a 2.25 MHZ crystal calibrating on a 5/16 in. flat bottom hole. Up to 5 in. thickness could be penetrated with this technique and no indications were found. In order to penetrate the thicker sections a 1 MHZ crystal was used. No indications were found at this sensitivity.

TESTING PLAN

Test specimens were removed from portions of the wheel given either the 2 step heat treatment (2 SHT) or 3-step heat treatment (3 SHT) per Table 2 at positions corresponding to top surface, mid-thickness and bottom surface at three locations -- hub, mid-radius and rim.

The primary test directions used were tangential at the hub and mid-radius and radial at the rim. Some axial tests were made at the hub.

Standard 0.505 in. diameter tensile specimens were used in accordance with ASTM E-8-69 and E-21-70. Rupture specimens having a gage length of 2 in. and 0.253 in. diameter were tested per ASTM E-139-70. Charpy v-notch impact specimens were tested in accordance with ASTM E-23-72.

TABLE 2

HEAT TREATMENTS GIVEN TO SECTIONS OF THE AS-FORGED 706 ALLOY WHEEL

2-STEP HEAT TREATMENT

Solution treat at 1800°F for one (1) hour
Water quench to 100°F
Heat to 1350°F, hold 8 hours at temperature
Furnace cool to 1150°F, hold a total of 10 hours and air cool
Total age time: 1350°F + 1150°F 18 hours

3-STEP HEAT TREATMENT

Solution treat at 1800°F for one (1) hour
Water quench to 100°F
Heat to 1550°F, hold 3 hours at temperature and air cool to RT
Heat to 1325°F, hold 8 hours at temperature
Furnace cool to 1150°F, hold a total of 10 hours and air cool to RT
Total age time: 1325°F , 1150°F 18 hours

RESULTS AND DISCUSSION

Tensile and Impact Properties

Table 3 gives the room temperature tensile and impact properties at each of the designated locations described above. Both tensile strength and ductility were relatively uniform through the thickness at each of the radial locations for the 2 SHT. Strength and ductility were improved at the rim location compared to the hub and mid-radius. Impact energy was uniform in both the axial and radial directions. Several axial tensile tests from the hub, not included in Table 3, gave slightly less ductility.

TABLE 3

SUMMARY OF ROOM TEMPERATURE TENSILE AND IMPACT PROPERTIES FROM 706 ALLOY WHEEL FORGING

A. 2-STEP HEAT TREATMENT

	Tensile				Impact (1)
Hub (1)	UTS(KSI)	.2YS(KSI)	% EL	% RA	Energy (Ft-Lbs)
TS (2)	169.0	135.0	18.0	21.2	35.0
MT	167.5	145.0	15.1	19.0	38.5
BS	172.0	138.7	17.0	20.5	35.5
Mid-Radius (1)					
TS	170.7	148.0	16.6	18.7	40.0
MT	170.5	139.0	15.6	18.3	38.5
BS	172.5	146.5	16.4	18.7	44.0
Rim (3)					
TS	177.0	144.5	20.6	30.7	39.0
MT	176.0	148.1	17.2	24.9	36.0
BS	177.0	146.2	19.5	28.7	33.5

B. 3-STEP HEAT TREATMENT

	Tensile				Impact (1)
Hub (1)	UTS(KSI)	.2YS(KSI)	% EL	% RA	Energy (Ft-Lbs)
TS	167.0	140.7	8.6	10.2	15.5
MT	165.0	139.8	7.8	9.8	17.5
BS	166.3	137.2	8.0	9.8	16.5
Mid-Radius (1)					
TS	169.0	125.2	9.4	11.3	15.5
MT	179.6	140.7	9.4	11.0	14.0
BS	170.3	144.5	9.4	11.4	14.5
Rim (3)					
TS	169.6	103.9	13.1	15.2	13.5
MT	171.6	139.2	12.5	12.5	14.5
BS	170.8	139.2	10.3	11.0	14.0

Notes: (1) Tangential orientation
(2) TS = Top Surface, MT = Mid-Thickness, BS = Bottom Surface
(3) Radial orientation

The same trends are true for the 3 SHT material. Two tensile values fell below the nominal level at the mid-radius and rim top surface positions. The cause of these lower values was not determined. Variable tensile results have been reported elsewhere (2) for Alloy 706 material given the 3 SHT after a rapid cool from solution heat treatment temperatures. It can be seen that the tensile ductility and impact energy values are lower than that for the 2 SHT, which was expected (1,2,3,4,5).

Table 4 contains tensile properties as a function of temperature at the mid-thickness positions at the hub and rim for the 2 SHT material. Table 5 gives corresponding values for the 3 SHT material. The higher temperature data show the same comparative trends as the room temperature data in Table 3.

Stress Rupture Properties

Stress rupture results from the rim are shown in Table 6. The characteristic low rupture ductility and notch sensitivity are apparent for the 2 SHT material. The 3 SHT data are more consistent and show much better ductility.

TABLE 4

TENSILE DATA FROM 706 ALLOY WHEEL FORGING, 2-STEP HEAT TREATMENT, MID-THICKNESS POSITION

A. HUB LOCATION (Tangential Orientation)

TEMPERATURE (°F)	UTS(KSI)	.2% YS(KSI)	% EL	% RA
RT	167.5	145.0	15.1	19.0
300	160.0	133.2	14.1	16.9
500	158.3	132.7	17.4	21.8
700	150.5	122.2	19.8	31.4
900	145.0	122.1	20.6	36.8

B. RIM LOCATION (Radial Orientation)

TEMPERATURE (°F)	UTS(KSI)	.2% YS(KSI)	% EL	% RA
RT	176.4	148.1	17.2	24.9
300	168.0	140.0	16.4	23.6
500	163.2	134.5	18.7	31.7
700	157.7	133.5	18.7	36.5
900	148.6	123.7	21.5	40.2
1000	150.5	128.0	18.7	40.2

TABLE 5

TENSILE DATA FROM 706 ALLOY WHEEL FORGING, 3-STEP HEAT TREATMENT, MID-THICKNESS POSITION

A. HUB LOCATION (Tangential Orientation)

TEMPERATURE (°F)	UTS(KSI)	.2% YS(KSI)	% EL	% RA
RT	165.0	139.8	7.8	9.8
300	156.2	134.5	11.3	8.4
500	157.2	130.0	15.4	10.2
700	156.7	126.5	10.9	13.2
900	>150.0	>124.0	(1)	(1)

B. RIM LOCATION (Radial Orientation)

TEMPERATURE (°F)	UTS(KSI)	.2% YS(KSI)	% EL	% RA
RT	168.3	141.2	8.6	11.0
300	163.1	133.0	9.4	11.4
500	160.0	128.0	10.2	13.2
700	157.2	123.8	12.1	16.9
900	153.9	122.0	13.9	23.0
1000	152.7	120.8	14.5	26.9

Note: (1) Coupling bar broke before specimen

Fracture Toughness

Fracture toughness specimens of the 2T compact tension type per ASTM E-399-72 were removed from the 2 SHT hub and tested. The specimen crack plane was in the radial-axial plane of the wheel. The first test was done at room temperature, and did not meet the validity requirements for plane strain (K_{Ic}). A K_Q value of 133 KSI $\sqrt{in.}$ was calculated. The second test was made at -50°F with the intent of increasing the yield strength and therefore increasing the chances for plane strain conditions. This test did not meet the validity criteria either and the calculated K_Q was 161 KSI $\sqrt{in.}$ Both of these K_Q values indicate a relatively high level of fracture toughness for the 2 SHT material.

TABLE 6

STRESS RUPTURE PROPERTIES FROM
706 ALLOY WHEEL FORGING, RIM LOCATION

A. 2-STEP HEAT TREATMENT (RADIAL ORIENTATION)

TEMPERATURE (°F)	STRESS (KSI)	LIFE, HOURS	% EL	% RA
1000	134	267.2	3.8	22.0
1000	138	341.2	2.5	12.7
1100	116	551.0	3.5	15.0
1100	120	73.2	2.2	12.0
1100	120	> 53.2	(1)	(1)
1100	120	> 20.0	(1)	(1)
1100	124	50.4	3.3	19.7
1200	100	93.0	2.5	12.6
1200	100	> 2.0	(1)	(1)
1250	85	145.8	12.3	22.6
1250	85	> 2.0	(1)	(1)

B. 3-STEP HEAT TREATMENT (RADIAL ORIENTATION)

TEMPERATURE (°F)	STRESS (KSI)	LIFE, HOURS	% EL	% RA
1000	138	33.3	10.0	15.2
1100	120	137.3	5.1	8.9
1100	120	128.9	7.8	12.7
1100	120	73.8	10.4	18.3
1200	100	70.5	9.2	22.8
1200	100	67.1	11.9	28.9
1250	85	238.2	12.6	26.6
1250	85	138.4	13.2	31.6

Notes: (1) Specimen broke in threads.

Microstructure

The nominal ASTM grain sizes at locations throughout the wheel are given in Table 7. They range from ~2.4 at the hub to ~4.5 at the rim. Figs. 3 and 4 show typical 2 SHT microstructures at 100X for the hub and rim, respectively. The hub microstructure shows extensive evidence of annealing twins. The rim microstructure has fine recrystallized grains interspersed with larger grains, some of which also contain annealing twins. The larger, angular precipitates are thought to be MC type carbides.

TABLE 7

GRAIN SIZE DETERMINATIONS
THROUGHOUT 706 ALLOY WHEEL FORGING
(ASTM - E112)

	TOP SURFACE	MIDDLE	BOTTOM SURFACE
HUB	2.42	2.80	3.10
MID-RADIUS	2.40	2.73	2.51
RIM	3.88	4.54	3.18

Figs. 5 and 6 contain typical microstructures for hub and rim material after the 3 SHT. Grain sizes and distribution are essentially equivalent to the 2 SHT material, but evidence of much heavier second phase precipitation at grain boundaries and on preferred orientations within the grains is apparent. Previous investigators (1,2,3,4,5,6) have identified these precipitates as either the HCP eta (Ni_3Ti) or the orthorhombic delta (Ni_3Cb) phases. The primary strengthening precipitate is considered to be either FCC γ' (Ni_3Ti) or BCT γ'' (Ni_3Cb) depending on the specific chemical composition and heat treatment involved. The remaining metallographic characterization is for material given the 2 SHT, since this was the primary heat treat condition of interest in the feasibility study.

Fractographic features from a room temperature tensile specimen taken from 2 SHT hub material are shown in Fig. 7. It was found that fractured surfaces from all locations exhibited a mixed mode of intergranular and transgranular fracture. However, the hub fractures were primarily intergranular and the rim fractures were primarily transgranular dimpled fractures. The large dimples in Fig. 7b apparently initiated at the larger second phase particles marked by an "o".

Relief type replicas for transmission electron microscopy were prepared by mechanically polishing and etching in 2 HCL: 1 HNO_3: 2 Glycerine. Photos were then taken of images from single stage, Ag/Pt shadowed, collodian replicas of these surfaces to show typical features.

All of the samples had an extremely fine intragranular precipitate with occasional, very narrow, denuded zones at some boundaries. Fig. 8 shows these features. The small black spots are extracted second phase particles which were inadvertently removed during replication.

Grain boundary conditions ranged from essentially clean boundaries to those containing heavy globular or continuous films as shown in Fig. 9. The heaviest grain boundary precipitation appeared to have occurred at the mid-radius location and an example of this area is seen in Fig. 10. Some of the intergranular precipitate displayed the characteristic cellular morphology of the HCP eta phase. Fig. 11 shows this condition.

Extraction type replicas were prepared by etching the polished surfaces about five minutes in 92 HCL: 5 H_2SO_4: 3 HNO_3 and removing particles in situ via a plastic tape. Small patches of silver were vapor-deposited onto these extraction replicas to serve as an internal standard for subsequent selected area electron diffraction (SED) analysis.

Fig. 12 shows the fine intragranular precipitate from the hub mid-thickness. Similar samples taken from the rim were essentially the same in appearance. Particles in these replicas were measured to range about 75-150 Å in diameter. Their non-uniform dispersion is thought to be an artifact resulting from the loss of some particles during etching, rinsing and drying of the sample prior to extraction. The SED patterns were consistent with an FCC lattice and are believed to be γ'. There were no super-lattice lines, the presence of which would indicate atomic ordering on the crystal lattice. The SED patterns showed continuous circles indicating no preferred orientation relationship between the γ' and the matrix. Separate samples extracted electrolytically in 20% H_3PO_4-H_2O solution and analyzed by x-ray diffraction gave lattice parameters for the γ' of 3.609 Å at the hub and 3.607 Å at the rim.

Grain boundary precipitates were also extracted and analyzed by SED. Fig. 13 shows a precipitate whose pattern was a single crystal consistent with a [001] zone of orthorhombic Ni_3Cb.

The precipitate shown in Fig. 14 had a pattern which fit the [0001] zone of hexagonal Ni_3Ti with a_o = 5.10 Å.

X-ray diffraction analysis was also performed on a sample extracted with 7% HCl-methanol. The extracted phase had a lattice parameter of 4.419 Å and was identified as MC type carbide.

SUMMARY AND CONCLUSIONS

The main goal of this feasibility program was reached in that an ingot of a superalloy material was successfully forged into a wheel of the appropriate size and heat treated to reasonable property levels. Specific conclusions which were drawn from the data presented above are as follows:

1. The forgeability of the 24 in. diameter by 11,000 lb EFM ingot of Alloy 706 was excellent with the forging procedures used.

2. The standard 1800°F solution heat treatment after forging resulted in grain sizes of 2.4 to 4.5 throughout the wheel.

3. The standard 2-step heat treatment resulted in improved tensile ductility and toughness when compared to the 3-step heat treatment. The 3-step heat treatment gave improved rupture ductility.

4. Second phases identified in material given the 2-step heat treatment were FCC γ' (Ni_3Ti), orthorhombic delta (Ni_3Cb), HCP eta (Ni_3Ti) and MC type carbides.

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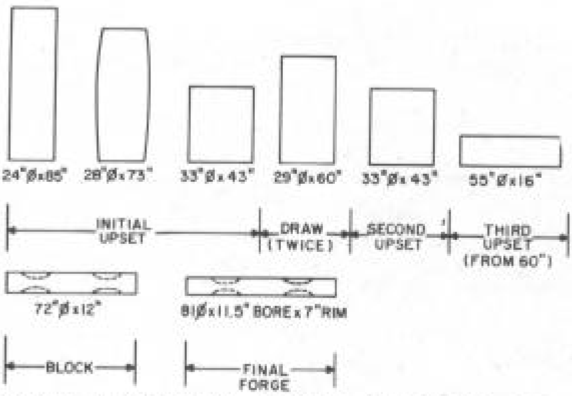


FIGURE 1. SCHEMATIC DIAGRAM OF FORGING PROCEDURE USED IN MAKING 706 ALLOY WHEEL FROM EFM INGOT. (COURTESY WYMAN-GORDON CO.)

FIGURE 2. AS FORGED 706 ALLOY WHEEL

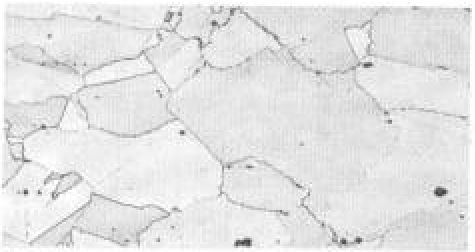


FIGURE 3. MICROSTRUCTURE OF HUB MATERIAL GIVEN 2-STEP HEAT TREATMENT. MID-THICKNESS IN RADIAL-AXIAL PLANE. 100X. ETCHANT: GLYCEREGIA

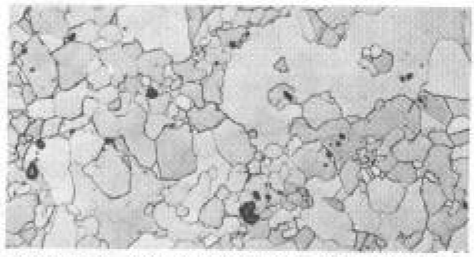


FIGURE 4. MICROSTRUCTURE OF RIM MATERIAL GIVEN 2-STEP HEAT TREATMENT. MID-THICKNESS LOCATION IN RADIAL-AXIAL PLANE. 100X. ETCHANT: GLYCEREGIA

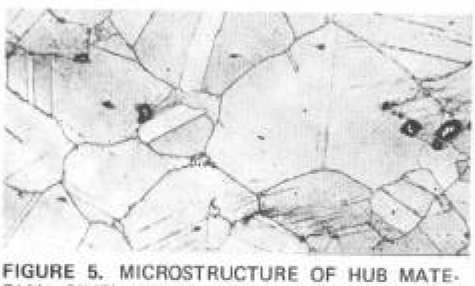


FIGURE 5. MICROSTRUCTURE OF HUB MATERIAL GIVEN 3-STEP HEAT TREATMENT. MID-THICKNESS LOCATION IN RADIAL-AXIAL PLANE. 100X. ETCHANT: GLYCEREGIA

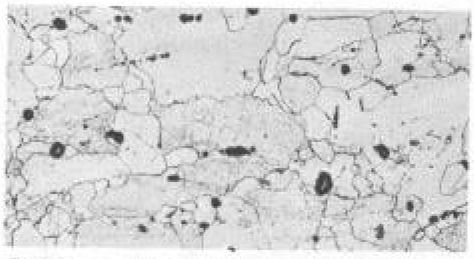
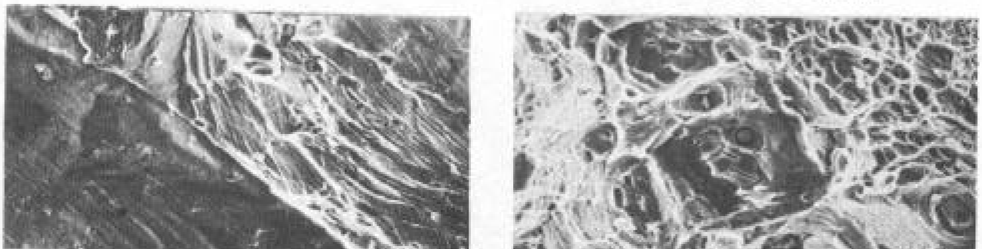


FIGURE 6. MICROSTRUCTURE OF RIM MATERIAL GIVEN 3-STEP HEAT TREATMENT. MID-THICKNESS LOCATION IN RADIAL-AXIAL PLANE. 100X. ETCHANT: GLYCEREGIA



a) INTERGRANULAR FRACTURE

b) TRANSGRANULAR DIMPLED FRACTURE

FIGURE 7. SCANNING ELECTRON MICROGRAPHS FROM THE FRACTURE SURFACE OF ROOM TEMPERATURE TENSILE SPECIMENS FROM MATERIAL GIVEN THE 2-STEP HEAT TREATMENT. ORIENTED TANGENTIALLY AT THE HUB MID-THICKNESS. 1000X

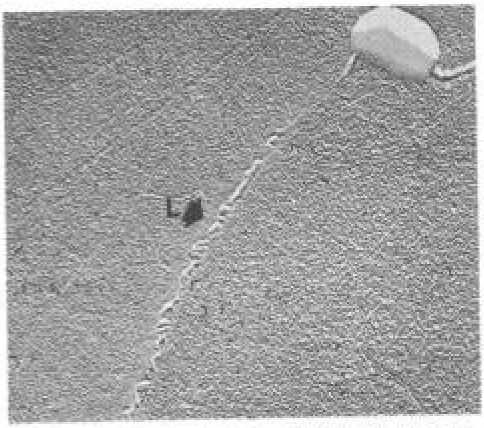


FIGURE 8. TRANSMISSION ELECTRON MICROGRAPH SHOWING A FINE INTRAGRANULAR PRECIPITATE WITH OCCASIONAL, VERY NARROW DENUDED ZONES (L) FOUND AT SOME BOUNDARIES. 2-STEP HEAT TREATMENT. SAMPLE LOCATION AT HUB MID-THICKNESS. 10,000X.

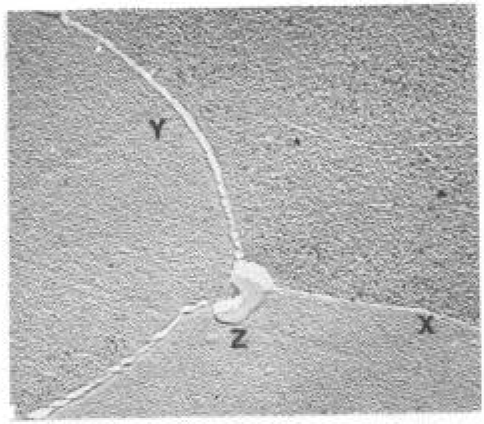


FIGURE 9. TRANSMISSION ELECTRON MICROGRAPH SHOWING EXAMPLES OF GRAIN BOUNDARIES ESSENTIALLY CLEAN OF PRECIPITATES (X), ONE WITH A CONTINUOUS FILM OF PRECIPITATE (Y), AND SOME GLOBULAR PRECIPITATE (Z). 2-STEP HEAT TREATMENT, SAMPLE LOCATION AT HUB MID-THICKNESS. 10,000X

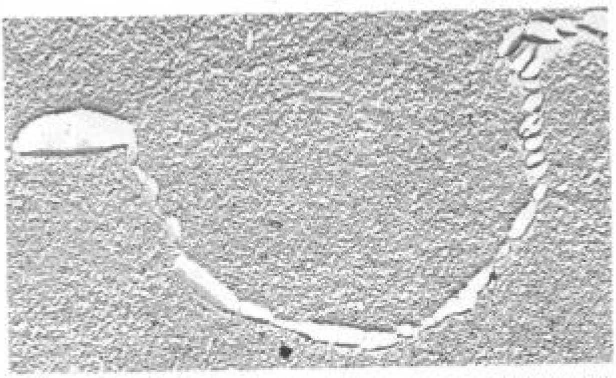


FIGURE 10. TRANSMISSION ELECTRON MICROGRAPH SHOWING EXAMPLE OF HEAVIER GRAIN BOUNDARY PRECIPITATION, 2-STEP HEAT TREATMENT. SAMPLE LOCATION MID-THICKNESS AT WHEEL MID-RADIUS. 10,000X

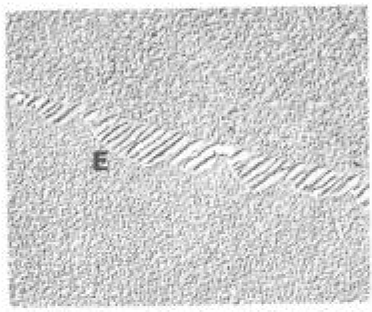


FIGURE 11. TRANSMISSION ELECTRON MICROGRAPH SHOWING CELLULAR PRECIPITATE (E) CHARACTERISTIC OF Ni_3Ti ETA PHASE. 2-STEP HEAT TREATMENT, SAMPLE LOCATION RIM MID-THICKNESS. 10,000X

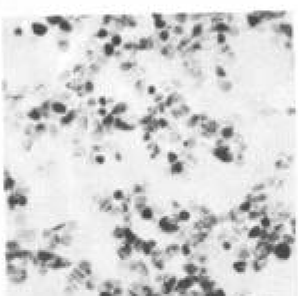


FIGURE 12. EXTRACTION REPLICA ELECTRON MICROGRAPH SHOWING FINE INTRAGRANULAR PRECIPITATE. 2-STEP HEAT TREATMENT. SAMPLE LOCATION HUB MID-THICKNESS. 148,000X

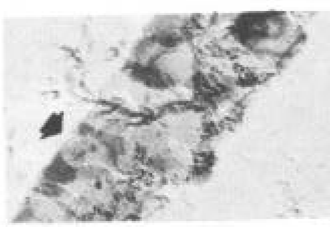


FIGURE 13. EXTRACTION REPLICA ELECTRON MICROGRAPH SHOWING A GRAIN BOUNDARY PRECIPITATE. SELECTED AREA ELECTRON DIFFRACTION PATTERN WAS A SINGLE CRYSTAL PATTERN CONSISTENT WITH A [001] ZONE OF ORTHORHOMBIC Ni_3Cb, PERPENDICULAR TO THE PLANE OF THE PAPER. 2-STEP HEAT TREATMENT. SAMPLE LOCATION HUB MID-THICKNESS. 74,000X

FIGURE 14. EXTRACTION REPLICA ELECTRON MICROGRAPH SHOWING A GRAIN BOUNDARY PRECIPITATE. SELECTED AREA ELECTRON DIFFRACTION PATTERN FIT THE [0001] ZONE OF HEXAGONAL Ni_3Ti. 2-STEP HEAT TREATMENT. SAMPLE LOCATION HUB MID-THICKNESS. 74,000X