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PROCESS DEMONSTRATION AND COST ANALYSIS OF A MASS PRODUCTION FORGING TECHNIQUE FOR AUTOMOTIVE TURBINE WHEELS - PHASE I

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
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Ann Arbor, Michigan 48105

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by

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Prepared for

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FOREWORD

This report is submitted in accordance with the requirements of Contract EPA 68-01-0477. It is the Phase I Final Engineering Report and covers all the work performed under the contract from 26 April 1973 to 26 July 1974.

Mr. Marvin M. Allen, Senior Project Metallurgist, is the program manager. Messrs. Bryant H. Walker, Senior Materials Test Engineer, and David J. Hill, Metallurgist, are the responsible engineers. This report carries the internal designation PWA FR-6690.

The EPA Project Officer for this contract is Phillip L. Stone, Materials and Structures Division, NASA-Lewis Research Center. Mr. Stone is working with EPA under a special technical assistance agreement between NASA and EPA. The EPA Project Coordinator for this contract is Robert B. Schulz, Office of Air and Waste Management.

ABSTRACT

Low cost fabrication of integrally-bladed automotive turbine wheels utilizing the GATORIZING™ forging process was demonstrated. Basic forging parameters were developed for the nickel-base alloy IN 100. Several wheels were produced and post forging heat-treating studies were conducted to develop an optimum combination of stress-rupture and LCF properties. Target goals for these properties were higher than those achieved in this initial study. The capabilities and limitations of the forging process are defined along with an estimate of turbine wheel costs in large production quantities.

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SUMMARY

This report describes the work performed under Phase I of a two-phase program. The objective of the overall program is to develop a low-cost forging technique for the production of integrally-bladed automotive gas turbine wheels. The Pratt & Whitney Aircraft GATORIZING™ forging technique is being used.

Phase I consisted of a process definition, process demonstration, mechanical properties determination, and a manufacturing cost estimate per unit based on a production rate of 1,000,000 wheels per year. The wheel selected as a model was the compressor-turbine wheel for the EPA/Chrysler Baseline Gas Turbine Engine. This wheel is 14.0 cm (5.5 in.) in diameter tip-to-tip. The material selected was the Ni-base alloy IN100.

In Phase I, the basic forging parameters for producing integrally-bladed turbine wheels were developed and several wheels were successfully produced. The optimum forging strain rate was determined to be 0.25 cm/cm/min (0.1 in./in./min), with a preform forging temperature of 1038°C (1900°F) and final wheel forging temperature of 1093°C (2000°F). The heat treatment selected to achieve an optimum combination of stress-rupture and low cycle fatigue (LCF) properties was a double solution at 1177°C (2150°F) and 1066°C (1950°F) followed by precipitation at 871°C (1600°F) and 982°C (1800°F), and aging at 649°C (1200°F) and 760°C (1400°F). Design data was obtained from wheels heat treated as described above. These data indicated that neither the stress rupture nor the low cycle fatigue properties met the target values of a 100 hr, 955°C (1750°F) stress-rupture strength of 121 MN/m^2 (17.5 ksi), and 5000 LCF cycles to failure at 927°C (1700°F) and a 0.5% strain range. The typical properties were, however, close to the target values (100 MN/m^2, 14.5 ksi and 3200 cycles, respectively) and were considered as good a combination of properties as could be achieved within the limits of the investigation using GATORIZED™ IN 100.

Design data curves and turbine wheel manufacturing flow sheets were prepared and are included in this report along with a description of the capabilities and limitations of the forging process. The estimated cost per finished wheel was about $50 in quantities of 1,000,000 per year.

SECTION I
INTRODUCTION

In 1970, the Environmental Protection Agency (EPA) initiated a research program with United Aircraft Research Laboratories (UARL) to conduct a study of several selected automotive gas turbine engine concepts that appeared to have the best possibility of meeting the U.S. Government's automotive engine exhaust emission standards for 1976. The study[1] included estimating the probable manufacturing cost of several versions of gas turbine engines in quantities of 100,000 and 1,000,000 units annually and comparing the cost of the candidate engines to current piston engines.

The major unknown in estimating the cost of the gas turbine engine was the manufacturing cost of the turbine wheel. It was assumed that, at the 1,000,000 unit annual rate, high-ductility, close-tolerance forging techniques would be used to produce the turbine wheels to nearly finished dimensions from the relatively expensive materials specified. Several proprietary versions of these basic techniques have been developed by United Aircraft for current military aircraft engine programs. The basic United Aircraft-patented process, developed and reduced to practice at the Florida Research and Development Center (FRDC) of Pratt & Whitney Aircraft (P&WA), is referred to as the GATORIZING™ forging process.

This process differs from previous hot isothermal forging methods in that the temperature and forging rate are controlled either to produce a condition of superplasticity in the material being forged, or to maintain a condition of superplasticity in material previously placed in that condition by special processing techniques. This condition is essentially one wherein a material, over a specific temperature and strain rate, flows at a very low stress and exhibits extreme ductility. Exploiting the superplastic state of the material allows forging of complex, contoured shaped wheels to extremely close tolerances, which substantially reduces the input weight of the material required and also reduces machining costs. In addition, smaller, less costly forging equipment than that required for conventional nickel base superalloy or titanium alloy forging can be used.

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[1]United Aircraft Research Laboratories Report K-971017-4, "Manufacturing Cost Study of Selected Gas Turbine Automotive Engine Concepts," dated August 1971.

The forged product produced by the GATORIZING process has two distinct advantages over a cast wheel. The enhanced ductility, toughness and cyclic capability inherent in a wrought product will contribute to the reliability and durability of the small turbine engine wheels. Another advantage of a forging is the greater consistency of part quality and freedom from internal defects.

In November 1972, EPA contracted with Chrysler Corporation for the development of an experimental gas turbine engine which would meet the 1976 Federal Emissions Standards, have good fuel economy, and would be competitive in performance, reliability and potential manufacturing cost with the conventional piston-engine-powered, standard size American automobile (EPA Contract No. 68-01-0459).

In support of the above program, EPA contracted with Pratt & Whitney Aircraft, Florida Research and Development Center, to demonstrate the feasibility of low-cost production of integrally-bladed automotive turbine wheels. This contract is being conducted as a two-phase program. The first phase, described herein, consisted of several major task areas: basic process demonstration, process parameter evaluation, generation of design data, definition of the manufacturing sequence, and a manufacturing cost estimate for IN 100 Chrysler-type compressor-turbine wheels. IN 100 was selected for several reasons: Pratt & Whitney Aircraft has a great amount of past experience forging the alloy; and it had the potential of meeting the Chrysler stress-rupture and low cycle fatigue life targets. Phase II of the contract has recently been initiated. In Phase II, the forging technique will be further refined and a material will be selected and characterized so as to meet the latest EPA/ Chrysler Upgraded Engine Requirements.

SECTION II
PROGRAM ELEMENTS AND DISCUSSION

A. TASK 1 - BASIC PROCESS DEMONSTRATION

Task 1 involved the selection of the processing parameters for the raw material, the initial GATORIZING parameters, and the selection of the baseline heat treatment. These parameters were based on extensive experience with IN100. The raw material was procured, the preform dies were designed and manufactured, and the initial preform was forged and evaluated. Task 1 is shown schematically in figure 1.

1. Raw Material Procurement and Evaluation

IN100 material, vacuum-induction melted and vacuum-arc remelted from virgin metals, was provided by Allvac Metals. The material was supplied from Allvac heat No. E-073, and the chemistries were within the acceptable range. The material was machined and canned in stainless steel for subsequent extrusion. Cameron Iron Works extruded the material at 1066°C (1950°F) through a 205.7 mm (8.1 in.) orifice, resulting in a reduction ratio of 6.8:1. The extruded material was then remachined to a 139.7 mm (5.5 in.) diameter mult, figure 2, and recanned in stainless steel, as shown in figure 3. This mult was re-extruded at RMI at 1066°C through a 62.23 mm (2.45 in.) diameter orifice. The extrusion breakthrough pressure was 805.3 MN/m^2 (58.4 ksi) and the run pressure was 722.6 MN/m^2 (52.4 ksi). The as-extruded material is shown in figure 4. The material structure, as-extruded, was 95 to 98% recrystallized fine grains, ASTM 11.5 to 16, with some isolated unrecrystallized areas. Representative photomicrographs are shown in figure 5. Standard tensile specimens were machined, and superplasticity tests were run. The test results, shown in table I, verified that the material was in a superplastic condition.

2. Preform Die Design and Fabrication

The dies used for the program were manufactured from TZM molybdenum. This material was selected because of its excellent thermal conductivity, elevated temperature strength, and wear resistance. It is very important that temperature uniformity be achieved from the center to the edge of the die stack in the GATORIZING process; experience has shown that temperature gradients are minimal in the radial direction in TZM molybdenum die stacks up to 76.2 cm (30.0 in.) in diameter.

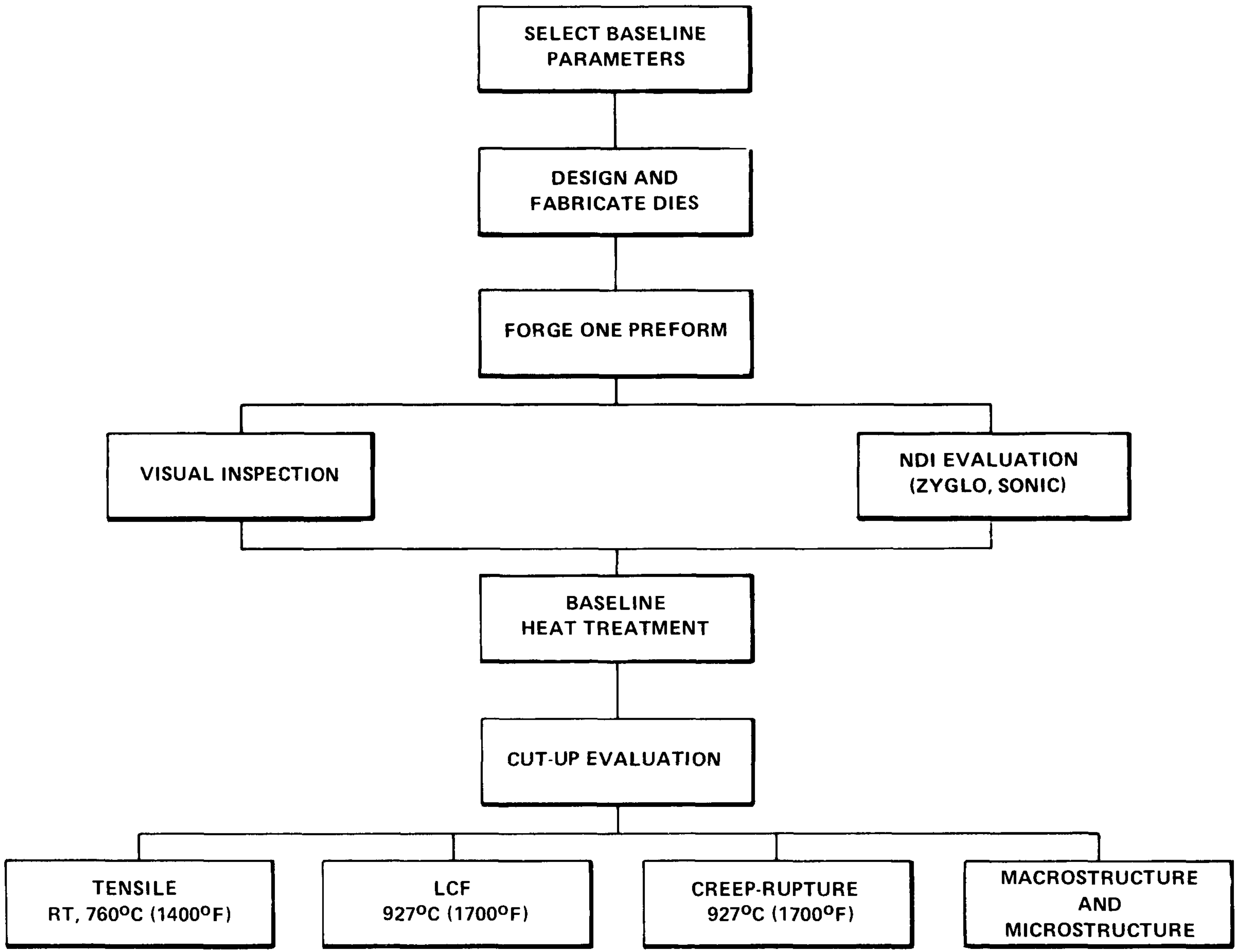


Figure 1. Phase I - Feasibility Demonstration and Cost Analysis; Task 1 - Basic Process Demonstration FD 72646A

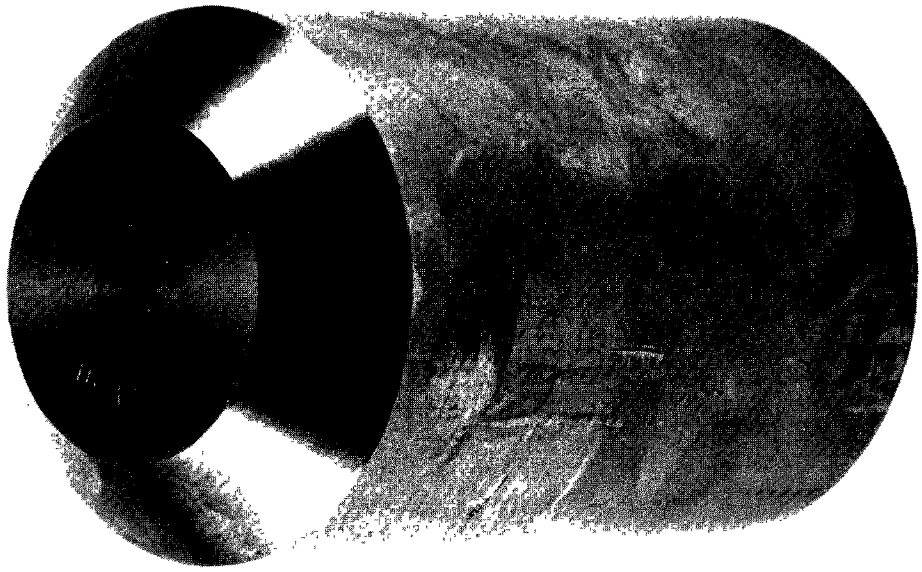


Figure 2. IN 100 Mult Ready for Canning Prior to Second Extrusion FC 29014

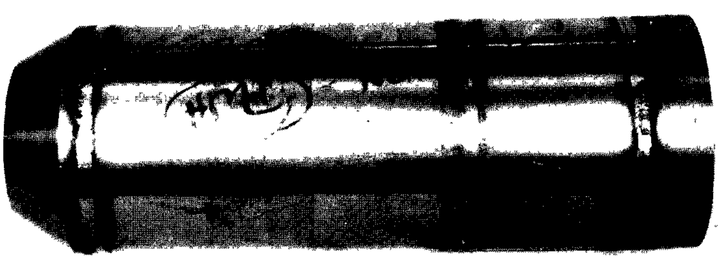
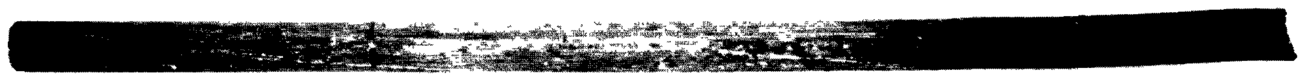


Figure 3. IN 100 Canned Extrusion Billet, 152.4 MM (6 In.) Diameter by 438.2 MM (17 1/4 In.) Long FAL 28671

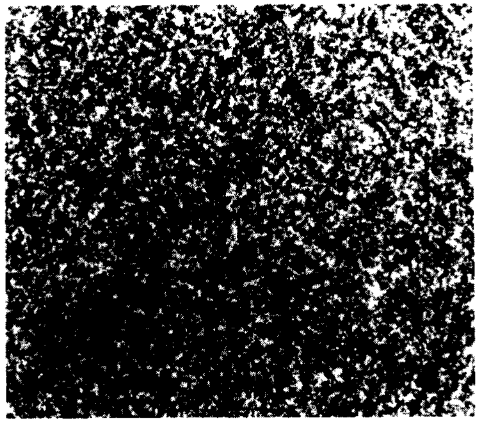


FE 131243

FE 130763

Figure 4. IN100 Extrusion - 62.23 mm (2.45 in.) Cut in Two Pieces for Shipping

FD 74444

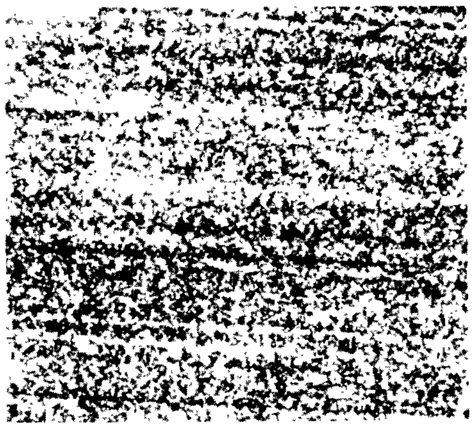


FAM 81111

EDGE TRANSVERSE

FAM 81110

CENTER TRANSVERSE



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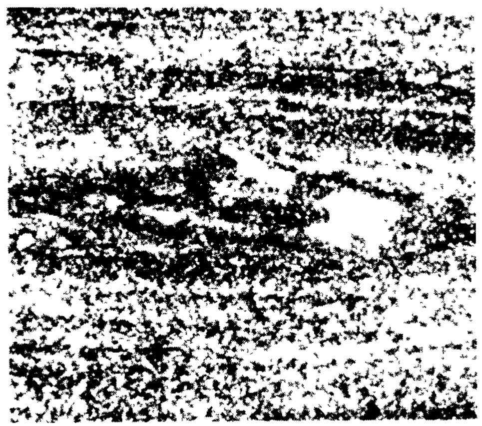


FAM 81109

CENTER LONGITUDINAL

Figure 5. Typical Microstructure of Double-Extruded IN100 Billet Stock FD 74445

Table I. IN100 Double Extruded Superplasticity Test Results

Specification No.	Temperature	Flow Stress, $N/m^2 \times 10^6$	psi	Elongation, %	Reduction of Area, %
1	1079°C (1975°F)	67.7	9820	445	99.7
2	1079°C (1975°F)	58.7	8510	295	99.7

Most of P&WA's experience with the GATORIZING forging process has been with this die material. Conventional machining and electrical discharge machining (EDM) techniques have been well established. The design of the dies to forge the preform and bladed wheel was based on our experience with die and insert designs, lubricants, and metal flow characteristics.

A two-step forging sequence was selected to GATORIZE the wheels. The first step produced a nonbladed oversized preform, which had a two-fold purpose: (1) to ensure proper metal distribution for forging the bladed wheel; and (2) to further enhance the forgeability of the material. The second forging step was for the purpose of reducing the disk area to final dimensions and filling the blade die insert cavities.

The preform configuration (figure 6) and preform dies were designed and the tooling fabricated. A cross-sectional view of the preform tooling is shown in figure 7 and photographs of the actual tooling are shown in figure 8.

3. Preform Forging and Evaluation

One forging mult, 44.45 mm (1.75 in.) in diameter by 85.85 mm (3.38 in.), was machined from the extruded stock. The baseline forging and heat treatment parameters had been established by prior experience with wrought IN 100. The mult was coated with a boron nitride lubricant and GATORIZED at 1038°C (1900°F) to the preform configuration. The forging completely filled the tooling with a 50% reduction flow stress of 23.4 N/m^2 (3400 psi) and exhibited an excellent surface finish. The strain rate averaged 0.25 cm/cm/min (0.10 in./in./min).

The preform was subsequently dimensionally checked, visually and die penetrant inspected for laps and other surface defects, and inspected for internal defects by X-ray and ultrasonic inspection techniques. The preform was within allowable dimensional tolerances and had no surface or internal defects. The as-forged preform exhibited a uniform, fully recrystallized fine grained structure (ASTM 14.5 to 16.5). The forging mult, forged preform, and representative microstructure are shown in figure 9.

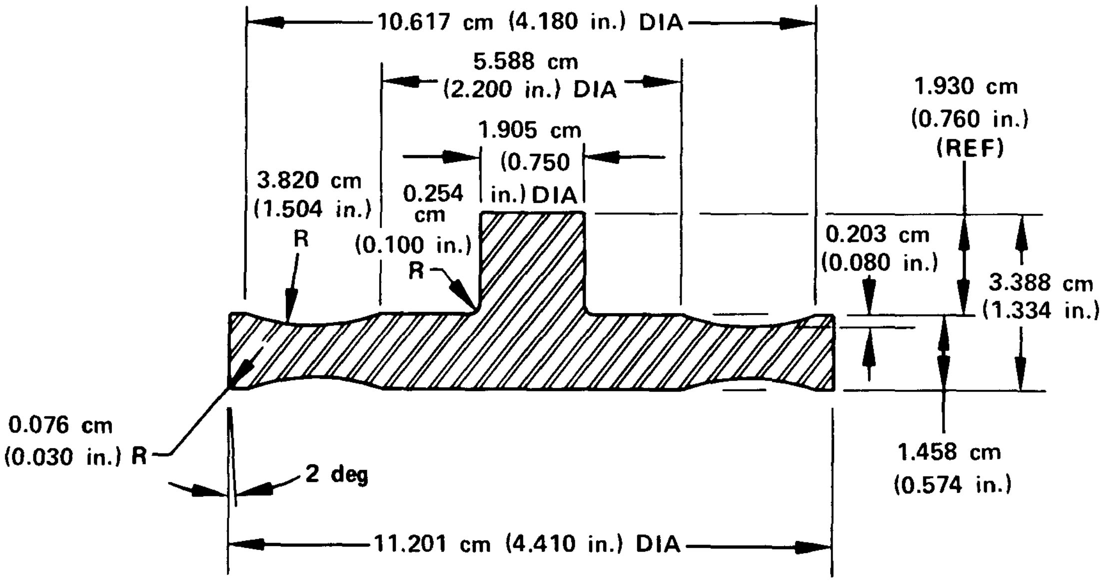


Figure 6. Cross Section of Phase I Disk Preform FD 71221A

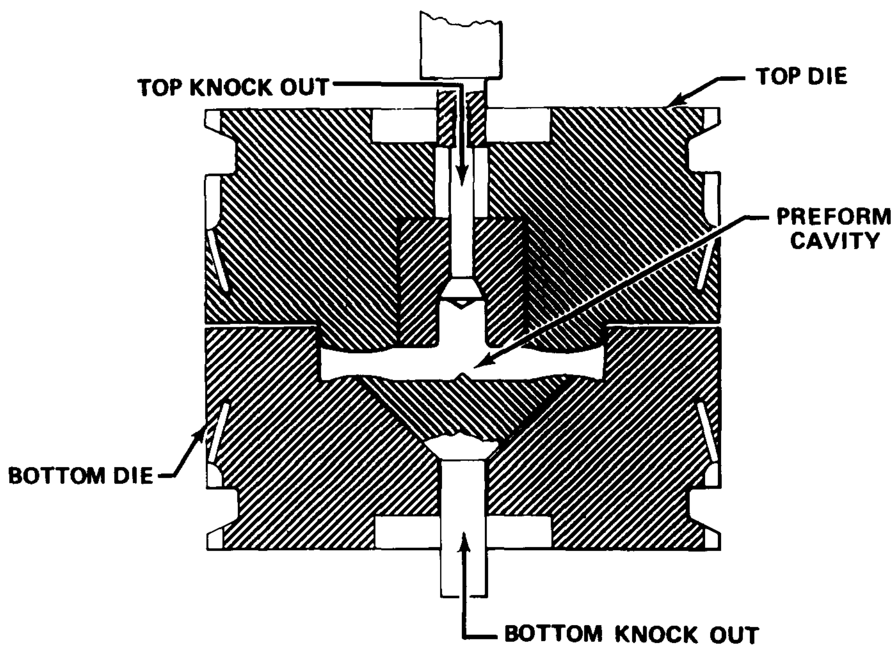


Figure 7. Tooling for Phase I - Task 1 Preform FD 72643

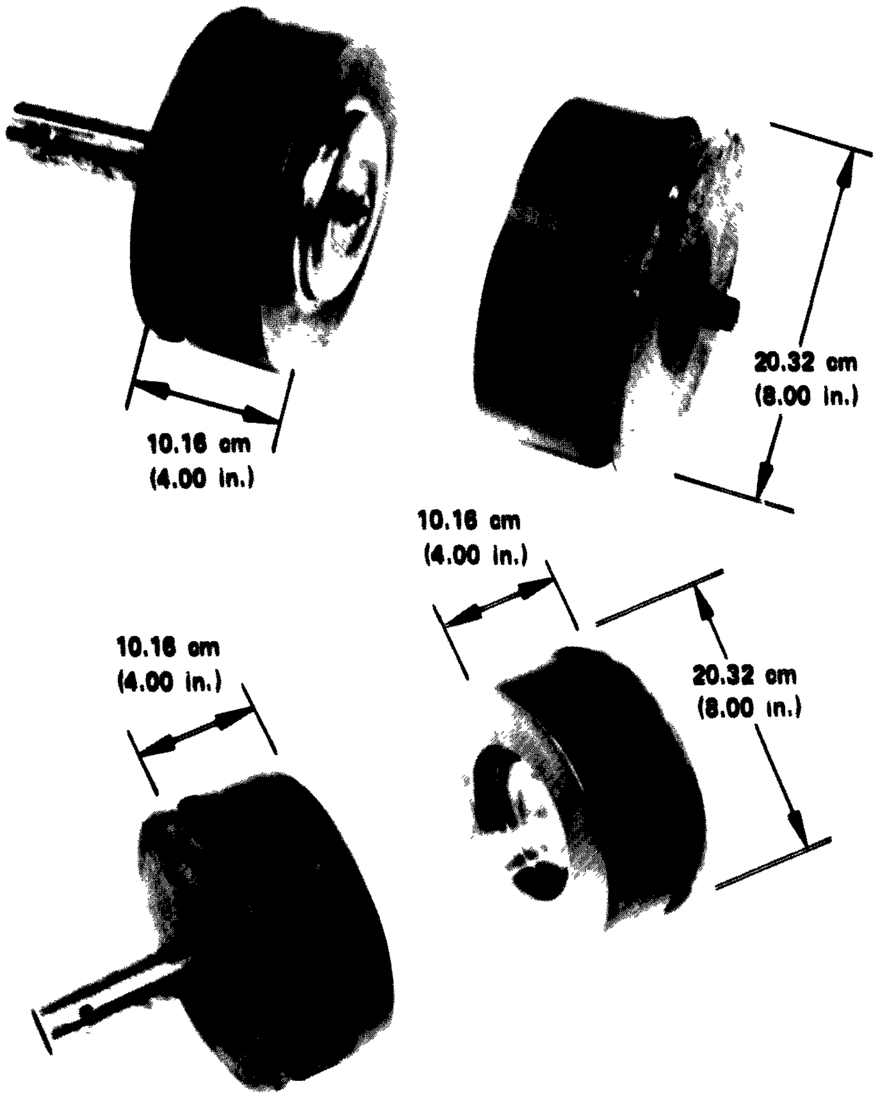
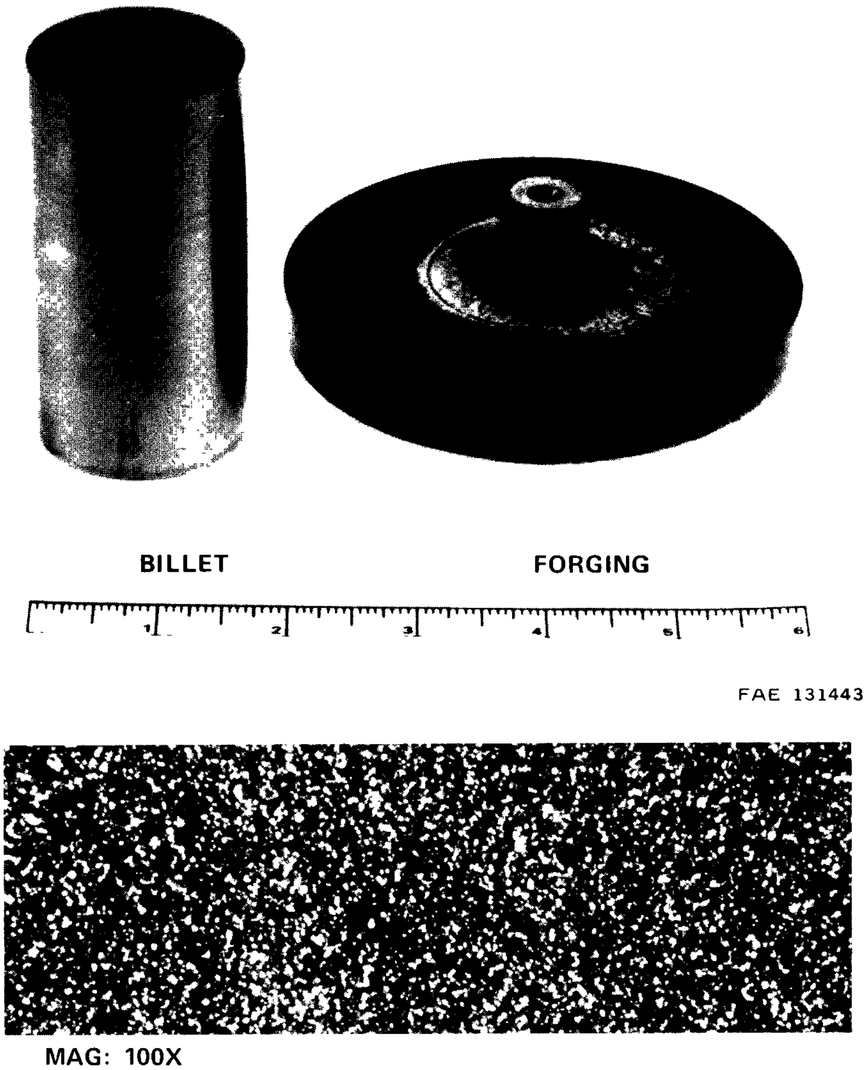


Figure 8. Finish Machined Preform Tooling

FE 130772A
FE 130773A
FD 75605A



TYPICAL MICROSTRUCTURE

Figure 9. Task I Wheel Preform FD 75604A

The selected baseline heat treatment was one which would give the high strength and LCF life typically required in a turbine disk alloy. At the time, it was anticipated that it might be necessary to preferentially heat treat the blades to establish the elevated temperature stress rupture capability. The baseline heat treatment was as follows:

Solution:	1121°C (2050°F)/2 hr/OQ (oil quench)
Precipitation:	871°C (1600°F)/40 min/AC (air cool)
	982°C (1800°F)/45 min/AC
Age:	649°C (1200°F)/24 hr/AC
	760°C (1400°F)/4 hr/AC

The preform was heat treated to the baseline heat treatment and test specimens were subsequently machined from the preform according to the diagram of figure 10. This cut-up procedure was essentially the same for all subsequent preform and bladed wheel evaluations.

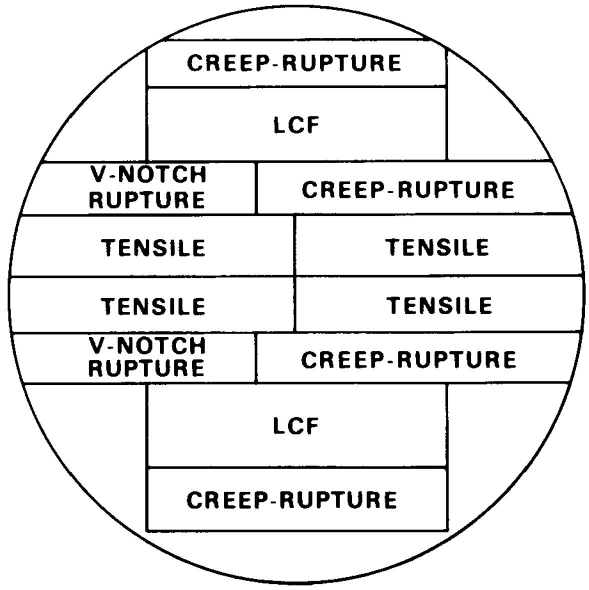


Figure 10. Diagram for Test Specimens Machined from Preform and Wheel FD 79231A

Task 1 mechanical property tests conducted included room temperature and 760°C (1400°F) tensile tests; 927°C (1700°F) creep rupture tests at 103.4 MN/m^2 (15 ksi); 68.9 MN/m^2 (10 ksi), and 34.5 MN/m^2 (5 ksi); 871°C (1600°F) creep rupture tests at 68.9 MN/m^2 (10 ksi); notch rupture tests at 927°C and 103.4 MN/m^2; and 927°C LCF tests at 1.0% and 2.0% total strain range. Time to 1% creep and time to rupture were recorded on the creep rupture tests. The results of the tests are tabulated in table II.

The heat treated preform exhibited a uniform fine grain microstructure with an ASTM grain size predominantly 10.5 to 13.5 with occasional 9.5. Electron microscopic review showed the structure to be typical of that afforded by the baseline heat treatment. Representative photomicrographs at 100X and 1000X are shown in figure 11. The question of preferential heat treatment of the blades was resolved in Task 2.

Table II. Results of Task 1 Evaluations

Heat Treatment: Baseline
Preform S/N: 2-4
Forge Temperature: 1038°C (1900°F)

TENSILE

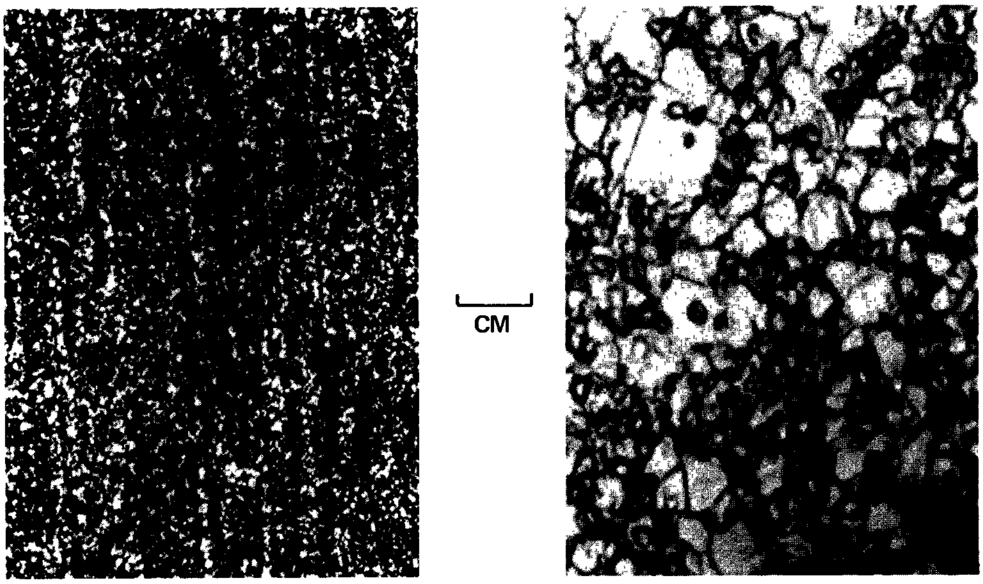
Test Temperature, °C	°F	0.2% Yield MN/m²	ksi	Ultimate MN/m²	ksi	Elongation, %	Red. of Area, %
RT	RT	1132.9	164.2	1421.3	206.0	11.3	11.1
760	1400	1059.1	153.5	1135.0	164.5	12.0	16.4
760	1400	1063.2	154.1	1139.1	165.1	11.3	10.4

CREEP RUPTURE

Test Temperature, °C	°F	Stress Level MN/m²	ksi	Rupture Life, hr	Elongation, %	Red. of Area, %	Time to 1.0% Creep, hr	V/N Rupture, hr
927	1700	103.4	15	1.6	100.8	70.0	0.1	--
927	1700	103.4	15	1.8	101.0	68.2	0.1	--
927	1700	68.9	10	4.8	133.0	84.7	0.2	--
927	1700	34.5	5	14.6	108.8	92.0	1.0	--
871	1600	68.9	10	35.7	68.0	83.6	2.2	--
927	1700	103.4	15	--	--	--	--	3.1
927	1700	103.4	15	--	--	--	--	3.9

STRAIN CONTROL LCF

Test Temperature, °C	°F	Total Strain, %	Mean Strain, %	Total Cycles	Remarks
927	1700	2.0	1.0	28	Failed
927	1700	1.0	0.5	335	Failed



MAG: 100X   MAG: 1000X

Figure 11. Task 1 Preform Microstructure Baseline Heat Treat   FD 84120

B. TASK 2 - PROCESS PARAMETER EVALUATION

Task 2 was designed to evaluate critical processing parameters, forging temperatures, forging strain rate, and heat treatment. Task 2 is shown schematically in figure 12. One of two preforms initially forged was used for gradient bars and heat treat samples to evaluate the microstructural response to thermal treatment. The second preform was heat treated to baseline parameters and evaluated in an identical fashion as the Task 1 part to further establish baseline properties. Subsequently six additional parts were forged to assess the effect of forging temperatures, strain rates, and heat treat variables on the final part. Only one parameter was varied at a time, the others being baseline. The forging temperature, forging strain rate, and heat treatment which yielded the best part consistent with mass production economics was applied to the Task 3 design data generation.

1. Preform Forging

The eight forging multiples were machined from the extruded stock and boron nitride coated. Four of these mults were forged into the preform configuration per Task 1 baseline parameters (i.e., 1038°C, 1900°F and 0.25 cm/cm/min, 0.10 in./in./min). Three mults were forged at alternate forging temperatures of 1010 °C (1850 °F), 1066 °C (1950 °F), and 1093 °C (2000 °F). One mult was forged at 1038 °C (1900 °F) at an accelerated strain rate of 0.38 cm/cm/min (0.15 in./in./min).

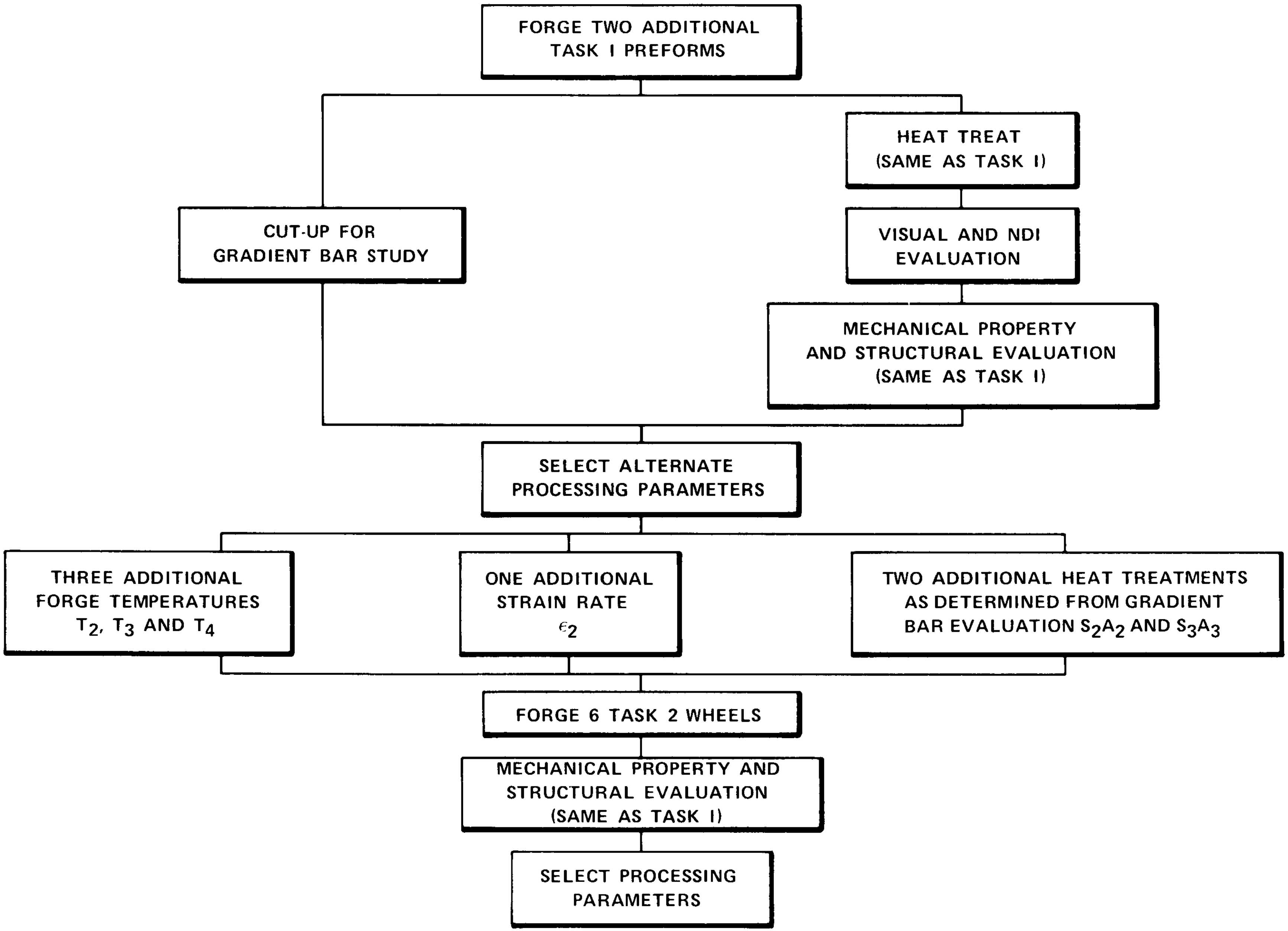


Figure 12. Phase I - Feasibility Demonstration and Cost Analysis; Task 2 - Process Parameter Evaluation FD 72647A

All eight were visually inspected, dimensionally checked, and found to be satisfactory. These preforms were used in the Task 2 evaluations as summarized in table III.

2. Additional Baseline Property Evaluation

Two of the four preforms forged at the baseline parameters (S/N 2-10 and 2-11) and the preform forged at the alternate strain rate (S/N 2-9) were held for subsequent reforging into the bladed wheel configuration. The third baseline preform (S/N 2-5) was given the baseline heat treatment, inspected by nondestructive inspection techniques, and evaluated using the same procedure as the Task 1 preform. The results are tabulated in table IV, and are equivalent to the Task 1 baseline properties.

3. Structural Response to Heat Treatment

Gradient bars were cut from the fourth baseline preform (S/N 2-6) to establish the structural response to heat treatment. These slices were held at various solution temperatures up to 1232°C (2250°F). Significant grain growth occurred at temperatures above 1149°C (2100°F). Typical microstructures from this study are shown in figure 13. The gradient bar study showed as expected that a notable variation in grain size was achievable in the material by varying the solution heat treatment temperature. The heat treatments for the Task 2 alternate heat treatment study and the Task 3 blade heat treatments were selected based on the results of this study.

4. Effect of Varying Forging Temperature

The final form dies were not yet completed, so it was decided to evaluate the effects of forge temperature on the preforms, rather than delay the program. Therefore, the three preforms forged at the alternate forge temperatures (S/N 2-3, 2-8, and 2-7) were heat treated to the baseline heat treat and evaluated per the Task 1 procedures. The data from the evaluations are tabulated in table V.

Table III. Summary of Task 2 Evaluations

S/N	Forge Temperature, Preform °C	Preform (°F)	Wheel °C	Wheel (°F)	Heat Treatment	Program Use	ASTM Grain Size Predominate	ASTM Grain Size Occasional
2-5	1038	1900	-	-	Baseline:	Baseline Data	10.5 - 13.5	9.5
2-3	1010	1850	-	-	1121°C (2050°F) Solution, Oil Quench	Forge Temperature Study	10.5 - 13.5	10.0
2-8	1066	1950	-	-	871°C (1600°F) Air Cool 982°C (1800°F) Air Cool	Forge Temperature Study	11.5 - 13.5	
2-7	1093	2000	-	-	649°C (1200°F) Air Cool 760°C (1400°F) Air Cool	Forge Temperature Study	9.5 - 12.5	13.5
2-6	1038	1900	-	-	Various	Gradient Bar Study		
2-9	1038	1900	1093	2000	Baseline	Alternate Strain Rate Study	11.5 - 13.5	
2-10	1038	1900	1093	2000	1177°C (2150°F) Solution, Air Cool + 1121°C (2050°F) Solution, Air Cool + Baseline Precipitation and Age	Alternate Heat Treat Study	3.0 - 4.0	7.0-10.0
2-11	1038	1900	1093	2000	1177°C (2150°F) Solution, Air Cool + 1066°C (1950°F) Solution, Air Cool + Baseline Precipitation and Age	Alternate Heat Treat Study	4.0 - 6.0	7.0 - 8.0

Table IV. Results of Task 2 Baseline Evaluation

Heat Treatment:	Baseline
Preform S/N:	2-5
Forge Temperature:	1038°C (1900°F)

TENSILE

Test Temperature,		0.2% Yield		Ultimate		Elongation,	Red. of Area,
°C	°F	M_N/m^2	ksi	M_N/m^2	ksi	%	%
RT	RT	1139.0	165.2	1475.5	214.0	12.0	15.9
760	1400	1019.1	147.8	1096.3	159.0	13.3	16.4
760	1400	1053.5	152.8	1109.4	160.9	13.3	17.9

CREEP RUPTURE

Test Temperature,		Stress Level		Rupture Life,	Elongation,	Red. of Area,	Time to 1.0%	V/N Rupture,
°C	°F	M_N/m^2	ksi	hr	%	%	Creep, hr	hr
871	1700	103.4	15	1.0	62.6	78.4	0.1	-
871	1700	103.4	15	1.0	151.0	83.9	0.1	-
871	1700	68.9	10	2.6	96.0	84.6	0.2	-
871	1700	34.5	5	12.1	153.0	92.5	0.7	-
871	1700	103.4	15	-	-	-	-	3.2
871	1700	103.4	15	-	-	-	-	3.2

STRAIN CONTROL LCF

Test Temperature,		Total Strain,	Mean Strain	Total Cycles	Remarks
°C	°F	%	%		
927	1700	2.0	1.0	48	Failed
927	1700	1.0	0.5	261	Failed

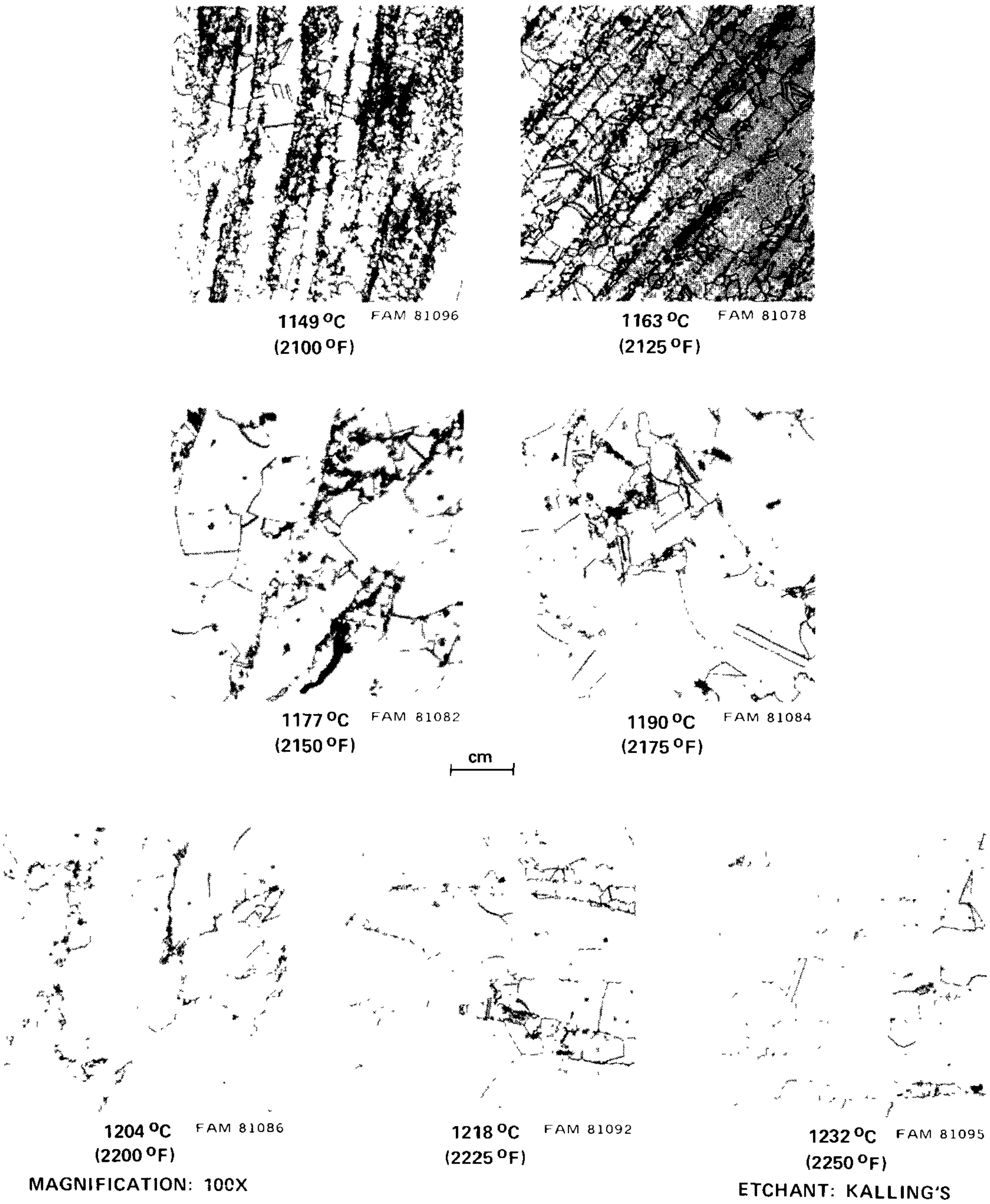


Figure 13. Blade Gradient Study FD 74447

Table V. Results of Task 2 Alternate Forge Temperature Evaluation

Heat Treatment:	Baseline
Preform S/N:	2-3, 2-7, 2-8
Forge Temperature:	1010°C (1850°F)
	1093°C (2000°F)
	1066°C (1950°F)

TENSILE

Test Temperature, °C	°F	S/N	0.2% Yield M_N/m^2	ksi	Ultimate M_N/m^2	ksi	Elongation %	Red. of Area, %
RT	RT	2-3	1159.1	168.0	1331.6	193.0	9.3	12.1
RT	RT	2-7	1106.7	160.4	1486.8	215.5	12.7	15.9
RT	RT	2-8	1116.3	161.9	1572.0	228.0	24.6	28.0
RT	RT	2-8	1108.7	160.8	1509.9	219.0	14.7	16.9
760	1400	2-3	1070.8	155.2	1121.9	162.6	12.0	14.5
760	1400	2-3	1054.9	152.9	1115.0	161.6	13.3	18.3
760	1400	2-7	1057.0	153.2	1131.5	164.0	3.3	4.3
760	1400	2-7	1067.4	154.7	1155.7	167.5	10.0	9.5
760	1400	2-8	1062.5	154.1	1130.0	163.9	14.7	17.2
760	1400	2-8	1034.2	150.0	1111.4	161.2	13.3	12.4

Table V. Results of Task 2 Alternate Forge Temperature Evaluation (Continued)

CREEP RUPTURE

Test Temperature, °C	°F	S/N	Stress Level M_N/m^2	ksi	Rupture Life, hr	Elongation, %	Red. of Area %	Time to 1.0% Creep, hr	V/N Rupture, hr
871	1600	2-3	68.9	10	25.2	159.0	87.8	1.3	-
871	1600	2-7	68.9	10	64.7	88.7	81.2	5.8	-
927	1700	2-3	103.4	15	0.6	142.0	68.2	<0.1	-
927	1700	2-3	103.4	15	1.3	115.0	70.3	<0.1	-
927	1700	2-7	103.4	15	3.0	41.9	62.0	0.2	-
927	1700	2-7	103.4	15	3.5	104.8	68.0	<0.1	-
927	1700	2-3	103.4	15	-	-	-	-	2.6
927	1700	2-3	103.4	15	-	-	-	-	2.2
927	1700	2-7	103.4	15	-	-	-	-	6.9
927	1700	2-7	103.4	15	-	-	-	-	5.7
927	1700	2-3	68.9	10	2.6	83.0	86.0	0.1	-
927	1700	2-7	68.9	10	5.2	90.1	82.0	0.3	-
927	1700	2-3	34.5	5	12.5	192.5	92.8	0.5	-
927	1700	2-7	34.5	5	27.3	232.9	91.5	1.6	-
927	1700	2-8	103.4	15	1.6	57.9	68.4	0.15	-
927	1700	2-8	103.4	15	2.1	69.4	72.8	0.18	-
927	1700	2-8	103.4	15	-	-	-	-	4.9
927	1700	2-8	103.4	15	-	-	-	-	4.0
927	1700	2-8	68.9	10	4.9	100.2	85.6	<0.3	-
927	1700	2-8	68.9	10	4.6	100.3	84.8	0.2	-
927	1700	2-8	34.5	5	15.7	139.0	89.5	0.8	-
927	1700	2-8	34.5	5	23.9	269.0	91.6	1.6	-

STRAIN CONTROL LCF

Test Temperature, °C	°F	S/N	Total Strain, %	Mean Strain, %	Total Cycles	Remarks
927	1700	2-7	2.0	1.0	21	Failed
927	1700	2-7	2.0	1.0	13	Failed

The forging temperature study showed that mechanical properties did not vary significantly with forging temperatures over the 1038°C (1900°F) to 1093°C (2000°F) range investigated. Room temperature tensile properties are shown in figure 14. There appeared to be a degradation in room temperature ultimate tensile strength with the 1010°C (1850°F) forging temperature. The reasons for the variation in tensile ductility have not been explained at this time. Elevated temperature ultimate and yield strength were insensitive to forging temperature over the entire range investigated as shown in figure 15. Again a degree of inconsistency in ductility was noted. The low cycle fatigue (LCF) test specimens from the preforms forged at 1010°C and 1098°C (S/N 2-3 and 2-8) were incorrectly machined and could not be tested. The LCF life of the preform forged at 1093°C (2000°F) was similar to the LCF properties of the baseline forgings. However, all of these initial tests were conducted at an excessively high, and unrealistic strain range. Subsequent LCF testing was done at a lower and more appropriate strain level of 0.5%. This lower strain range was selected based on the results of an analytical analysis of the wheel using stresses and temperature gradients supplied by the Baseline Engine Contractor.

5. Bladed Wheel Die Design and Manufacture

The final integrally bladed wheel tooling was designed per Chrysler drawing No. 2443630, with the exception of the pockets located in both sides of the disk rim. The pockets were excluded for the Phase I feasibility demonstration for two reasons: (1) it was felt that the primary goal of this initial program was to demonstrate the feasibility of economically GATORIZING an integrally bladed wheel of the type used in automotive gas turbines, and (2) it is highly probable that the final wheel design can be modified to exclude pockets, because of the improved structural uniformity and higher levels of mechanical properties, especially LCF, associated with the wrought product.

A cross section of the tooling for the final bladed wheel design is shown in figure 16. The cavities for the 53 blades are formed by simple split inserts. This concept is shown by the 5X model in figure 17. The finished machined tooling is shown in figure 18.

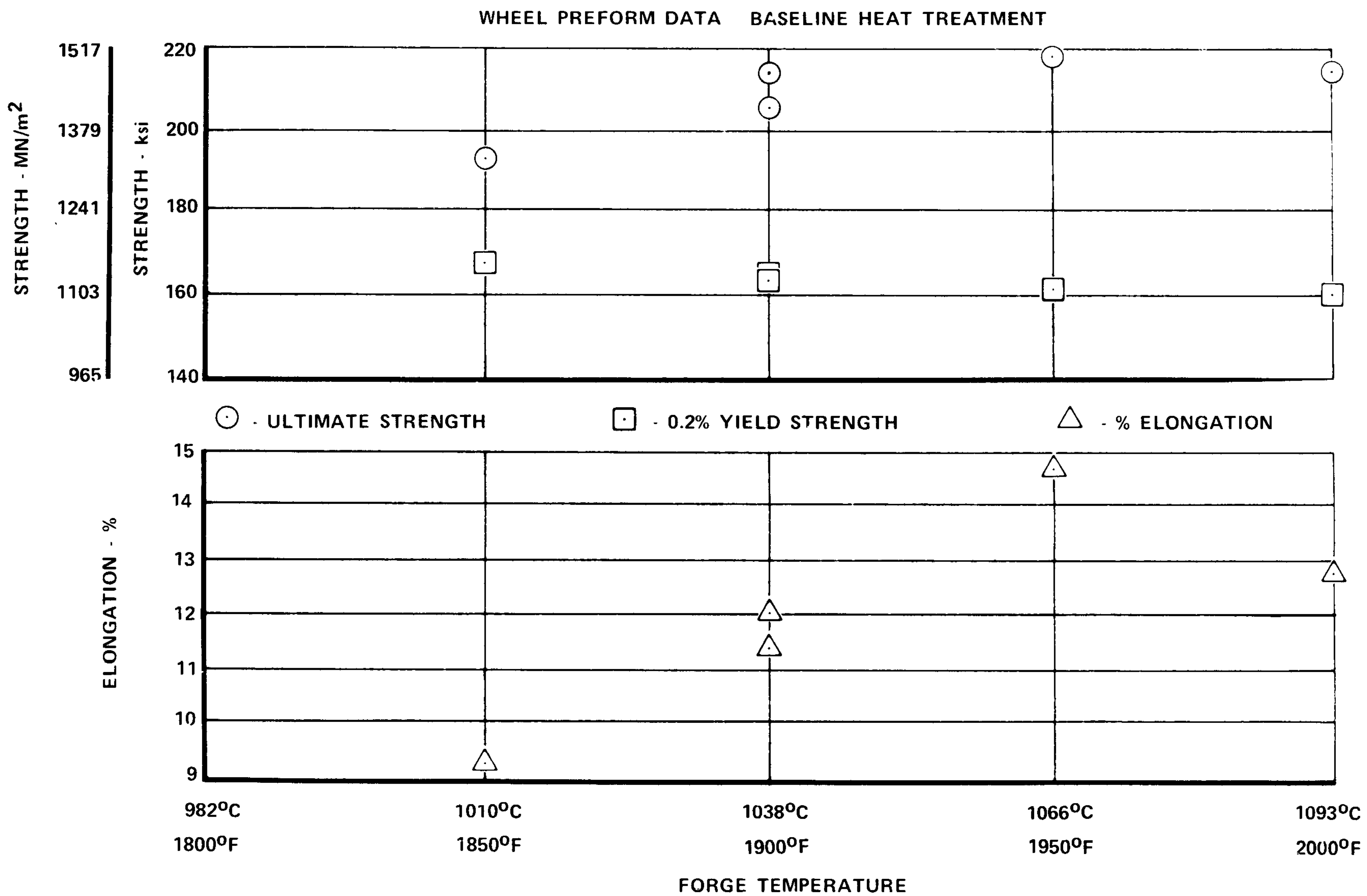


Figure 14. Room Temperature Tensile Properties vs Forging Temperature FD 79235A

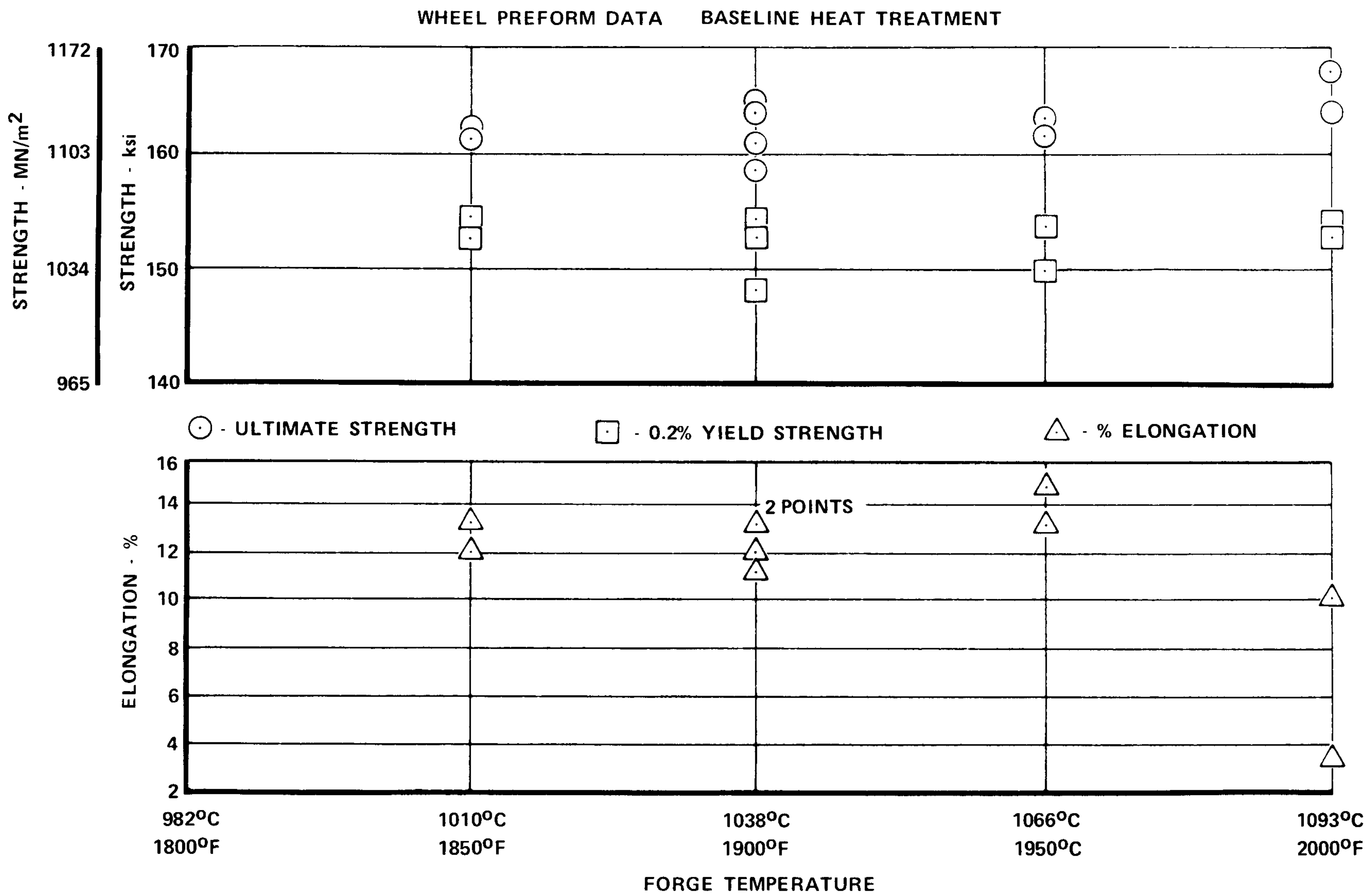


Figure 15. 760°C (1400°F) Tensile Properties vs Forging Temperature

FD 79234A

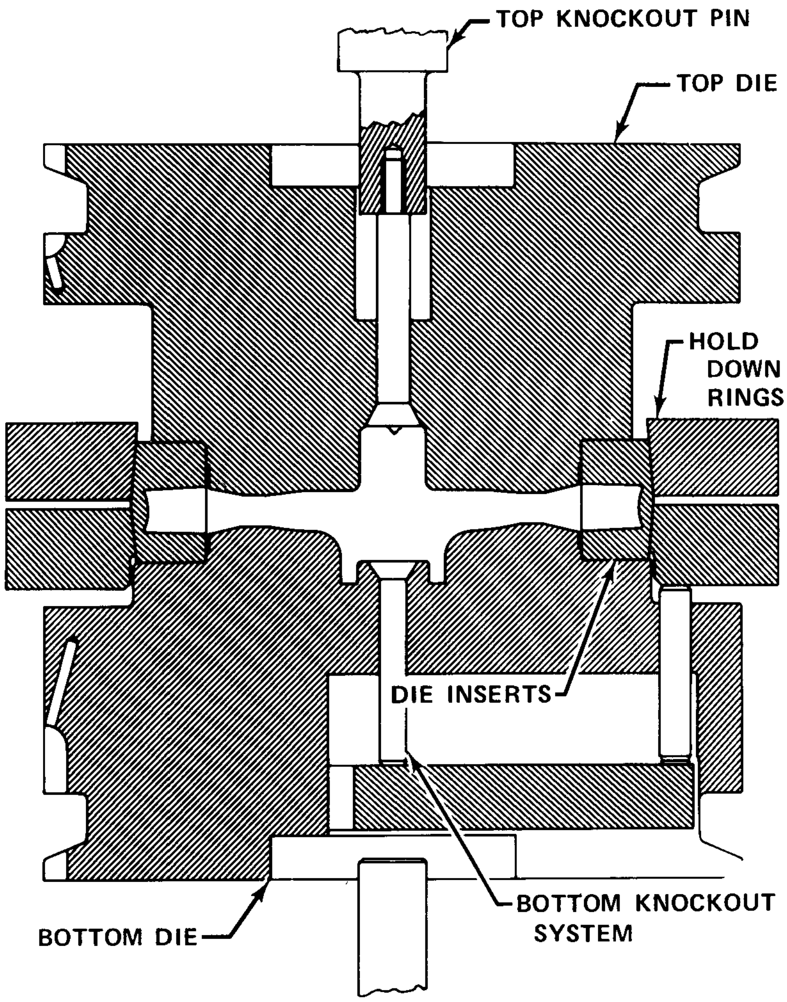


Figure 16. Tooling for Phase I - Task II Bladed Wheel FD 74448B

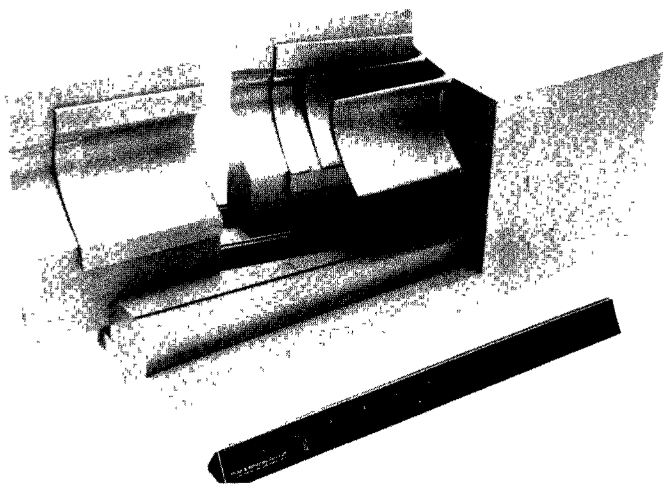


Figure 17. Blade Insert Concept Used for Finish Die Design FE 129863A

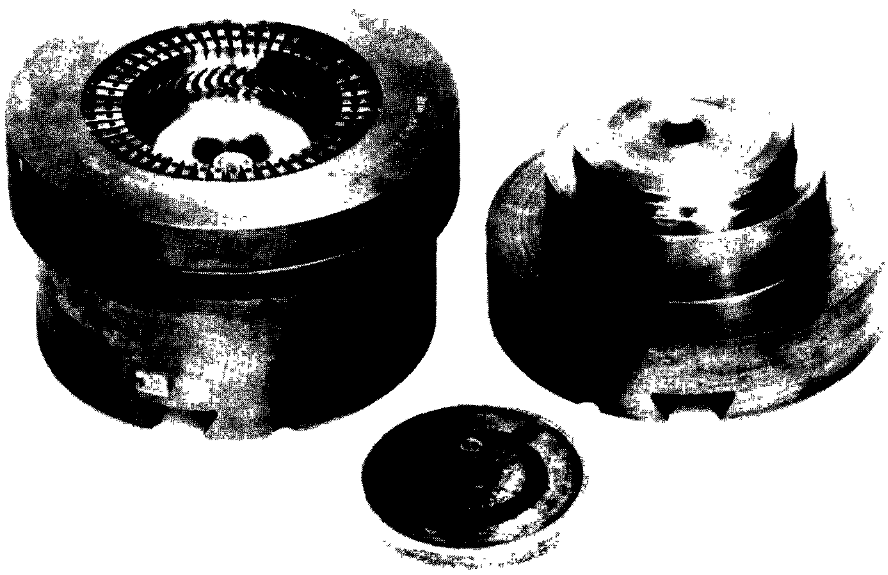


Figure 18. Finish Machined Bladed Wheel Tooling Preform FC 29992 FD 79228A

6. Wheel Forging

The remaining three Task 2 preforms were machined to clean up the outside diameter and assure concentricity in the final form die. The preforms were coated with the boron nitride lubricant. Because the Task 2 forging temperature study indicated that forging temperature had no significant effect on mechanical properties, a forging temperature of 1093°C (2000°F) was selected to assure optimum forgeability. The baseline strain rate was used for the initial trials. The first bladed wheel forging trial (S/N 2-10) resulted in the partially bladed wheel shown in figure 19. The lack of blade fill was attributed to the degree of taper in the airfoil thickness (root to tip). The blade cavities were opened up 0.25 mm to 0.51 mm (0.01 to 0.02 in.) to minimize the frictional forces. In addition, there were problems removing the inserts at room temperature due to the large difference in coefficient of thermal expansion between IN 100 and the TZM molybdenum dies. Because tooling was not available (required tooling will be available in Phase II) to remove the inserts while at the forging temperature a portion of the twist was taken out of the airfoil to facilitate insert removal at room temperature. The resulting modified blade cross sections are shown in figure 20. The first forging attempt with the modified blade inserts (S/N 2-14) resulted in a fully bladed wheel as shown in figure 21. The S/N 2-11 preform was then also successfully forged.

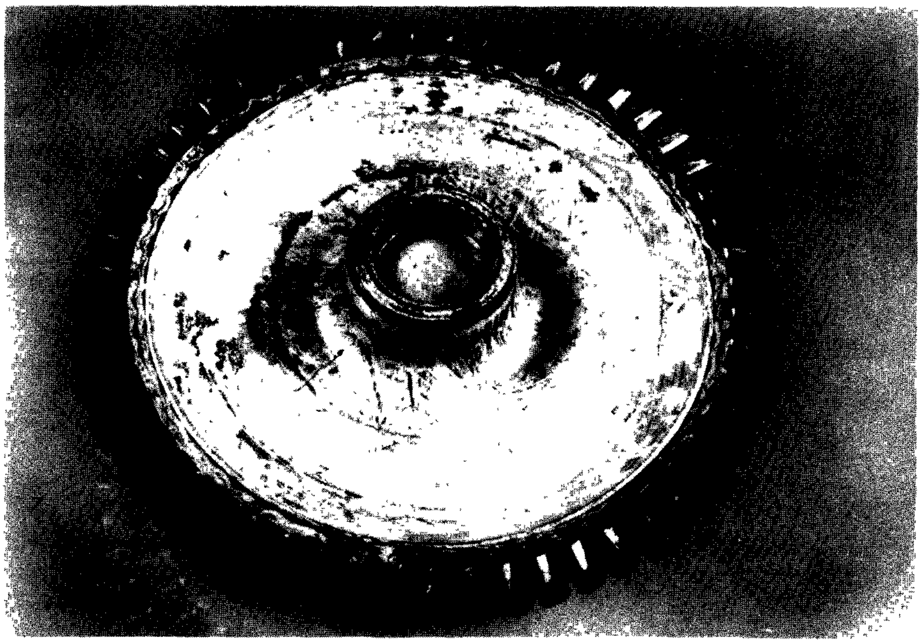


Figure 19. Initial Bladed Wheel Forging FE 137261
FD 79237A

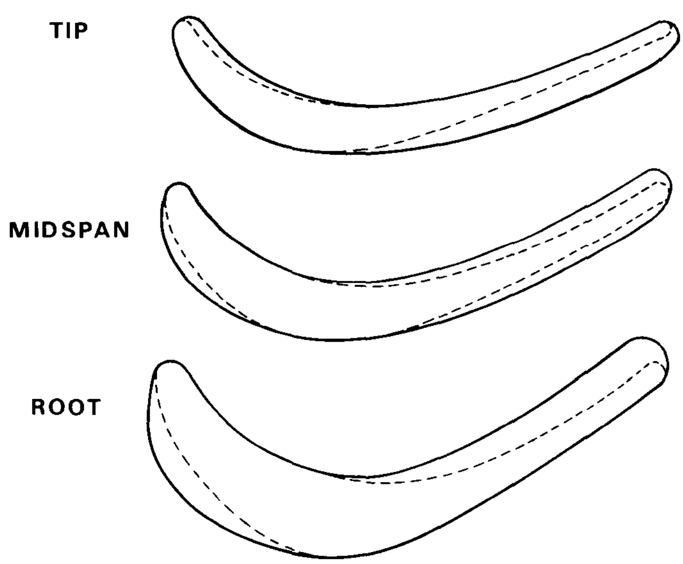


Figure 20. Modified Blade Cross-Section FD 79246

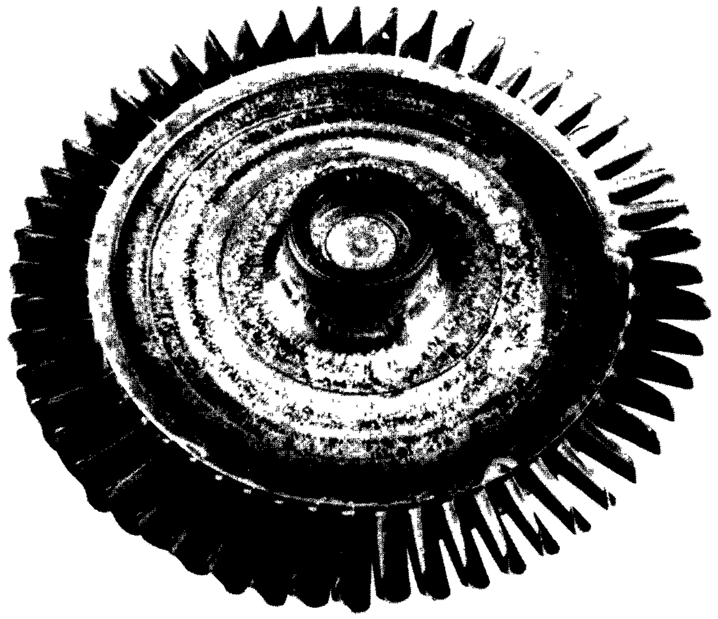


Figure 21. Fully Bladed Wheel Forging KFE 135874
FD 79238A

The bladed wheel forging trials established initial relationships between blade shape and forgeability. The successful forging of the blades after slight enlargement of the die insert cavities was attributed to the reduction of die surface friction relative to the flow stress over the increased cross-sectional area. It is expected that further refinement of the blade shape can be made to further characterize blade shape and forgeability relationships.

7. Effect of Varying Forging Strain Rate

The S/N 2-9 wheel was successfully forged at the accelerated strain rate from the preform forged at the same accelerated strain rate. This wheel was given the baseline heat treatment, cut up and evaluated per Task 1 parameters. The mechanical property test results are given in table VI. The properties were typical of the baseline forgings. The grain size was ASTM 11.5 to ASTM 13.5 which was also typical of the baseline forgings. Thus it was determined that varying the forging strain rate over the range studied, 0.25 to 0.38 cm/cm/min (0.10 to 0.15 in./in./min), did not adversely affect mechanical properties or structure. The baseline strain rate did provide slightly better forgeability and was therefore specified for the mass production processing parameters.

Table VI. Results of Task 2 Alternate Strain Rate Evaluation

Heat Treatment:	Baseline
Wheel S/N:	2-9
Forge Temperature:	1038°C/1093°C (1900°F/2000°F)

TENSILE

Test Temperature, °C	°F	0.2% Yield M_N/m^2	ksi	Ultimate M_N/m^2	ksi	Elongation, %	Red. of Area %
RT	RT	1090.8	158.2	1389.3	201.5	11.3	12.4
760	1400	1038.4	150.6	1103.8	160.1	4.0	8.4
760	1400	999.1	144.9	1069.4	155.1	7.3	11.4

CREEP RUPTURE

Test Temperature, °C	°F	Stress Level M_N/m^2	ksi	Rupture Life, hr	Elongation, %	Red. of Area %	1.0% Creep hr	V/N Rupture, hr
927	1700	103.4	15	1.5	89.5	68.8	0.1	-
927	1700	103.4	15	1.4	66.2	57.0	0.1	-
927	1700	103.4	15	-	-	-	-	4.4
927	1700	103.4	15	-	-	-	-	4.5

STRAIN CONTROL LCF

Test Temperature, °C	°F	Total Strain, %	Mean Strain, %	Total Cycles	Remarks
927	1700	0.5	0.25	3168	Failed
927	1700	0.5	0.25	2884	Failed

8. Mechanical Property Response to Alternate Heat Treatments

The Task 2 alternate heat treatment study was aimed at establishing a single wheel heat treatment which would achieve a compromise structure combining the high tensile strengths typical of fine grain structure with the good rupture life of large grained material, while maintaining an adequate LCF life. Two heat treatments were determined from the gradient studies with this aim in mind. The two remaining wheel forgings (S/N 2-10 and 2-11) were each given one of these two heat treatments:

Solution: (1) 1177°C (2150°F)/2 hr/AC + 1121°C (2050°F)/2 hr/AC

(2) 1177°C (2150°F)/2 hr/AC + 1066°C (1950°F)/2 hr/AC

Both heat treatments included the following precipitation and age cycles:

871°C (1600°F)/40 min + 982°C (1800°F)/45 min +
649°C (1200°F)/24 hr + 760°C (1400°F)/4 hr

All cycles were air cooled.

These Task 2 wheels were cut up and evaluated. The grain size of the wheel given the 1177°C (2150°F)/1121°C (2050°F) double solution (S/N 2-10) was predominantly ASTM 3-4, with occasional ASTM 7-10. The S/N 2-11 wheel which was solutioned at 1177°C (2150°F)/1066°C (1950°F) had a slightly smaller grain size of predominantly ASTM 4-6, with occasional ASTM 7-8. The mechanical property test data are presented in table VII.

It was felt that the differences in the mechanical properties could not be adequately explained on the basis of grain size alone, so an Electron Microscopic (EM) examination was conducted on material from both rotors. The EM review showed differences in the secondary phases, probably due to the different double solution cycles. Representative electron photomicrographs are shown in figure 22. Further study is needed to characterize the relation of these phases to the heat treatments, and how they affect mechanical properties.

Table VII. Results of Task 2 Mechanical Property Response to Heat Treat Evaluation

Heat Treatment: *
Wheel S/N: 2-10 & 2-11
Forge Temperature: 1038°C (1900°F)

TENSILE

Test Temperature, °C	°F	S/N	0.2% Yield M_N/m^2	ksi	Ultimate, M_N/m^2	ksi	Elongation, %	Red. of Area, %
RT	RT	2-10	979.1	142.0	1094.9	158.8	4.7	8.5
RT	RT	2-11	999.0	144.9	1327.2	192.5	12.0	17.6
760	1400	2-10	932.9	135.3	1115.6	161.8	6.7	8.4
760	1400	2-10	937.7	136.0	1111.4	161.2	5.3	7.4
760	1400	2-11	978.4	141.9	1143.1	165.8	8.0	9.0
760	1400	2-11	980.4	142.2	1043.2	151.3	1.3	4.4

CREEP RUPTURE

Test Temperature, °C	°F	S/N	Stress Level, M_N/m^2	ksi	Rupture Life, hr	Elongation, %	Red. of Area, %	1.0% Creep, hr	V/N Rupture, hr
927	1700	2-10	103.4	15	360.9	4.9	2.8	164.8	-
927	1700	2-10	103.4	15	480.2	7.0	2.4	236.0	-
927	1700	2-11	103.4	15	198.2	3.7	3.6	93.5	-
927	1700	2-11	103.4	15	116.5	6.3	6.0	34.3	-
927	1700	2-11	103.4	15	336.2	Discontinued**			
927	1700	2-11	103.4	15	330.3	Discontinued**			
927	1700	2-10	103.4	15	-	-	-	-	159.7 Discont.
927	1700	2-11	103.4	15	-	-	-	-	185.1 Discont.

Table VII. Results of Task 2 Mechanical Property Response to Heat Treat Evaluation (Continued)

STRAIN CONTROL LCF

Test Temperature, °C	°F	S/N	Total Strain, %	Mean Strain %	Total Cycles	Remarks
927	1700	2-10	0.5	0.25	2769	Failed
927	1700	2-10	0.5	0.25	3109	Failed
927	1700	2-11	0.5	0.25	5768	Failed
927	1700	2-11	0.47	0.235	9313	Failed

*S/N 2-10 1177°C (2150°F) Solution, Air Cool + 1121°C (2050°F) Solution, Air Cool + Baseline Precipitation and Age

S/N 2-11 1177°C (2150°F) Solution, Air Cool + 1066°C (1950°F) Solution, Air Cool + Baseline Precipitation and Age

**Equipment breakdown

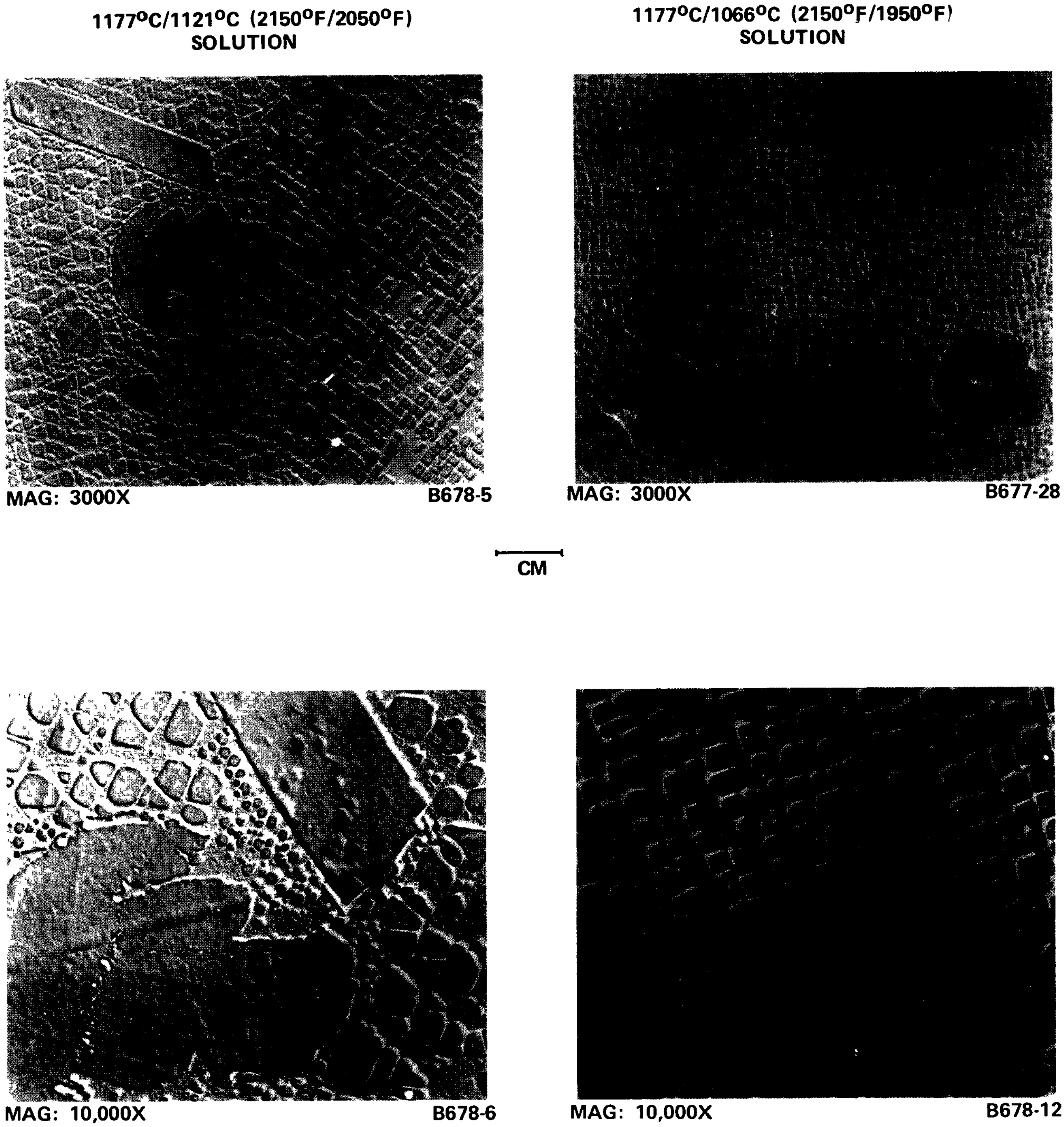


Figure 22. Task II Alternate Heat Treatment Evaluation - Electron Photomicrographs FD 84121

The mechanical property data points from these wheel forgings are presented in figures 23, 24, and 25, along with data points from the baseline evaluations and the Task 3 blade property characterization. The curves are preform data from figure 28. These figures show that, while sacrificing tensile strength (compared to baseline), one of the alternate heat treatments (1177°C, 2150°F/1066°C, 1950°F) resulted in the highest LCF capability and maintained close to the desired level of stress rupture strength. This heat treatment was, therefore, selected for use in part 2 of Task 3.

C. TASK 3 - GENERATION OF DESIGN DATA

Task 3 was twofold as shown schematically in figure 26. The first part involved selecting and evaluating heat treatments designed to enhance the high temperature rupture properties of the blades. This part was conducted concurrently with Task 2. The second part was the establishment of complete design curves for the short time, long time and cyclic properties of the wheel. A summary of the Task 3 evaluations is given in table VIII.

1. Blade Property Characterization

As mentioned previously, it was initially planned to preferentially heat treat the blades of the finished wheel to enhance the rupture properties. In an effort to determine a structure for the blades that would result in a good balance of stress rupture life and ductility, solution heat treatment temperatures of 1163°C and 1177°C (2125°F and 2150°F) were selected from the gradient study. These solution temperatures result in structures which are most likely to have optimum 927°C - 982°C (1700°F - 1800°F) capabilities. The grain structures resulting from the 1163°C and 1177°C (2125°F and 2150°F) solution are a compromise between the fine grains in the material given the baseline heat treatment (figure 11) and the excessively large grains resulting from solution heat treatment temperatures above 1177°C (figure 13). The fine grains generally have poor creep and rupture lives, while extremely coarse grained structures normally exhibit poor rupture ductility and reduced low-cycle fatigue properties.

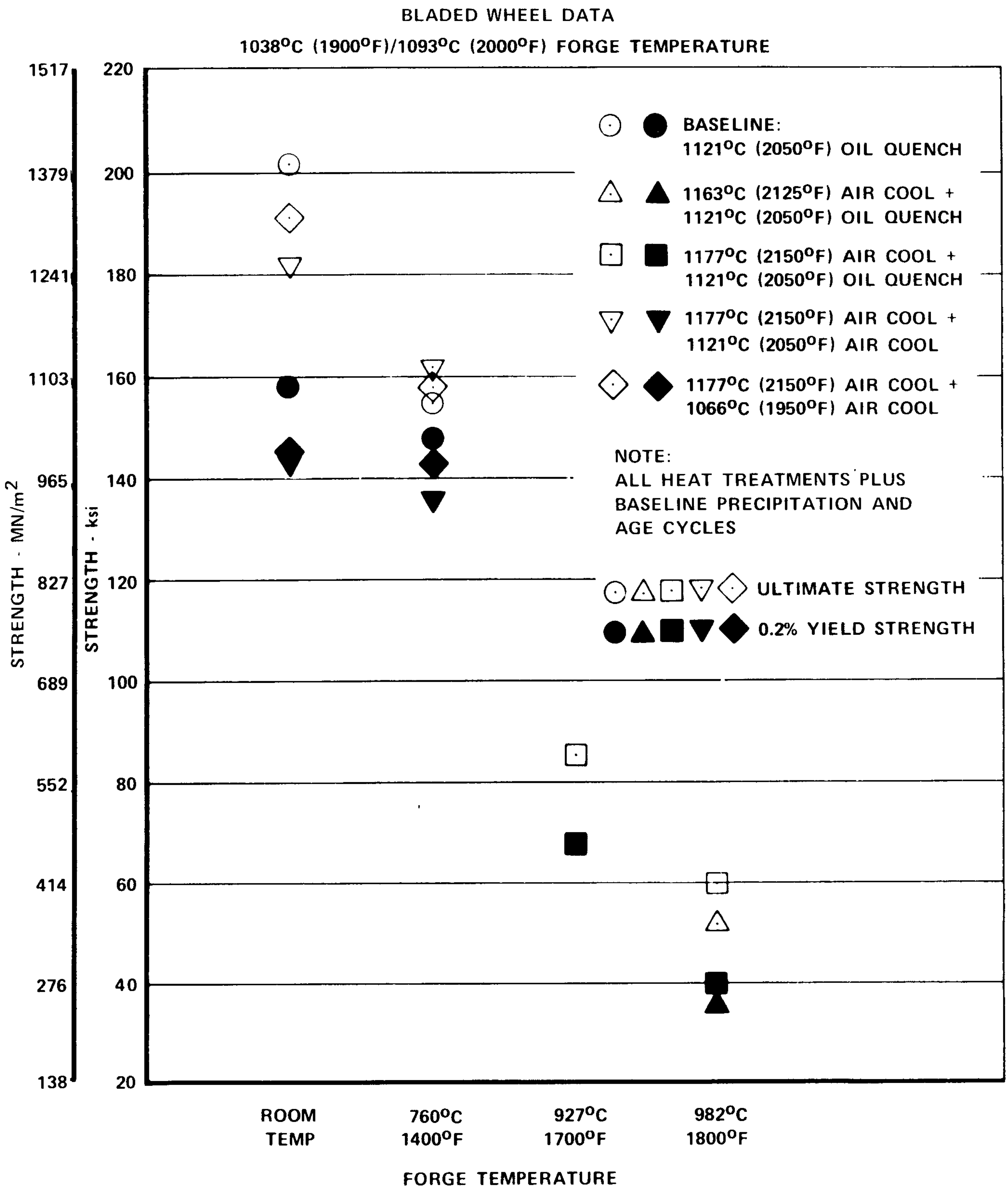


Figure 23. Tensile Properties vs Heat Treatment FD 79245A

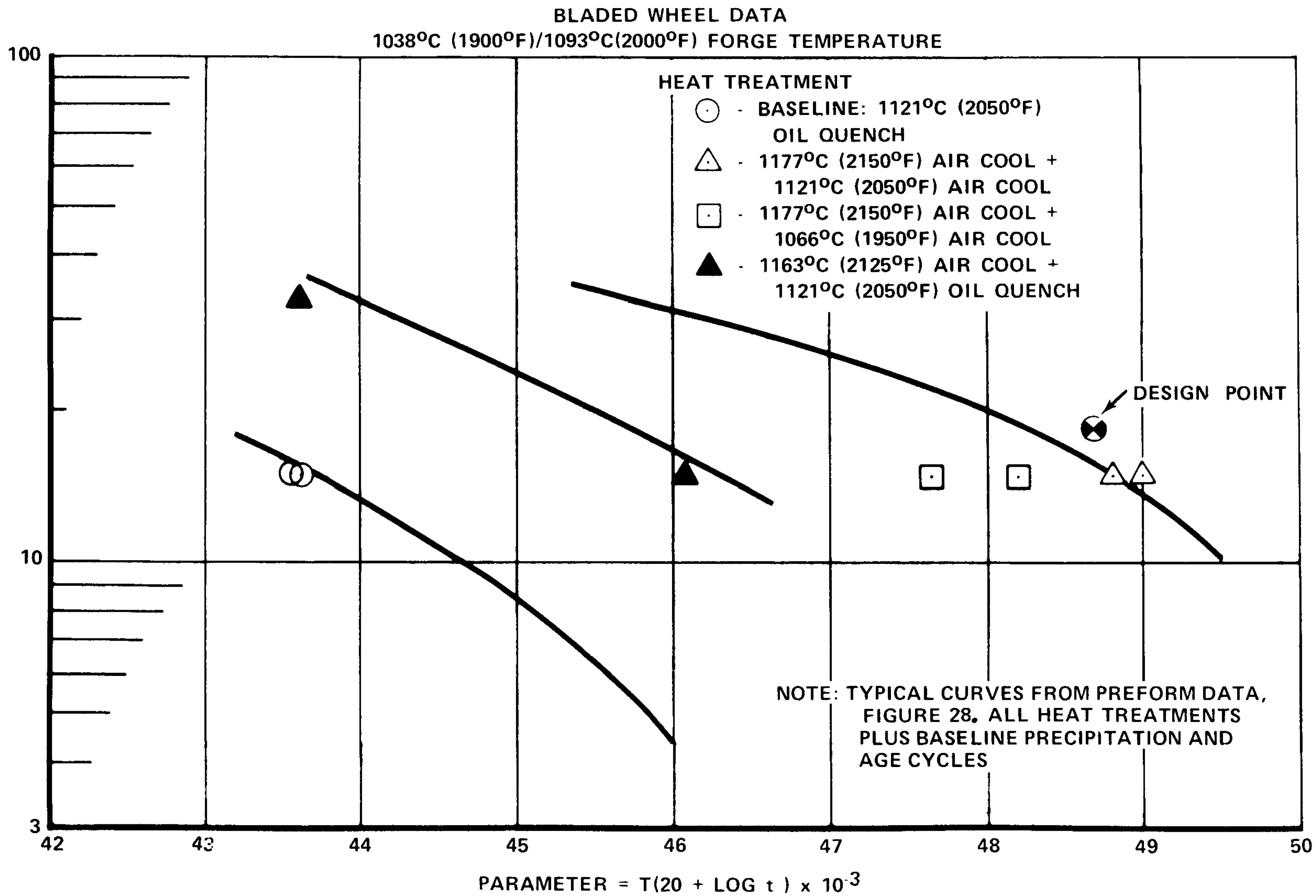


Figure 24. Stress Rupture Capability vs Heat Treatment

FD 79241A

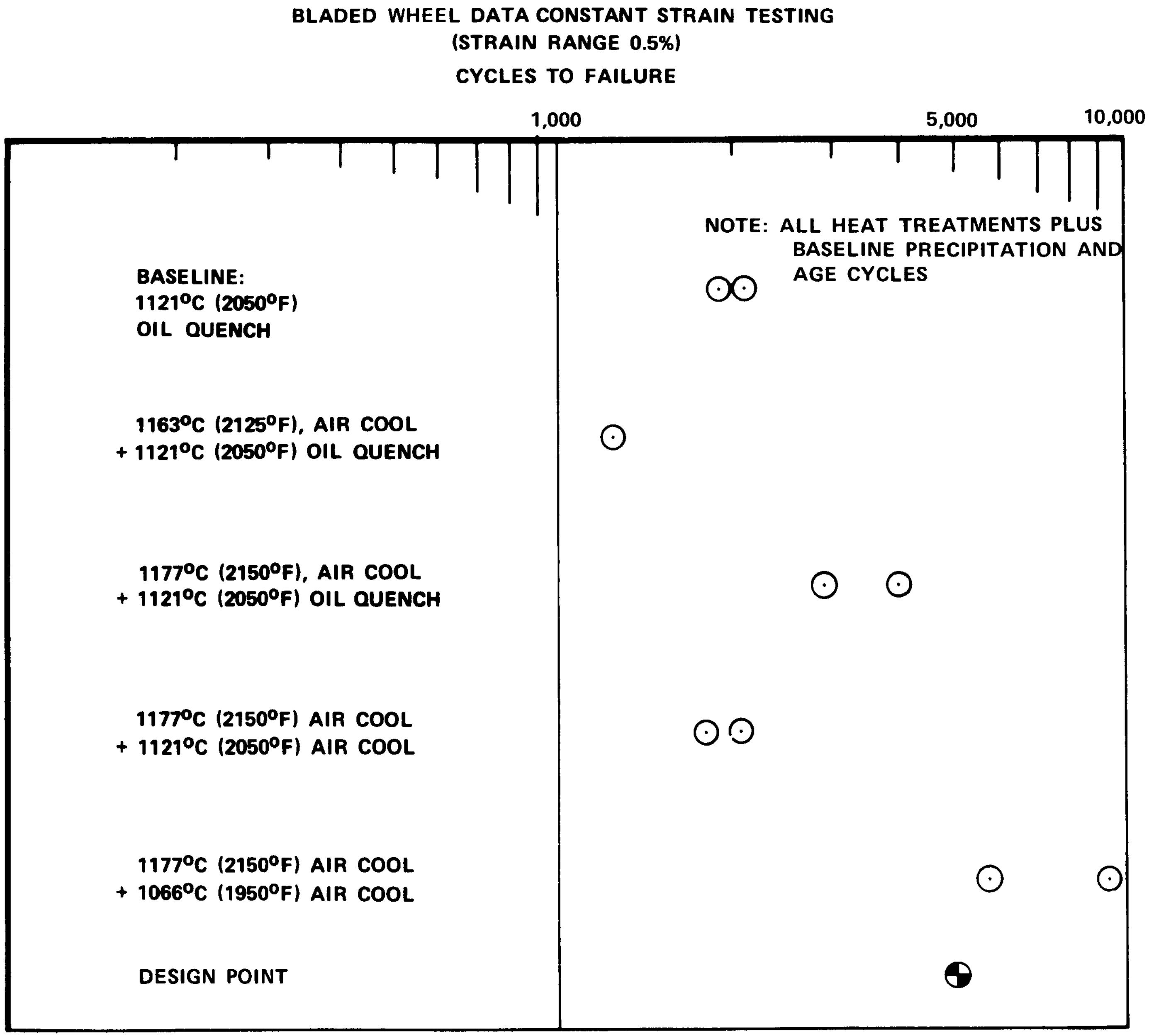


Figure 25. 927°C (1700°F) LCF Capability vs Heat Treatment

FD 79242A

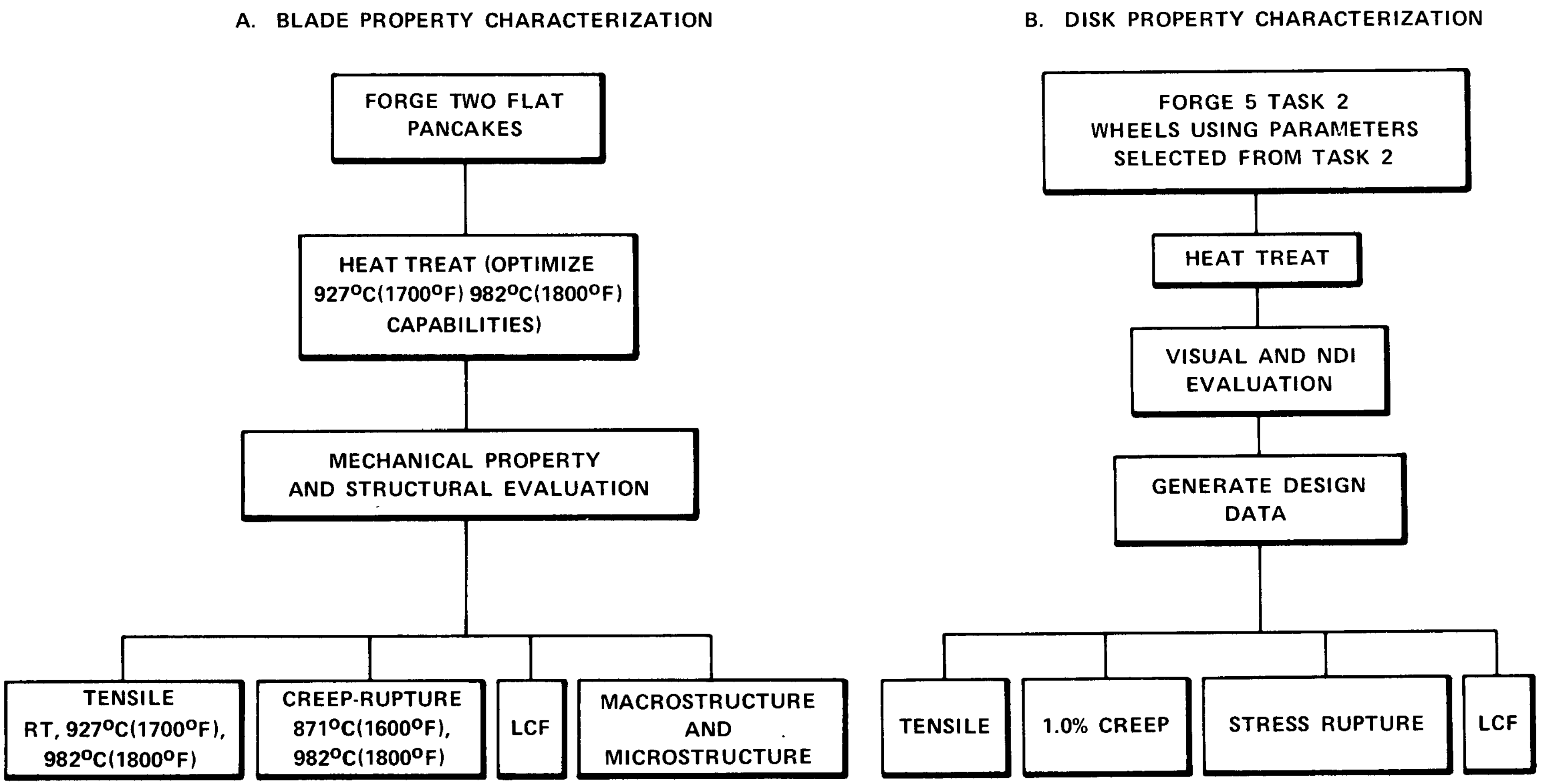


Figure 26. Phase I - Feasibility Demonstration and Cost Analysis; Task 3 - Generation of Design Data FD 72645A

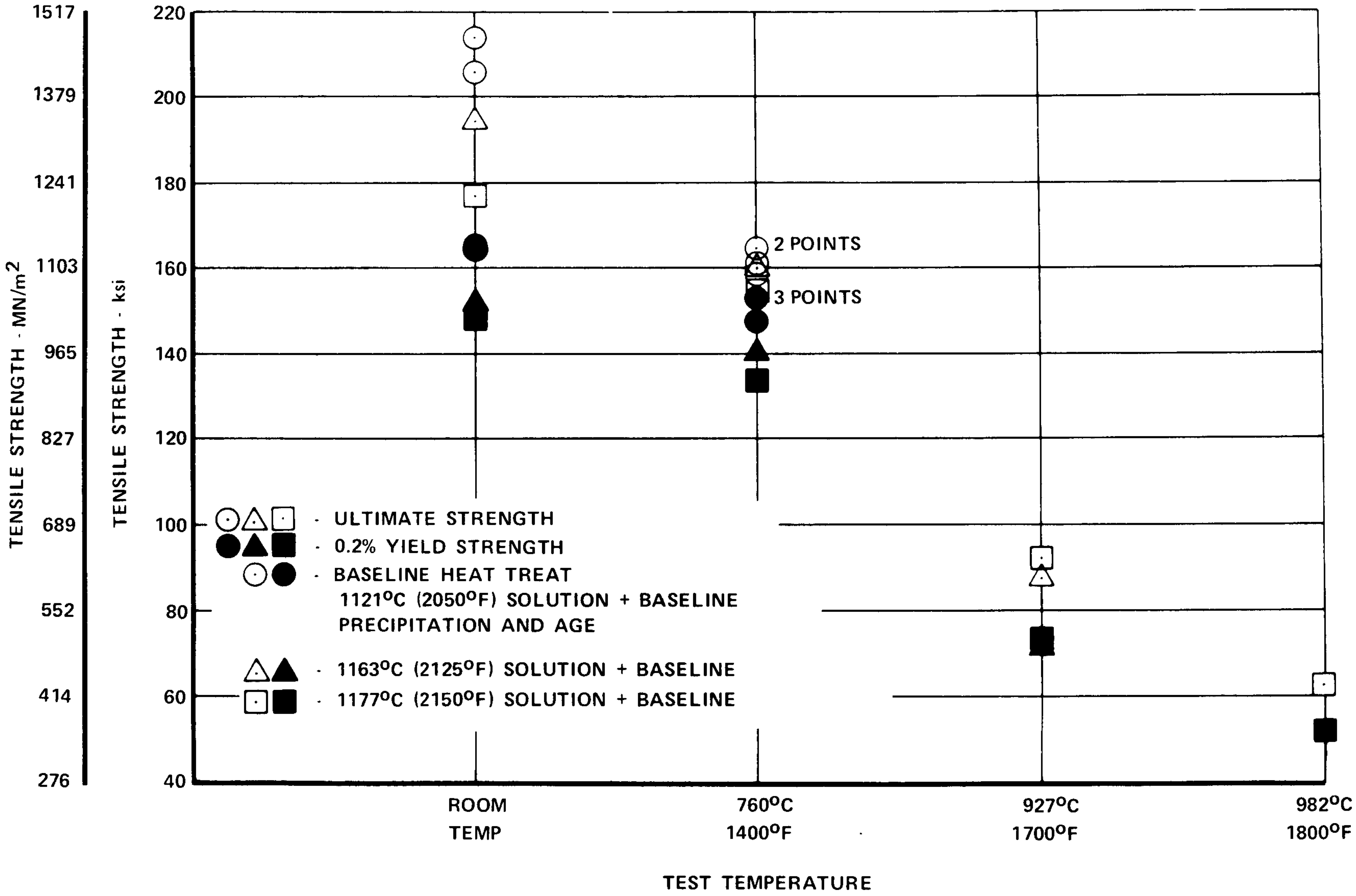


Figure 27. Tensile Properties vs Solution Temperature Preform Data 1038°C (1900°F) Forge Temperature FD 79239A

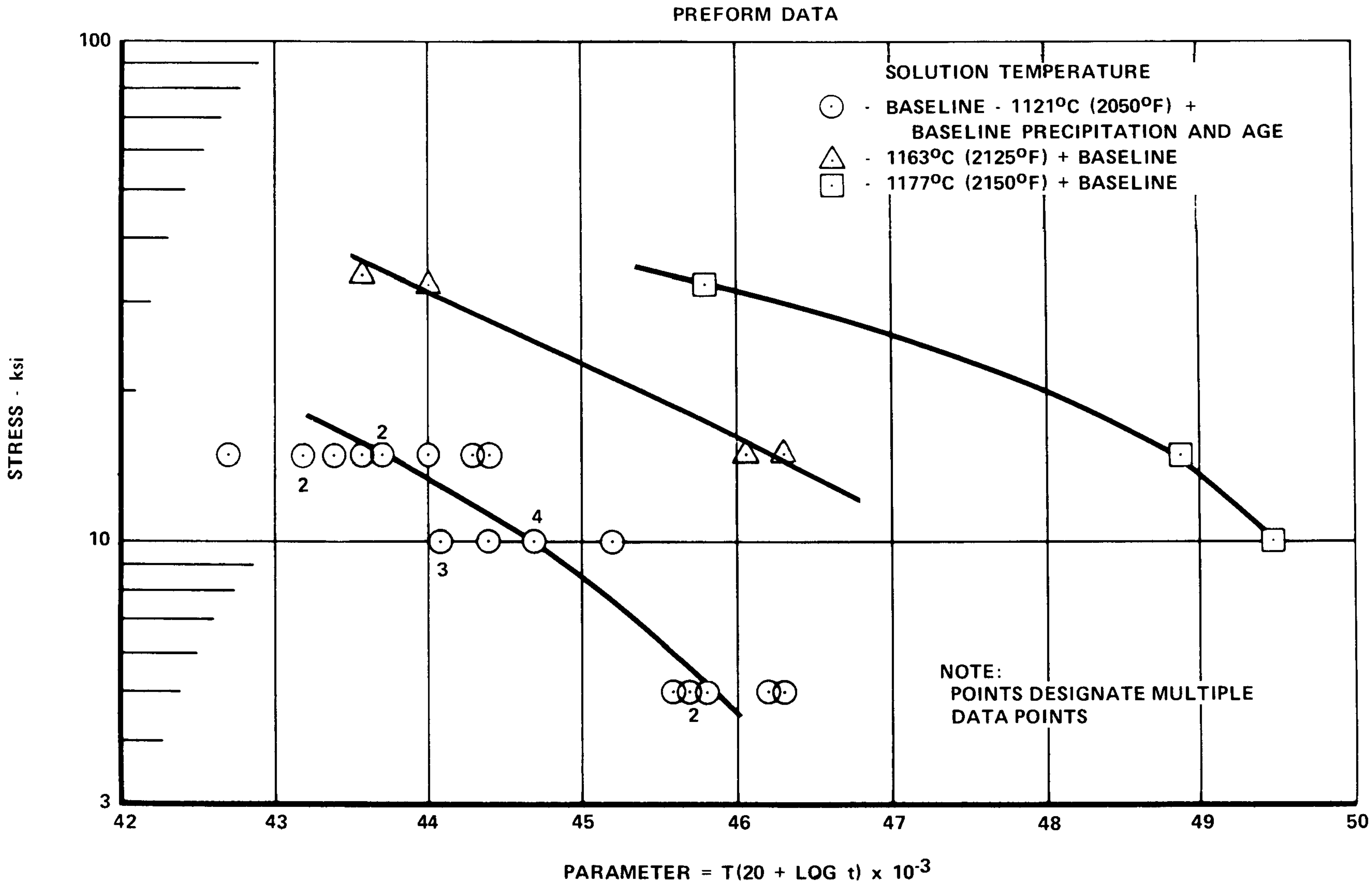


Figure 28. Stress Rupture Capability vs Solution Temperature

FD 79240A

Table VIII. Summary of Task 3 Evaluations

S/N	Forge Temperature Preform °C	Forge Temperature Preform (°F)	Forge Temperature Wheel °C	Forge Temperature Wheel (°F)	Heat Treatment	Program Use	ASTM Grain Size Predominate	ASTM Grain Size Occasional
2-2A	1038	1900	-	-	1163°C (2125°F) Solution, Air Cool + Baseline	Blade Property Characterization	4.0 - 6.0 and 8.0 - 13.5	
2-2B	1038	1900	-	-	1177°C (2150°F) Solution, Air Cool + Baseline	Blade Property Characterization	3.0 - 4.0	6.0 - 8.0
2-6B	1038	1900	-	-	1177°C (2150°F) Solution, Air Cool + Baseline	Blade Property Characterization	2.0 - 4.0	5.0 = 10.0
2-12A	1038	1900	1093	2000	1163°C (2125°F) Solution, Air Cool + Baseline	Blade Property Characterization	3.0 - 4.0	6.0 - 10.0
2-12B	1038	1900	1093	2000	1177°C (2150°F) Solution, Air Cool + Baseline	Blade Property Characterization	4.0 - 6.0	6.0 - 8.0
2-13 2-15 2-16 2-17 2-18	1038	1900	1093	2000	1177°C (2150°F) Solution, Air Cool + 1066°C (1950°F) Solution, Air Cool + Baseline Precipitation and Age	Disk Property Characterization	4.0 - 6.0	6.0 - 8.0

It was anticipated that the wheel would require a protective high temperature coating on the blades and platforms for erosion/corrosion resistance. The application of the coating requires a 760°C (1400°F) pack coating application cycle followed by a high temperature diffusion cycle. A coating study determined that the coating diffusion cycle was compatible with and therefore could be achieved during the 1121°C (2050°F) solution treatment portion of the baseline heat treatment. The 760°C (1400°F) pack coating application cycle was therefore the only additional operation required.

The coating application cycle 760°C (1400°F) was not included in the heat treatment of wheels or preforms for mechanical property testing since it is followed by a high temperature solution cycle which would negate any structural effects from the lower temperature cycle. In conducting the coating study, it was found that there were no adverse effects on the coating from the oil quench used in the baseline heat treatment. Thus the coating of wheels could easily be included in any of the heat treatments studied in the program.

Two forging mults were machined from the extruded stock. These were boron nitride coated and forged into the preform configuration at the baseline parameters. One preform (S/N 2-12) was subsequently forged into a bladed wheel at 1093°C (2000°F). Both the preform (S/N 2-2) and the bladed wheel were cut in half. One half from each part was given the 1163°C (2125°F) solution cycle for 2 hours, and the other half of each disk was given the 1177°C (2150°F) solution for 2 hours. A segment of S/N 2-6 was also used in this evaluation. All pieces were air cooled. The disk halves subsequently received the baseline heat treat and were cut up for mechanical property testing.

Evaluation of these disk halves included room temperature, 927°C and 982°C (1700°F and 1800°F) tensile properties, 871°C and 982°C (1600°F and 1800°F) creep rupture properties, 927°C (1700°F) low cycle fatigue properties, and a microstructural evaluation. The mechanical property test results are listed in table IX, and the preform data are plotted in figures 27 and 28. Baseline preform data are also shown. For comparison with the Task 1 and 2 results, Task 3 wheel results are also included in figures 23, 24, and 25, as mentioned previously. The microstructural evaluation showed a grain size of predominantly duplexed ASTM 3-6 and ASTM 8-13.5 from the 1163°C (2125°F) solution and predominantly ASTM 3-6 from the 1177°C (2150°F) solution.

Table IX. Results of Task 3 Blade Property Characterization Evaluation

Heat Treatment:	*
Preform S/N:	2-2A & B, 2-6B
Forge Temperature:	1038°C (1900°F)
Wheel S/N:	2-12A & B
Forge Temperature:	1038°C/1093°C (1900°F/2000°F)

TENSILE

Test Temperature, °C	°F	S/N	0.2% Yield, M_N/m^2	ksi	Ultimate, M_N/m^2	ksi	Elongation, %	Red. of Area, %
RT	RT	2-2A	1047.3	151.9	1336.9	193.9	11.3	13.6
RT	RT	2-2B	1020.4	148.0	1221.8	177.2	10.0	11.6
760	1400	2-6A	946.6	137.3	1097.6	159.5	18.0	19.4
760	1400	2-6A	966.0	140.1	1116.9	162.0	9.3	11.0
760	1400	2-6B	923.2	133.9	1114.9	161.7	24.0	21.2
760	1400	2-6B	898.4	130.3	1083.9	157.2	5.3	6.5
927	1700	2-6B	535.7	77.7	633.6	91.9	4.7	7.4
927	1700	2-12B	464.7	67.4	584.7	84.8	3.3	6.7
982	1800	2-6B	358.5	52.0	429.2	62.2	2.7	3.3
982	1800	2-12B	276.5	40.1	410.2	59.5	2.7	2.2

CREEP RUPTURE

Test Temperature, °C	°F	S/N	Stress Level, M_N/m^2	ksi	Rupture Life, hr	Elongation, %	Red. of Area %	Time to 1.0% Creep, hr	V/N Rupture, hr
871	1600	2-2B	224	32.5	165.3	2.5	4.8	49.0	-
871	1600	2-2A	224	32.5	22.1	7.4	7.2	5.5	-
871	1600	2-12A	224	32.5	14.5	6.5	8.3	4.4	-
871	1600	2-6B	138	20	657.8	Discontinued**	-	643.5	-
871	1600	2-2A	345	50	-	-	-	-	3.7
871	1600	2-6B	345	50	-	-	-	-	21.2
982	1800	2-2A	103.4	15	3.0	14.1	24.1	0.4	-
982	1800	2-2B	103.4	15	42.7	5.9	3.6	13.7	-
982	1800	2-6B	68.9	10	86.8	9.6	18.1	23.5	-
982	1800	2-12A	103.4	15	2.2	16.8	15.0	0.2	-

Table IX. Results of Task 3 Blade Property Characterization Evaluation (Continued)

STRAIN CONTROL LCF

Test Temperature, °C	°F	S/N	Total Strain, %	Mean Strain, %	Total Cycles	Remarks
927	1700	2-12A	0.5	0.25	2382	Failed
927	1700	2-12B	0.5	0.25	5069	Failed
927	1700	2-12B	0.5	0.25	3859	Failed

*S/N 2-2A, 2-12A — 1163°C (2125°F) Solution, Air Cool + Baseline

S/N 2-2B, 2-6B, 2-12B — 1177°C (2150°F) Solution, Air Cool + Baseline

**Equipment Failure

2. Disk Property Characterization

Processing parameters selected from Task 2 which provided optimum wheel properties were used for forging five preforms and subsequently five wheels. The preform forging temperature was 1038°C (1900°F), the wheel forging temperature was 1093°C (2000°F), and the strain rate was 0.25 cm/cm/min (0.1 in./in./min). These wheels were heat treated to the Task 2 alternate heat treat utilizing the 1177°C (2150°F) + 1066°C (1950°F) double solution cycles.

The five wheels were visually inspected and evaluated by nondestructive inspection techniques. All were within dimensional tolerances and no internal or external defects were detected. The wheels were cut up and machined into test specimens. A variety of testing parameters were used to establish design curves. The testing parameters and test results are listed in table X. The design curves are presented in figures 29, 30, 31, 32, and 33. These curves are discussed in Task 4.

D. TASK 4 - DEFINITION OF MANUFACTURING PROCESS

The Task 4 manufacturing process definition consists of detailed process sheets for the manufacture of the finished wheel and a description of the capabilities and limitations of the forging process.

1. Manufacturing Flow Sheet

Table XI is a detailed list of the operations required in the processing sequence designed for the mass production of GATORIZED automotive gas turbine wheels.

2. Capabilities and Limitations of Forging Process

The GATORIZING forging process has the capability to forge complex, contoured shaped parts to extremely close tolerances (±0.051 mm (0.002 in.)) with no surface cracking. Parts can be forged to near finished shape with very minimal machining to obtain finish dimensions. Finish machining will only be required to deburr, tip blades to length, turn bearing surfaces, and remove metal for balancing.

Table X. Results of Task 3 Disk Property Characterization Evaluation

Heat Treatment: 1177°C (2150°F) Solution, Air Cool + 1066°C (1950°F) Solution, Air Cool + Baseline Precipitation and Age
Wheel S/N: 2-13, 2-15, 2-16, 2-17 and 2-18
Forge Temperature: 1038°C/1093°C (1900°F/2000°F)

TENSILE

Test Temperature, °C	°F	S/N	0.2% Yield M_N/m^2	ksi	Ultimate, M_N/m^2	ksi	Elongation, %	Red. of Area, %
RT	RT	2-16	989.4	143.5	1279.0	185.5	10.7	13.8
316	600	2-15	958.4	139.0	1202.4	174.4	8.0	11.4
316	600	2-16	954.9	138.5	1245.2	180.6	10.7	14.4
316	600	2-17	981.1	142.3	1244.5	180.5	11.3	14.7
649	1200	2-13	996.3	144.5	1168.7	169.5	5.3	10.5
649	1200	2-15	998.4	144.8	1226.6	177.9	7.3	12.6
649	1200	2-18	1000.4	145.1	1273.5	184.7	13.3	15.3
760	1400	2-15	960.4	139.3	1105.2	160.3	6.7	8.9
871	1600	2-13	646.0	93.7	715.0	103.8	2.7	5.9
871	1600	2-17	618.5	89.7	763.9	110.8	6.7	8.5
871	1600	2-18	626.0	90.8	765.3	111.0	3.3	5.4
982	1800	2-16	315.8	45.7	405.4	58.8	3.3	2.2
982	1800	2-17	299.9	43.5	346.1	50.2	2.7	4.4
982	1800	2-18	314.4	45.6	402.7	58.4	3.3	1.6

Table X. Results of Task 3 Disk Property Characterization Evaluation (Continued)

CREEP RUPTURE

Test Temperature, °C	°F	S/N	Stress Level, M_N/m^2	ksi	Rupture Life, hr	Elongation, %	Red. of Area, %	Time to 1.0% Creep, hr	V/N Rupture, hr
760	1400	2-15	344.7	50	321.4 Disc.	-	-	-	-
760	1400	2-16	488.2	65	334.7	5.64	6.9	160.2	-
760	1400	2-17	488.2	65	301.0	5.2	8.7	117.4	-
760	1400	2-13	551.6	80	76.2	11.1	11.2	26.1	-
760	1400	2-18	551.6	80	84.1	12.4	12.1	29.1	-
871	1600	2-13	344.7	50	5.4	5.2	3.3	2.4	-
871	1600	2-17	448.2	65	1.4	3.8	6.8	0.5	-
871	1600	2-18	448.2	65	0.9	2.4	3.2	0.5	-
871	1600	2-16	551.6	80	0.2	4.8	3.6	<0.1	-
871	1600	2-18	551.6	80	0.2	3.9	4.4	<0.1	-
927	1700	2-16	206.8	30	8.9	1.8	3.6	3.8	-
927	1700	2-17	206.8	30	7.3	3.5	3.6	2.6	-
927	1700	2-15	103.4	15	74.3	7.0	17.6	15.1	-
927	1700	2-18	103.4	15	225.1	7.2	6.5	84.2	-
871	1800	2-17	68.9	10	67.8	20.9	17.6	16.4	-
871	1800	2-15	103.4	15	10.3	9.3	9.2	2.9	-
871	1800	2-16	103.4	15	25.3	7.4	8.0	7.6	-
760	1400	2-15	551.6	80	-	-	-	-	231
760	1400	2-16	551.6	80	-	-	-	-	144.3
871	1600	2-18	448.2	65	-	-	-	-	4.6
871	1600	2-13	448.2	65	-	-	-	-	3.3
927	1700	2-18	344.7	50	-	-	-	-	1.1
927	1700	2-17	344.7	50	-	-	-	-	1.3
982	1800	2-16	103.4	15	-	-	-	-	85.2
982	1800	2-17	103.4	15	-	-	-	-	91.9

Table X. Results of Task 3 Disk Property Characterization Evaluation (Continued)

STRAIN CONTROL LCF

Test Temperature, °C	°F	S/N	Total Strain, %	Mean Strain, %	Total Cycles	Remarks
927	1700	2-13	0.5	0.25	3,537	Failed
927	1700	2-13	0.3	0.15	52,255	DNF
927	1700	2-15	0.7	0.35	861	Failed
927	1700	2-15	0.5	0.25	1,595	Failed
927	1700	2-16	0.5	0.25	4,865	Failed
927	1700	2-16	0.7	0.35	951	Failed
927	1700	2-17	0.4	0.20	38,391	Failed
927	1700	2-17	0.5	0.25	2,315	Failed
927	1700	2-18	0.4	0.20	82,645	DNF
927	1700	2-18	0.7	0.35	496	Failed

Table XI. Manufacturing Flow Sheet

Operation	Description
5	Cast Master Melt Ingots
10	Prepare Ingot for Remelting
15	Produce Remelt Ingot
20	Prep Ingot for Canning
25	Can Ingot
30	Extrude Ingot to 6.35 cm (2.5 in.) Dia.
35	Remove Can from Extrusion
40	Inspect Extrusion
45	Store for Manufacturing
50	Cut Extrusion into Multiples
55	Degrease Mults
60	Lubricate with Boron Nitride
65	Preheat Mult
70	Load into Preform Press
75	Gatorize Preform Disk
80	Eject Preform and Cool
85	Trim Flash and Turn OD Concentric to Hub
90	Degrease Preform
95	Lubricate with Boron Nitride
100	Assemble Ring of Inserts and Preform Disk Package
105	Preheat Package
110	Load Package into Press
115	Gatorize Final Form Wheel
120	Eject Package and Cool to Room Temperature
125	Disassemble Package
130	Inspect, Relubricate, and Return Inserts to Load Station
135	Barrel Finish Wheel
140	Solution Heat Treat Wheel
145	Plunge Grind Blade Tips to Correct Dia.
150	Apply Aluminide Coating
155	Stabilization and Age Heat Treat Wheel
160	Dimensional Check with Sigma Test
165	Finish Machine Wheel Hubs
170	Deburr and Polish Wheel
175	Final Inspect
180	Degrease
185	Identify and Store
190	Ship Parts

The primary limitation on the shape of parts which can be forged is the development of laps during forging. Lapping is a condition that results from metal flow from two directions after the outside diameter of the forging is in contact with the die walls. Lapping may be prevented by using a two-step forging with ID entrance angles as low as 2 deg, if required. The only limitations are that during the first forging step, lapping be prevented, and during the second forging step the surface area of the forging is always increasing. A decreasing surface area would create a lap.

The advantages of a two-step forging operation are a savings in material input weight and a savings in the cost of machining away the excess metal. The advantages of a one-step operation are in the elimination of the need for a second set of forging dies and the saving of one forging operation on every part. The lubrication requirements are less severe on a two-step forging operation in that the preform can be lubricated prior to the final forging operation.

Certain special considerations have to be made in designing the airfoil for successful forging of integrally bladed wheels. Airfoil cross-sectional areas should have the following characteristics to enhance forging:

1. Near constant to constant airfoil thickness
2. Minimum chord taper
3. Maximum permissible leading and trailing edge radii
4. Minimum airfoil twist
5. Airfoil solidity ratio not more than 4 blades/2.54 cm (1.00 in.) of disk rim.

3. Design Data Sheets

The design data sheets were generated in the Task 3 disk property characterization. Typical tensile vs temperature data and 927°C (1700°F) low cycle fatigue life data are shown in figures 29 and 30 respectively. Typical creep and stress rupture data are shown on the Larson-Miller plots of figures 31 and 32. Figure 33 is a trade-off curve demonstrating graphically how a change in grain size affects rupture and LCF lives. These curves all represent typical properties and are based on the limited testing that was done during Phase I.

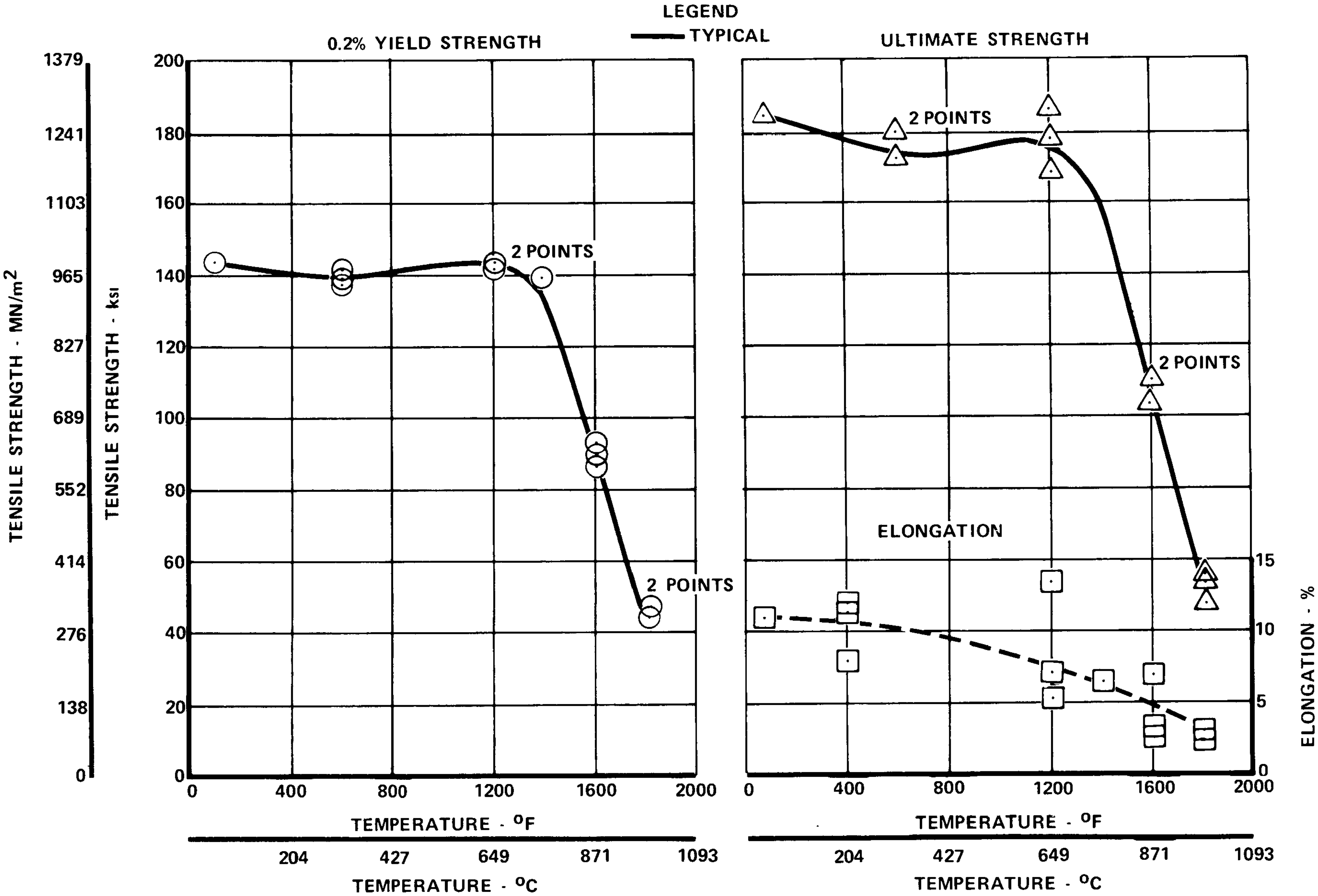


Figure 29. Automotive Turbine Wheel Design Data Tensile Properties of Wrought IN100

FD 84122

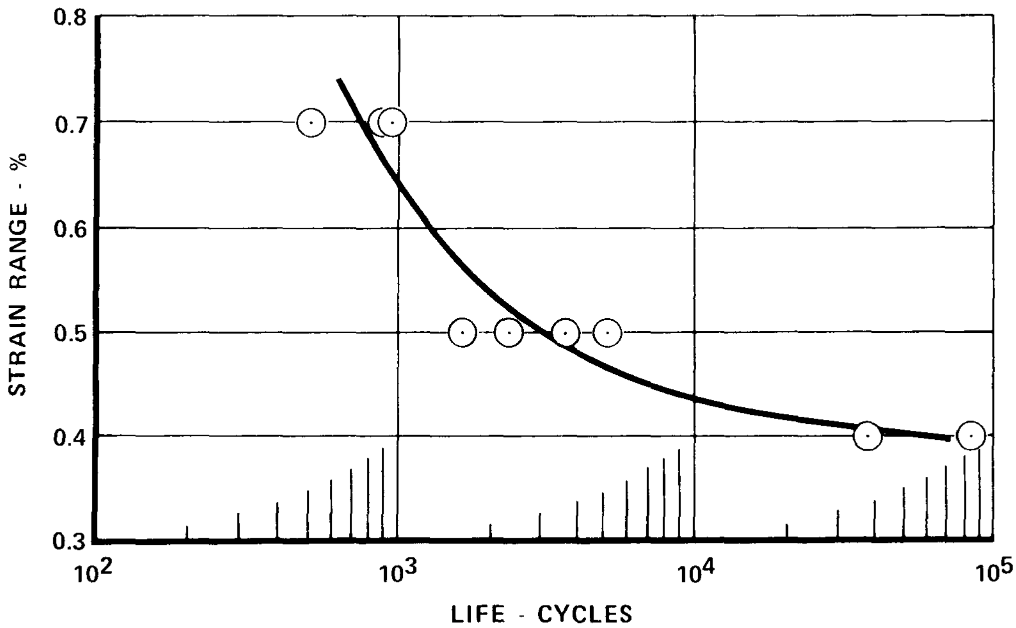


Figure 30. EPA Automotive Turbine Wheel Design Data LCF 927°C (1700°F) IN100 FD 84123

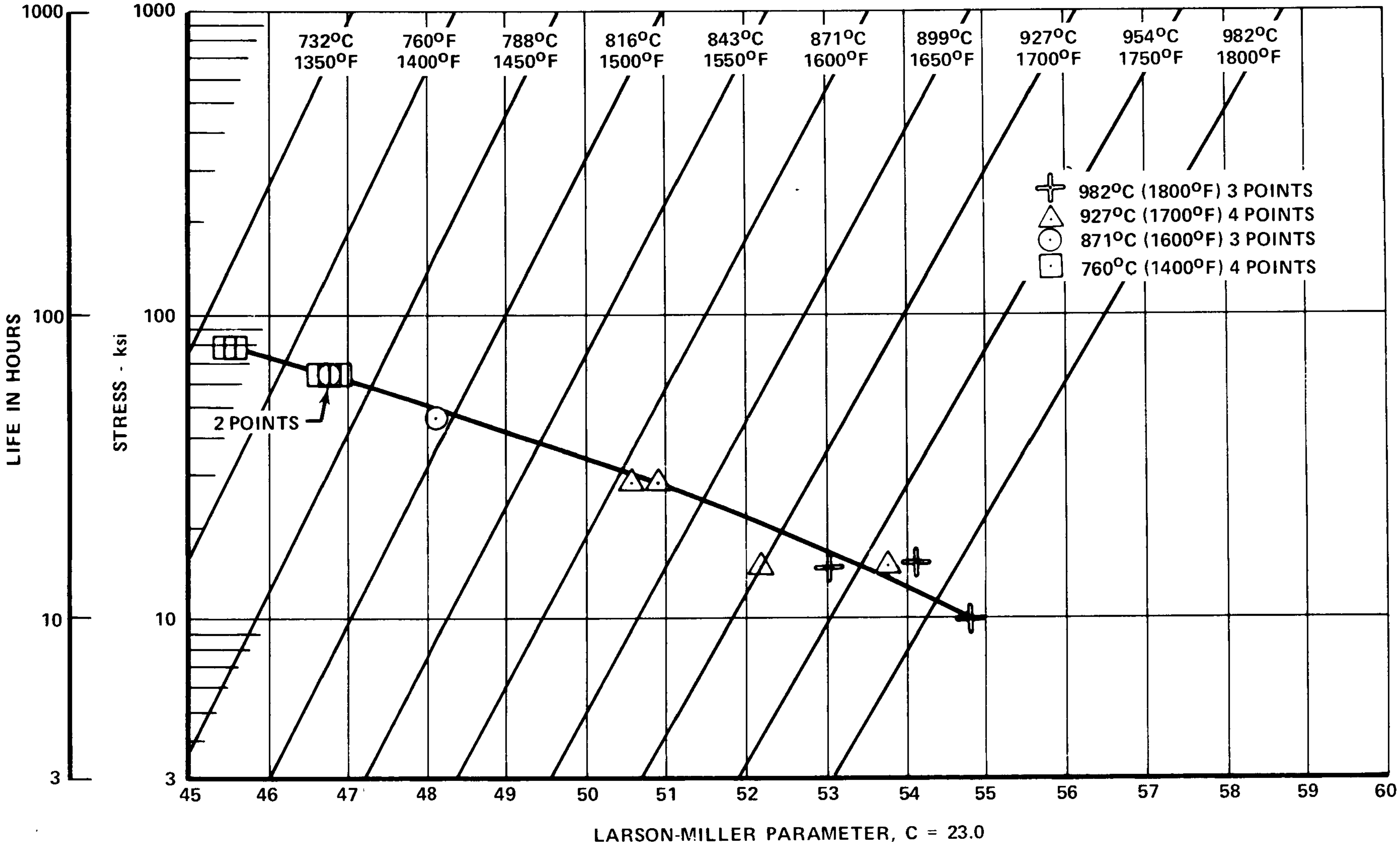


Figure 31. EPA Automotive Turbine Wheel Design Data IN100 Larson-Miller Plot of 1.0% Creep Life FD 84124

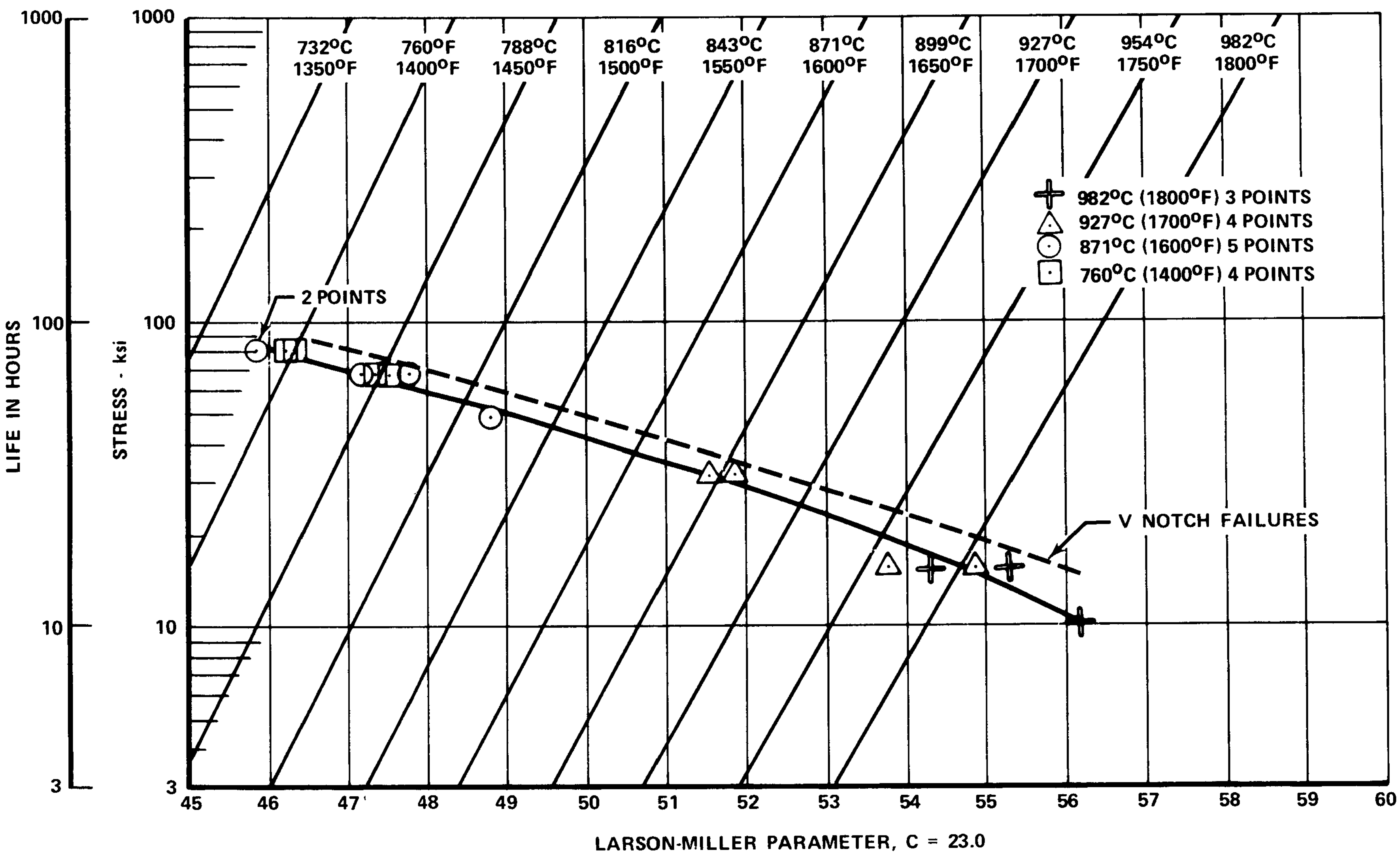


Figure 32. EPA Automotive Turbine Wheel Design Data IN100 Larson-Miller Plot of Stress Rupture Life FD 84125

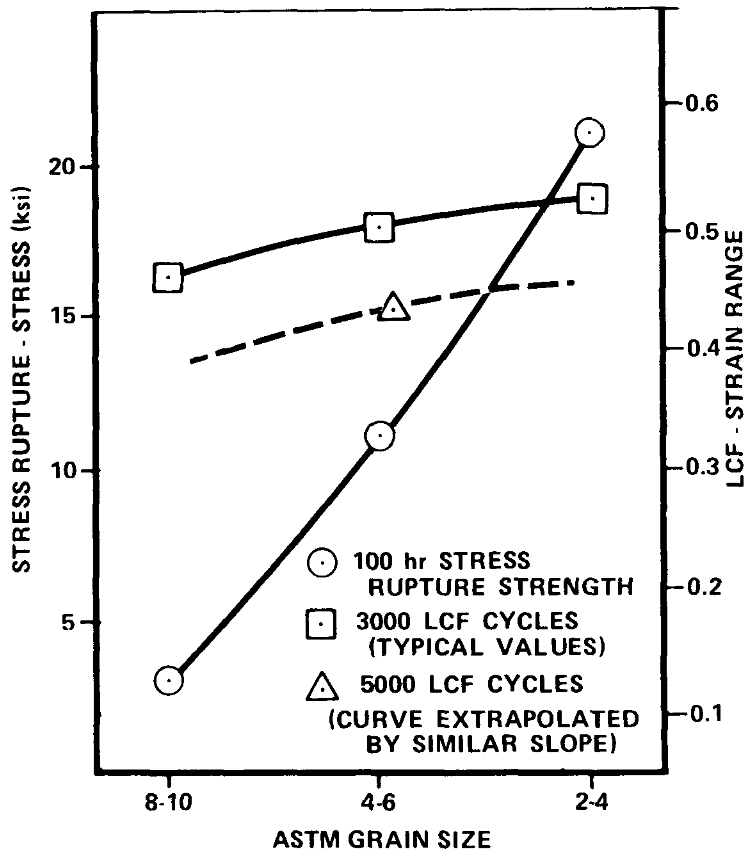


Figure 33. Trade-Off Curve: LCF and Rupture vs Grain Size FD 84127

The use of these curves for actual design would be dependent on design philosophy. For example, in a growth limited application (yield or creep), a design might be based on typical properties in that the part grows based on the average properties. On the other hand, a burst or rupture limited criteria would probably dictate the use of a minimum curve, which minimum would depend on the desired confidence level.

E. TASK 5 - MANUFACTURING COST STUDY

1. Background

For the purposes of this study, a projected manufacturing process, and a complete facility, shown in figure 34, suitable for volume production of automotive turbine wheels was developed based on the manufacturing flow sheet generated in Task 4. This process includes the physical manufacturing cost elements and all other significant cost elements necessary to project a meaningful unit cost for automotive turbine wheels.

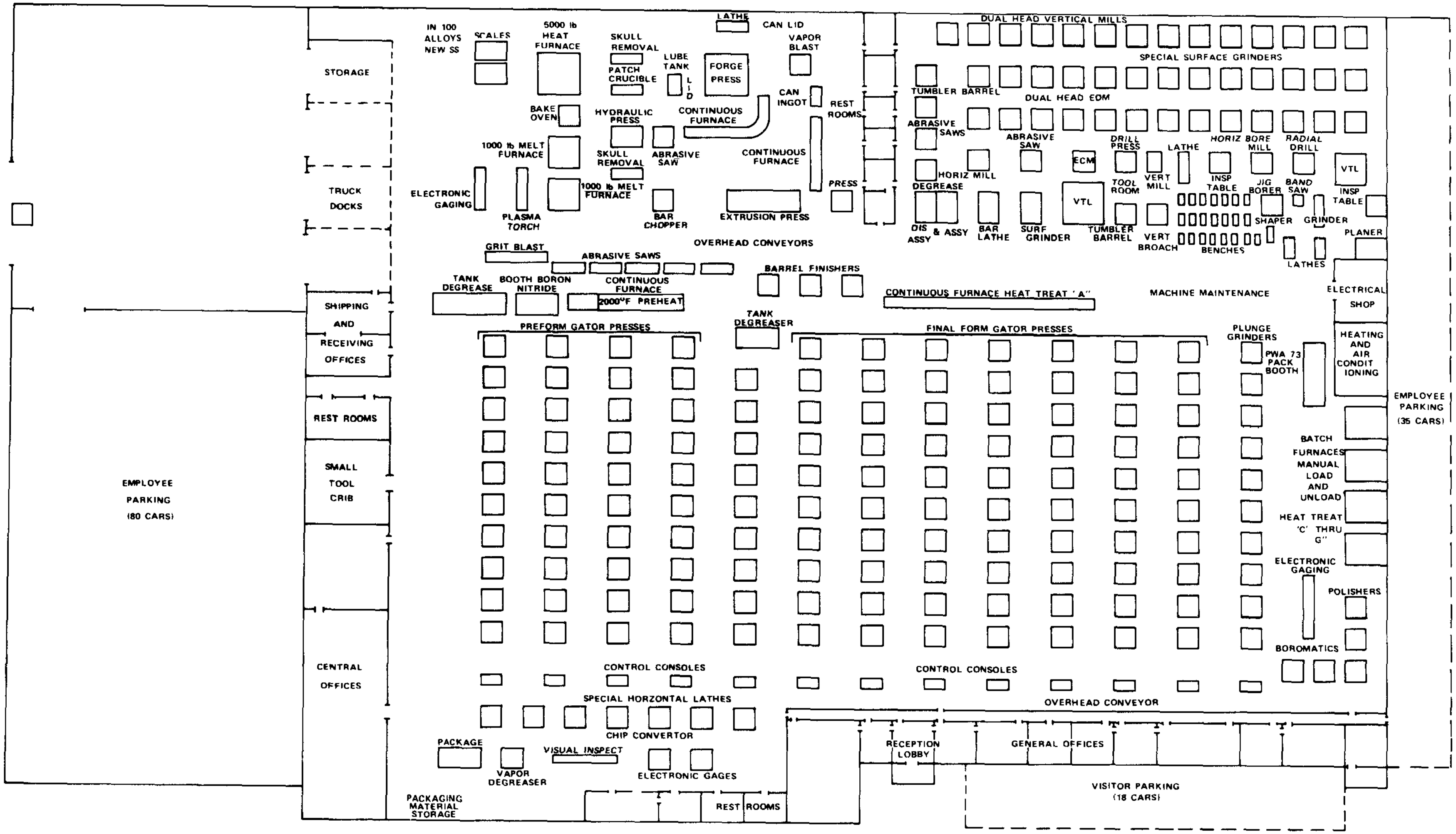


Figure 34. Plant Layout EPA Rotor Production 191,000 sq ft

FD 84126

For purposes of comparison, this cost study was patterned after that conducted by Williams Research Corporation for the EPA under Contract EPA-460/9-73-001. With one exception, Williams' assumptions were used to establish a baseline for this cost study. This exception is that the wheel produced in the "P&WA" facility is complete with gas path coating and ready for final assembly and balancing, whereas, the wheel produced in the Williams' facility is a raw casting requiring finish machining and coating before assembly.

2. Manufacturing Assumptions

The following assumptions were made to generate the manufacturing facility and cost to produce automotive turbine wheels:

1. The manufacturing facility will be a complete production operation in that raw materials are received in the form of alloy constituents to make up the master melts, and finished wheels ready for assembly are shipped out.

2. The facility is designed to eliminate labor where possible by use of automated production techniques.

3. The production facility will operate 249 days, two 8-hour shifts, 5 days per week. Additional upkeep is planned for furnace overhaul and system maintenance.

4. Capital depreciation on all facilities except the building were carried over 8 years. The building was carried over 40 years.

5. Labor floor/floor prime was estimated assuming all operations are automated where possible.

6. Tooling life was estimated to be 25 thousand forging cycles with 25 resinks and insert tooling to have a 100 forging cycle life.

7. Performance variation of 1.333 was used for determination of manpower requirements.

8. General and administrative costs were set to be 10%; same as Williams Research Corp. report.

9. Corporate profit was set at 25%; same as Williams Research Corp. report.

3. General Process Description

In the effort to produce wrought turbine wheels at low cost, the proposed manufacturing process utilizes current technology casting methods, conventional superalloy extrusion, P&WA's patented forging technique (known as GATORIZING), and typical high volume, automated production.

Melting is carried out in two steps; the first, to alloy master heat ingots, and the second, to produce remelt ingots. The material is then conditioned to a superplastic state by extruding the remelt ingots. The wheels are then forged to final dimensions utilizing the GATORIZING process to maintain the material in a superplastic condition. The desired mechanical properties of the wheels are then restored utilizing production heat treat techniques.

The finishing operations, such as cleaning, deburring, blade tipping, lathe turning the hubs and applying blade coatings, use either current or modifications of current production practices.

4. Cost Summary

The cost summary was developed analyzing all cost elements that would normally be associated with a manufacturing operation of this type.

The major cost centers within this study were:

1. Materials
2. Manpower
3. Capitalization.

The first cost center considered raw material production, extrusion cans, forging die material, expendable tools, scrap factors, freight and other pertinent items to this category.

Manpower was established by analyzing the manufacturing operation for direct labor, indirect supporting labor, and indirect salaried requirements. A plant manpower description broken down on a per shift basis is shown in table XII. Table XIII is a summary of general and administrative costs incurred in the operation of this facility.

The final cost center considered a complete manufacturing facility including operation equipment, building, grounds, support equipment, etc. A summary of the major facilities cost is listed in table XIV.

From these three major cost centers overhead rates were established. The general and administrative fees and profit were computed to establish a final selling price of $51.77 per turbine wheel. A condensed cost summary is given in table XV.

Table XII. Manpower Requirement Summary Automotive Turbine Wheel Manufacturing Facility

Description	Shift 1	Shift 2	Shift 3	Total
Direct Hourly	73	71		144
Indirect Hourly	12	10		22
Indirect Salary	38	16		54
G&A Personnel	16	2	1	19
Totals	139	99	1	239

Table XIII. Summary of General and Administrative Estimated Cost

Description	Total
Salaries & Benefits (Insurance, Pensions, etc.)	$ 348,000
IR&D Monies	2,632,000
Expenses (Insurance, Office Supplies, Utilities, etc.)	855,000
Total	$3,835,000

Table XIV. Estimated Cost Summary of Facilities

Item	Description	Est. Cost Total
A	Ingot Production and Extrusion Facilities	$ 4,792,000
B	Wheel Production Facilities	13,286,000
C	Tool Build and Maintenance Facility	1,889,000
D	Equipment Maintenance Facilities	940,000
E	Support Facilities	2,177,000
F	Building and Grounds	6,845,000
	Total	$29,929,000

Table XV. Cost Summary
(GATORIZED Automotive Turbine Wheel)

I	Raw Material			
	A.	Metal per pound (as converted ingot)		$ 5.76
	B.	Die Material (per pound of wheel)		2.29
	C.	Freight and Expendable Tools (per pound of wheel)		0.47
	D.	Initial Die Material (3 sets)		0.60
	E.	Scrap Cost @ 5%		0.30
			Subtotal	$ 9.42
	F.	15% Contingency		$ 1.41
	G.	Cost per pound of wheel		$10.83
	H.	Cost per rotor @ 2.7 lb/wheel		$29.25
II	Labor & Overhead			
	A.	Direct Labor/Wheel		$ 1.50
	B.	Overhead/Wheel		
		1. Depreciation	$3.05	
		2. Wages, fringes and benefits, Indirect	$1.17	
		3. Fringes and benefits for direct labor	$ .52	
		4. Indirect expenses	$2.86	
		(Overhead is 508%)		
		5. TOTAL		$ 7.60
	C.	Labor Plus Overhead/Wheel		$ 9.10
III	Totals			
	A.	Raw Materials/Wheel		$29.25
	B.	Labor plus Overhead/Wheel		9.10
			Subtotal	$38.35
	C.	Plus G&A and Profit		13.42
			Total Cost Per Wheel	$51.77

SECTION III
SUMMARY OF RESULTS

This study provides adequate evidence that volume production of automotive turbine wheels utilizing the GATORIZING process is within the current state-of-the-art. Integrally bladed turbine wheels were successfully forged and it was demonstrated that control of the LCF-stress-rupture life tradeoff can be achieved with heat treat variations.

The selling price of a mass-produced turbine wheel, based upon a material/labor ratio of 75%/25% and an overhead of 508% at the projected study level of one million parts per year could be less than $55.00. The capitalization of a complete facility to manufacture 1,000,000 turbine wheels per year would cost $29,930,000. The impact of alternate production rates of 100,000 and 10,000,000 rotors per year will be studied in more detail in Phase II of this contract.

SECTION IV
RECOMMENDATIONS

Based on the findings of Phase I, it is recommended that Phase II consist primarily of: a detailed design analysis to produce a turbine wheel design more compatible with the forging technique and still compatible with the performance characteristics of the Chrysler Baseline Gas Turbine Engine; and the production of several integrally-bladed turbine wheels for engine verification and other qualification testing. After initial wheel forgings of IN 100 are produced, a second Ni-base alloy, modified IN 792, will be introduced into the program. The modified IN 792 is reported to have superior hot corrosion resistance and mechanical properties consistent with the Upgraded Engine Requirements.