EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M

European Project for the development of HTR Technology - Materials for the HTR

CONTRACT N°
FIKI-CT-2000-00032
&
FIKI-CT-2001-00135

Information on Udimet 720

Special Metal Corporation
Report TR-88-002 - 1988

Dissemination level : CO
Document Number: HTR-M-03/01-D-2-2-60

HTR-M & M1
Information on Turbine Materials

Udimet Alloy 720

UDIMET® ALLOY 720

by

R. E. Sczerzenie, S. O. Mancuso
P. W. Keefe, G. E. Maurer, W. J. Boesch

TR-88-002

May 1988

CLASS I - UNRESTRICTED REPORT

REPORT COVER PAGE

CLASSIFICATION Class I - Unrestricted ACTION NUMBER TR-88-002

TITLE UDIMET® ALLOY 720

ABSTRACT

UDIMET Alloy 720 is a unique, nickel-base, gamma prime strengthened superalloy which is used in elevated temperature applications. This report describes the chemical composition, physical metallurgy, physical and mechanical properties, and the processing technology of wrought **UDIMET Alloy 720.**

Special Metals Corporation believes the information contained herein to be reliable and accurate. These data are intended to be average expected values and should not be interpreted to be values for specifications or design purposes. **Special Metals Corporation** assumes no responsibility for results obtained or damages incurred from the use of these data in whole or in part.

Alloy 720 is a patented alloy of **Special Metals Corporation;** U.S. Patent No. 4,093,476 and corresponding foreign patents.

DISTRIBUTION: Authors
Library (2)
S. J. Vonk
Staff (Circulate)

WRITTEN BY/DATE _____ _____

APPROVED BY/DATE _____ _____

APPROVED BY/DATE _____ _____

DESCRIPTOR LIST

Authors:
F. E. Sczerzenie
S. O. Mancuso
P. W. Keefe
G. E. Maurer
W. J. Boesch

UDIMET Alloy 720
Nickel-base alloy

®**UDIMET** is a registered trademark of **Special Metals Corporation**

CONTENTS

1.0 INTRODUCTION

2.0 CHEMICAL COMPOSITION

3.0 PHYSICAL METALLURGY
- 3.1 Phases Present
- 3.2 Physical Reactions
- 3.3 Phase Stability
- 3.4 Oxidation Resistance
- 3.5 Hot Corrosion Resistance

4.0 HOT WORKABILITY

5.0 HEAT TREATMENT
- 5.1 Heat Treatment for Creep Resistance
- 5.2 Cooling Rate Effects
- 5.3 Heat Treatments for High Strength

6.0 MACHINING AND WELDING UDIMET ALLOY 720
- 6.1 Machining UDIMET Alloy 720
- 6.2 Welding UDIMET Alloy 720

7.0 PHYSICAL PROPERTIES
- 7.1 Density
- 7.2 Melting Range
- 7.3 Thermal Expansion
- 7.4 Modulus of Elasticity

8.0 MECHANICAL PROPERTIES
- 8.1 Creep and Stress Rupture
- 8.2 Tensile Properties
- 8.3 Impact Properties
- 8.4 Fatigue Properties
- 8.5 Crack Growth Rate

ENDNOTES

ADDITIONAL REFERENCES

FIGURES

APPENDIX I - METALLOGRAPHIC PREPARATION OF UDIMET ALLOY 720

APPENDIX II - DIFFERENTIAL THERMAL ANALYSIS OF UDIMET ALLOY 720

[redacted]

UDIMET® ALLOY 720

1.0 INTRODUCTION

UDIMET® Alloy 720 is a unique, nickel-base gamma prime strengthened superalloy which is used in elevated temperature applications requiring either high tensile strength with a fine-grain structure (commercial designation, **UDIMET Alloy 720-HS**) or high creep resistance with a coarse-grain structure (commercial designation, **UDIMET Alloy 720-CR**). In addition to its excellent strength, **UDIMET Alloy 720** has superior hot-corrosion resistance when compared to other wrought superalloys in the marketplace.

To achieve consistently reliable properties at a reasonable cost, the alloy is manufactured by conventional vacuum induction melting followed by vacuum arc remelting and subsequent processing by conventional hot working and heat treatment techniques. The chemical composition of **UDIMET Alloy 720** has been carefully balanced to provide structural and surface stability. The alloy has therefore been selected for a wide range of applications involving high temperature and severe environmental conditions. This report describes the chemical composition, physical metallurgy, physical and mechanical properties, and processing technology of wrought **UDIMET Alloy 720**.

While this document primarily describes cast-wrought material, **UDIMET Alloy 720** can also be used in cast or powder metallurgical forms. It is anticipated that the mechanical properties of these forms will be closely approximated by the cast-wrought properties, with appropriate variations for grain size and thermomechanical history. Cast **UDIMET Alloy 720** is an attractive candidate alloy when complex or hollow shapes are needed in hot-corrosion or creep-resistance applications. Powder metallurgical billet is an alternative when microstructural uniformity is required in large size forging stock.

®**UDIMET** is a registered trademark of **Special Metals Corporation**

2.0 CHEMICAL COMPOSITION

The following is the nominal chemistry of **UDIMET Alloy 720:**

	wt%		wt%
Chromium	18.0	Aluminum	2.5
Cobalt	14.7	Carbon	0.035
Molybdenum	3.0	Boron	0.033
Tungsten	1.25	Zirconium	0.030
Titanium	5.0	Nickel	Balance

3.0 PHYSICAL METALLURGY

3.1 Phases Present:

The major carbide and boride phases found in **UDIMET Alloy 720** are:

- MC-type carbide, rich in titanium, tungsten and molybdenum
- $M_{23}(C,B)_6$-type carboboride, rich in chromium
- M_3B_2-type boride, rich in chromium and molybdenum with some tungsten and titanium
- MB_2-type boride, very rich in chromium with small amounts of tungsten and molybdenum

3.2 Physical Reactions:

The following are the typical reaction temperatures for **UDIMET Alloy 720.** Variations in these temperatures will be obtained with changes in chemistry and thermomechanical history. See Appendix II for more details.

Gamma Prime Solvus	Incipient Melting	Solidus	Liquidus
°C 1147	°C 1195	°C 1238	°C 1335
(°F) (2097)	(°F) (2183)	(°F) (2260)	(°F) (2345)

3.3 Phase Stability:

In order to control structural stability at high temperatures, **UDIMET Alloy 720** is melted to strict chemical requirements in terms of electron vacancy number (N_v).[1] After prolonged exposure at about 845°C (1553°F), **UDIMET Alloy 720** resists the deleterious microstructural changes that can adversely affect the ductility of other superalloys. The amount of carboboride formation at the grain boundaries by the reaction M_3B_2 + MC + gamma → gamma prime + $M_{23}(C,B)_6$ is restricted by the low carbon content of the alloy and altered by the free boron and borides already present. This limits the coarse and continuous agglomeration of $M_{23}(C,B)_6$, which can decrease the crack propagation resistance of other superalloys. There is little evidence of harmful sigma phase formation after long exposures at 760°C (1400°F) to 815°C (1500°F). At higher temperatures in the range of 845°C (1553°F) to 900°C (1650°F) and at higher N_v's, **UDIMET Alloy 720** has precipitated small amounts of sigma on long-term aging.

3.4 Oxidation Resistance:

The oxidation resistance of **UDIMET Alloy 720** is considered adequate for applications up to 980°C (1796°F). Above this temperature, the oxidation resistance is somewhat inferior to that of **UDIMET Alloy 700** because of the lower aluminum content of **UDIMET Alloy 720.**

3.5 Hot Corrosion Resistance:

The 18% chromium content of **UDIMET Alloy 720** provides excellent resistance to hot corrosion attack. Since the amount of chromium carbide formed at the grain boundaries is limited due to the low carbon content, the extent of chromium depletion near the grain boundaries is also limited. This minimizes the susceptibility of grain boundaries to hot corrosion attack.

4.0 HOT WORKABILITY

Once the initial ingot structure has been refined, **UDIMET Alloy 720** exhibits

excellent workability, provided the proper working temperature range is maintained. The alloy's high volume percent gamma prime inhibits grain growth at typical hot-working temperatures, producing a fine-grained structure that exhibits exceptional hot ductility. Experience indicates that **UDIMET Alloy 720** responds favorably to a wide variety of thermomechanical processing techniques ranging from conventional open die forging to isothermal forging.

The thermomechanical processability of **UDIMET Alloy 720** has been evaluated by high strain rate tensile testing.[2] The results of some of these tests have been compiled into a series of graphs which represent typical properties of the material at various temperatures, Figures 4.1-4.4. The %RA vs temperature curve is considered to be most representative of the material's hot workability or the ease of thermomechanical processing. In general, high temperature alloys exhibiting %RA's greater than 30% over a reasonable temperature range are considered to have good workability. As seen in Figure 4.1, **UDIMET Alloy 720** has good workability in the temperature range from 925°C (1700°F) to 1120°C (2048°F). Above 1120°C (2048°F), ductility drops off rapidly due to excessive grain growth, which results from the solutioning of gamma prime. Grain boundary oxidation also reduces workability at these temperatures. Below 925°C (1697°F), the material rapidly strain hardens, which makes processing very difficult.

The effect of preheat temperature also affects workability by influencing grain structure and precipitates. In the case of **UDIMET Alloy 720**, preheat temperatures at or below 1120°C (2048°F) will not noticeably affect the workability, whereas temperatures above about 1150°C (2102°F) have been observed to greatly reduce forgeability. Experiments on small bars suggest that uniform, fine-grained structures can be produced with forging preheat temperatures in the range of 1100°C (2012°F) to 1120°C (2048°F).

As with all highly alloyed superalloys, **UDIMET Alloy 720** exhibits a tendency toward surface cracking when metal surface temperatures are not properly maintained. Precautions such as coating of the workpiece to retain heat and to provide high temperature lubrication, heating of the dies to reduce workpiece chilling, and limiting on-die times to control workpiece heat loss

should be utilized.

5.0 HEAT TREATMENT

The mechanical properties listed in this brochure were obtained on specimens having one of the heat treatments given in Table 5.1.

Table 5.1. UDIMET Alloy 720 Heat Treatments

CR	HS1	HS2
1170°C (2138°F)- 4 hrs-AC	1105°C (2021°F)- 2 hrs-OQ	1115°C (2039°F)- 4 hrs-OQ
1080°C (1976°F)- 4 hrs-AC	760°C (1400°F)- 8 hrs-AC	650°C (1202°F)-24 hrs-AC
845°C (1553°F)-24 hrs-AC	650°C (1202°F)-24 hrs-AC	760°C (1400°F)- 8 hrs-AC
760°C (1400°F)-16 hrs-AC		

5.1 Heat Treatment for Creep Resistance:

The creep resistance (CR) heat treatment produces a balanced combination of stress rupture, tensile, and impact properties. Heat treatments incorporating coating cycles are successful. Microstructures of as-rolled and heat-treated **UDIMET Alloy 720-CR** are presented in Figures 5.1 and 5.2.

For optimum creep resistance, **UDIMET Alloy 720-CR** is initially heat treated for 4 hours at 1170°C (2138°F) and air cooled. This heat treatment cycle is well above the solvus temperature of the fine and intermediate gamma prime precipitates present in the as-hot-worked condition, Figure 5.1.b. It is also in the middle of the observed solutioning temperature range of the very coarse gamma prime phase 1142°C (2088°F) to 1186°C (2167°F), Figure 5.1.b. The broad gamma prime solutioning range observed in Figure AII.1 of Appendix II results in part from the dynamic nature of differential thermal analysis (DTA) combined with the time-dependent nature of diffusion-controlled solutioning of large gamma prime particles. In practice,

a four-hour hold at 1170°C (2138°F) is sufficient to fully solution the coarse gamma prime.

Solutioning of the coarse gamma prime and the $M_{23}(C,B)_6$ carboboride phases present in the as-wrought structure produces a relatively large grain size, typically in the range of ASTM 0 to 2, Figure 5.2.a. Any residual M_3B_2 borides not transformed to MB_2 borides during hot working are also transformed during the initial heat treatment. Residual MC-type carbides and MB_2 borides act to prevent excessive grain growth. A fine, uniform gamma prime forms upon air cooling from the solutioning temperature, Figure 5.2.b.

The second-stage heat treatment of 4 hours at 1080°C (1976°F) followed by air cooling precipitates and grows a relatively coarse gamma prime. Simultaneously, it precipitates both MC-type carbides and MB_2-type borides, primarily at the grain boundaries, Figure 5.2.b. This limits the formation of $M_{23}(C,B)_6$-type carbides in subsequent aging treatments. Following this cycle of the heat treatment, gamma prime and incipient melting reactions are distinct and are easily determined by DTA, Figure I-2. The gamma prime solvus and incipient melting temperatures are 1150°C (2102°F) and 1195°C (2183°F), respectively.

The third- and fourth-stage heat treatments of 24 hours at 845°C (1553°F) and 16 hours at 760°C (1400°F), respectively, are aging treatments. Very fine gamma prime precipitates within the grains and the grain boundary carbides are somewhat coarsened.

5.2 Cooling Rate Effects:

The effect of the cooling rate from the solution heat treatment temperature is important for the control of grain boundary morphology and resultant mechanical properties[3]. Improvements in both stress-rupture life and impact strength can be achieved by cooling at a rate between 30° and 85°C/min (54° to 153°F/min). This range of cooling rates allows the development of convoluted grain boundaries. Figure 5.5 shows a good grain boundary structure etched in high relief for

scanning electron microscopy. Thin carboboride networks decorate the convoluted grain boundary structure. This reduces grain boundary sliding and increases resistance to intergranular fracture.

5.3 Heat Treatments for High Strength: FG

The high strength (HS) heat treatments have been found to produce exceptional tensile strengths and ductilities resulting from a fine grain structure and a fine gamma prime morphology. This structure also accounts for a slight decrease in elevated temperature creep resistance.

For optimum high temperature strength, **UDIMET Alloy 720-HS** is given a partial solution heat treatment for 2 hours at 1105°C (2021°F) or 4 hours at 1115°C (2039°F) and oil quenched. During these cycles, the lower solvus temperature gamma prime (the finer intragranular particles in Figure 5.1.b) is solutioned and partially reprecipitated as a higher solvus temperature phase, while the very coarse gamma prime is not appreciably affected. The very coarse gamma prime prevents undesirable grain growth, Figures 5.3.b and 5.4.b. The oil quench restricts the precipitation of fine gamma prime during cooling. High-temperature carbide and boride reactions are similar to those already described during the heat treatment of **UDIMET Alloy 720-CR.**

For the HS1 heat treatment, during the 760°C (1400°F) aging cycle, $M_{23}(C,B)_6$ carbides and MB_2 borides are precipitated at the grain boundaries. Fine gamma prime also precipitates.

Heat treatment at 650°C (1202°F) ages the gamma prime. No noticeable precipitation of $M_{23}(C,B)_6$ carbides and MB_2 borides occurs.

For the HS2 heat treatment, the 650°C (1202°F) treatment prior to the 760°C (1400°F) treatment causes the precipitation of a maximum number of very fine gamma prime particles in the structure. This produces a high tensile strength.

Since gamma prime in **UDIMET Alloy 720** coarsens rapidly at temperatures above about 760°C (1400°F), long-time service is recommended to be restricted to that temperature.

6.0 MACHINING AND WELDING UDIMET ALLOY 720

6.1 Machining UDIMET Alloy 720:

UDIMET Alloy 720, like most high strength gamma prime strengthened superalloys, is easiest to machine in the solution-treated condition with a nominal hardness of Rockwell C 37 to 38. After machining close to final dimensions, the workpiece can be aged to a hardness range of Rockwell C 41 to 43; finish to critical dimensions by grinding or polishing.

Lathe machining requires tooling with high rigidity; carbide tooling with a negative rake angle, 50 to 15° lead angle, and a 0.157-cm (0.062-inch) cutting nose radius with a chip breaker has given the best results. Rough machining may be done at 12 to 18 surface meters (40 to 60 surface feet) per minute at feeds of 0.02 to 0.038 cm (0.009 to 0.015 inch) per revolution with depth of cut of 0.1 to 0.254 cm (0.040 to 0.1 inch) depending upon material size, machine size, tooling, horsepower, and rigidity. Finish machining may be done at 18 to 33 surface meters (60 to 110 surface feet) per minute at feeds of 0.01 to 0.02 cm (0.004 to 0.008 inch) per revolution with depth of cut of 0.002 to 0.1 cm (0.001 to 0.040 inch). Flood cool with water and a soluble coolant.

6.2 Welding UDIMET Alloy 720:

The relatively high gamma prime volume fraction of **UDIMET Alloy 720** and the rapid rate of gamma prime precipitation during solidification of the alloy make it prone to microcracking during welding and to cracking during the post-weld heat treatment. Some welding success has been achieved.[4] This requires a lengthy pre-weld heat treatment as well as a closely controlled welding cycle and post-weld heat treatment. The pre-weld heat treatment, in general, coarsens

the gamma prime and softens the matrix to accommodate thermal stresses in the heat affected zone (HAZ) during welding. The post-weld heat treatment relieves stresses in the HAZ prior to reheat treatment. Under the best conditions, some microcracking is generally unavoidable.

The above-mentioned welding behavior is experienced when **UDIMET Alloy 720** is used for both the base material and the filler material. Depending upon the application, different filler materials may be used which afford increased weldability at the expense of mechanical properties in the weld-affected zone.[5] One material which has been used successfully as filler material is **UDIMET Alloy 520.**

7.0 PHYSICAL PROPERTIES

7.1 Density:

The density of **UDIMET Alloy 720** is 8.08 kg/m^3 (0.292 lb/in^3).

7.2 Melting Range:

The melting range of **UDIMET Alloy 720,** that is, the temperature range from the major solidus to the liquidus, is 1194° to 1338°C (2180° to 2440°F) depending on thermomechanical history, as shown in Appendix II.

7.3 Thermal Expansion:

Thermal expansion data for **UDIMET Alloy 720-HS** is given in Table 7.3.

Table 7.3. Thermal Expansion of UDIMET Alloy 720-HS

Temperature		Thermal Expansion	
°C	(°F)	10^{-6} m/m/°C	10^{-6} (in/in/°F)
24	(76)		
93	(200)	12.24	(6.8)
454	(850)	13.81	(7.67)
538	(1000)	14.18	(7.88)
621	(1150)	14.27	(7.93)
649	(1200)	14.60	(8.11)
704	(1300)	14.99	(8.33)
760	(1400)	15.21	(8.45)
982	(1800)	16.92	(9.4)

7.4 **Modulus of Elasticity:**

The Modulus of Elasticity of **UDIMET Alloy 720-HS**, for temperatures from 24°C (76°F) to 760°C (1400°F) is given in Table 7.4.

Table 7.4. Modulus of Elasticity [Young's Modulus (E)]

Temperature		E	
°C	(°F)	MPa X 10^{-3}	psi X 10^{6}
24	(76)	227	(33.00)
93	(200)	197	(28.63)
454	(850)	192	(27.84)
538	(1000)	188	(27.3)
621	(1150)	183	(26.6)
649	(1200)	177	(25.6)
704	(1300)	168	(24.3)
760	(1400)		

8.0 MECHANICAL PROPERTIES

8.1 **Creep and Stress Rupture:**

Typical **UDIMET Alloy 720-CR** creep properties and the projected rupture life are given in the Larson-Miller Parameter Graph, Figure 8.1.

Figure 8.2 shows 0.2% creep and the stress rupture properties of **UDIMET Alloy 720** with the HS2 heat treatment.

8.2 Tensile Properties:

Tensile properties of **UDIMET Alloy 720-CR** and **UDIMET Alloy 720-HS** are given in Figures 8.3 and 8.4, respectively. Figure 8.5 compares the ultimate strengths of the -CR and -HS heat treat conditions. Above 871°C (1600°F), **UDIMET 720-CR** is stronger than **UDIMET 720-HS** due to the coarser grain size of the -CR material.

The tensile strength of **UDIMET Alloy 720** is compared to that of Waspaloy® and Inconel® Alloy 718 in Figure 8.6. With the HS heat treatment, **UDIMET Alloy 720** is stronger than other alloys through 760°C (1400°F). **UDIMET Alloy 720-CR** is substantially stronger than Waspaloy through 980°C (1796°F).

8.3 Impact Properties:

Typical 900° (1652°F) charpy V-notch impact properties of **UDIMET Alloy 720-CR** and **UDIMET Alloy 720-HS** are given in Table 8.3.

Table 8.3. Charpy V-Notch Properties at 900°C (1652°F)

Heat Treatment	Impact kg-m	Strength ft-lbs
CR	1.24	9.0
HS2	1.66	12.0

8.4 Fatigue Properties:

Fatigue properties of **UDIMET Alloy 720** are presented in Figures 8.7 through 8.11. These are typical properties generated over a wide

---

®Waspaloy is a registered trademark of United Technologies
®Inconel is a registered trademark of International Nickel

range of test conditions. Figures 8.7 and 8.8 represent typical plots of load-controlled low cycle fatigue (LCF) test data run on **UDIMET Alloy 720-HS** given the HS2 heat treatment. Figure 8.7 presents data acquired at a temperature of 540°C (1004°F) with a stress ratio, R, of 0.0 (R is defined as the ratio of minimum stress to maximum stress) and a frequency (F) of 20 cycles per minute (0.33 Hz), from a notched test bar with a stress concentration factor, K_t, of 3. The log of the stress range, or maximum stress, is plotted on the Y-axis, and the log of the number of cycles required to initiate a crack is plotted on the X-axis. Figure 8.8 presents data obtained from a smooth bar sample (K_t = 0) at 620°C (1148°F) with R and F equal to 0.0 and 0.33 Hz, respectively. The log of the number of cycles to failure is plotted on the X-axis.

Figures 8.9 through 8.11 represent typical strain-controlled LCF data for samples given the HS2 heat treatment. Figures 8.9 and 8.10 represent tests run at 540°C (1004°F), F = 20 cpm and K_t = 1. The strain ratio, R, is -1 and 0 for Figures 8.9 and 8.10, respectively. Figure 8.11 presents data from tests run at both 540°C (1004°F) and 705°C (1301°F) with R = -1, K_t = 0, and F = 20 cpm (0.33 Hz).

8.5 Crack Growth Rate:

Typical crack growth rate data for **UDIMET Alloy 720-HS** is presented in Figure 8.12. This data was acquired from material given the HS2 heat treatment and tested at 650°C (1202°F) with a stress ratio, R, of 0.05. The log of the crack growth rate, da/dn, is plotted on the Y-axis, and the log of the alternating crack tip stress intensity, ΔK, is plotted on the X-axis.

ENDNOTES

1. C. T. Sims et al, Superalloys II, John Wiley and Sons, New York, 1987, p.233.

2. F. E. Sczerzenie and G. E. Maurer, "Development of UDIMET 720 for High Strength Disk Applications," in Superalloys 1984, ed. J. K. Tien, et al, TMS-AIME, Warrendale, PA, 1984, pp.573-582.

3. G. J. Stelma, et al, "The Effect of Cooling Rate on Udimet 720," TR-82-002, Special Metals Corporation, New Hartford, NY, 1982.

4. P. W. Keefe, "Titanium Hot Die Forging Alloy," [Classified, Class III Report], TR-86-006, Special Metals Corporation, New Hartford, NY, 1986.

5. M. Prager and C. S. Shira, "Welding of Precipitation Hardening Nickel-Base Alloys," Welding Research Council Bulletin No. 128, New York, February 1968.

ADDITIONAL REFERENCES

Allen, J. M. and Whitlow, B. A., "Observations on the Interaction of High-Mean Stress and Type II Hot Corrosion on the Fatigue Behavior of a Nickel-Base Superalloy," Journal of Engineering Gas Turbines Power (Trans. AIME), **107**, (1), 1985, pp.220-224.

Barrett, C. A., "The Effect of Variations of Cobalt Content on the Cyclic Oxidation Resistance of Selected Nickel-Base Superalloys," pp.211-231 in Alternate Alloying for Environmental Resistance, AIME, Warrendale, Pennsylvania, 1987.

Boesch, W. J., "Nickel Base Alloy," U.S. Patent 4,093,476, June 6, 1978.

Bratton, R. J. et al, "Evaluation of Present-Day Thermal Barrier Coatings for Industrial/Utility Applications," Thin Solid Films, **73**, (2), 1980, pp. 429-437.

Burke, M. A. et al, "The Effect of Boron and Carbon on the Microstructural Chemistries of Two Wrought Nickel-Base Superalloys," Scripta Metallurgica, **18**, (1), 1984, pp.91-94.

Castillo, R., "Remaining Creep Life Prediction of Service-Exposed Nickel-Base Superalloys," pp.261-281 in Nickel Metallurgy, Vol. II: Industrial Applications of Nickel, The Canadian Institute of Mining and Metallurgy, Montreal, Quebec, 1986.

Jacobi, C. and Schreider, K., "Gas Turbine Blades in Construction, Manufacture and Practical Application," Tech. Mitt., **75**, (8), 1982, pp.406-411.

Kaufman, M. J. et al, "The Use of Convergent-Beam Electron Diffraction to Determine Local Lattice Distortions in Nickel-Base Superalloys," Philosophical Magazine A, **54**, (1), 1986, pp.79-92.

Lau, S. K., and Bratton, R. J., "Degradation Mechanisms of Ceramic Thermal Barrier Coatings in Corrosive Environments," pp.305-317 in High-Temperature Protective Coatings, TMS/AIME, Warrendale, PA, 1982.

Porter, A. and Ralph, B., "The Recrystallization of Nickel-Base Superalloys," Journal of Materials Science, **16**, (3), 1981, pp.707-713.

Porter, A. and Ralph, B., "Recrystallization Mechanisms in Wrought Nickel-Base Superalloys," pp.147-152 in Recrystallization and Grain Growth of Multi-Phase and Particle-Containing Materials, Riso National Laboratory, Roskilde, Denmark, 1980.

Ricks, R. A. et al, "The Growth of Gamma Prime Precipitates in Nickel-Base Superalloys," Acta Metallurgica, **31**, (1), 1983, 43-53.

Tsuji, I. et al, "Mechanical Properties and Microstructures in UDIMET 720 After Long-Term, High-Temperature Heating," Transactions of the Iron and Steel Institute of Japan, **24**, (10), 1984, p.B356.

Warmuth, F. J. and Sczerzenie, F. E., "Optimum Homogenization for UDIMET 720 VAR Ingots," [Classified, Class III Report], TR-86-001, Special Metals Corporation, New Hartford, NY, 1986.

Whitlow, G. A. et al, "Intermediate Temperature, Low-Cycle Fatigue Behavior of Coated and Uncoated Nickel-Base Superalloys in Air and Corrosive Sulfate Environments," pp.269-276 in Advances in Life Prediction Methods, American Society of Mechanical Engineers, New York, NY, 1983.

Whitlow, G. A. et al, "Effects of Frequency on the Corrosion Fatigue of UDIMET 720 in a Molten Sulfate Salt," pp.321-331 in Ultrasonic Fatigue, TMS/AIME, 1982.

Whitlow, G. A. et al, "The Effects of a Liquid Sulfate/Chloride Environment on Superalloy Stress Rupture Properties at 704°C," Metallurgical Transactions A, **15A**, (1), 1984, pp.23-28.

Figure 4.1. UDIMET ALLOY 720 HOT WORKABILITY

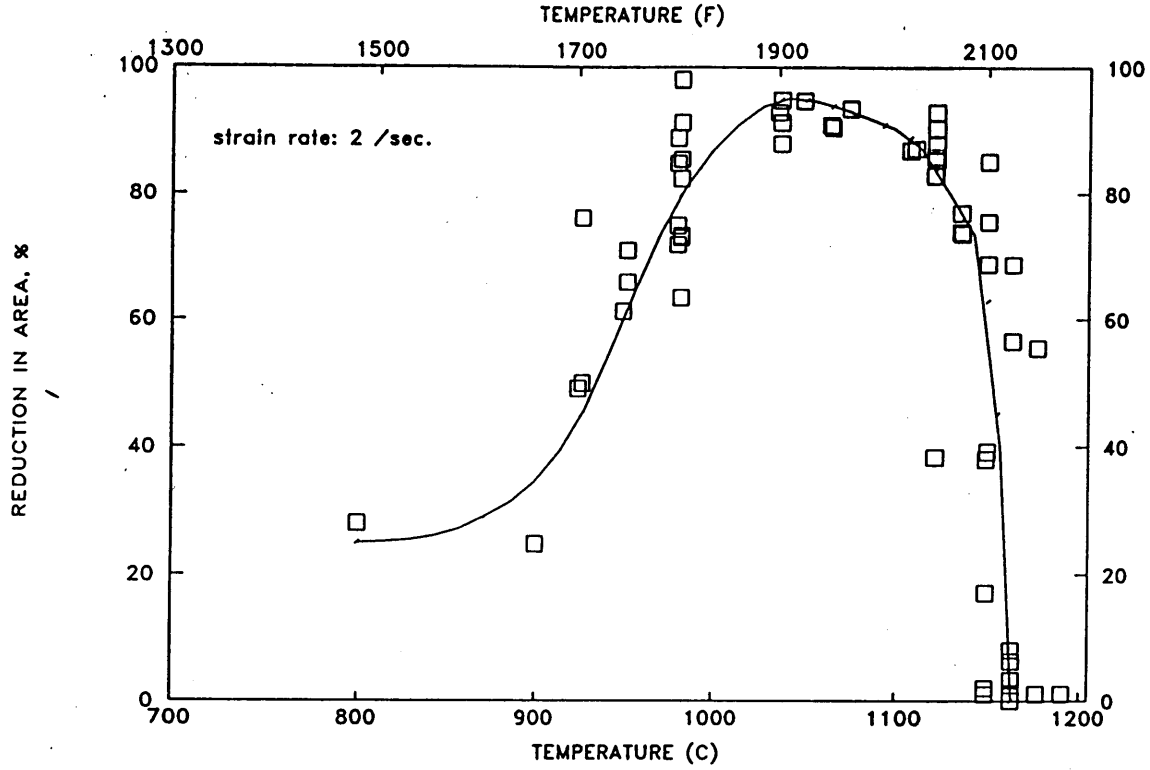


Figure 4.2. UDIMET ALLOY 720 HOT WORKABILITY

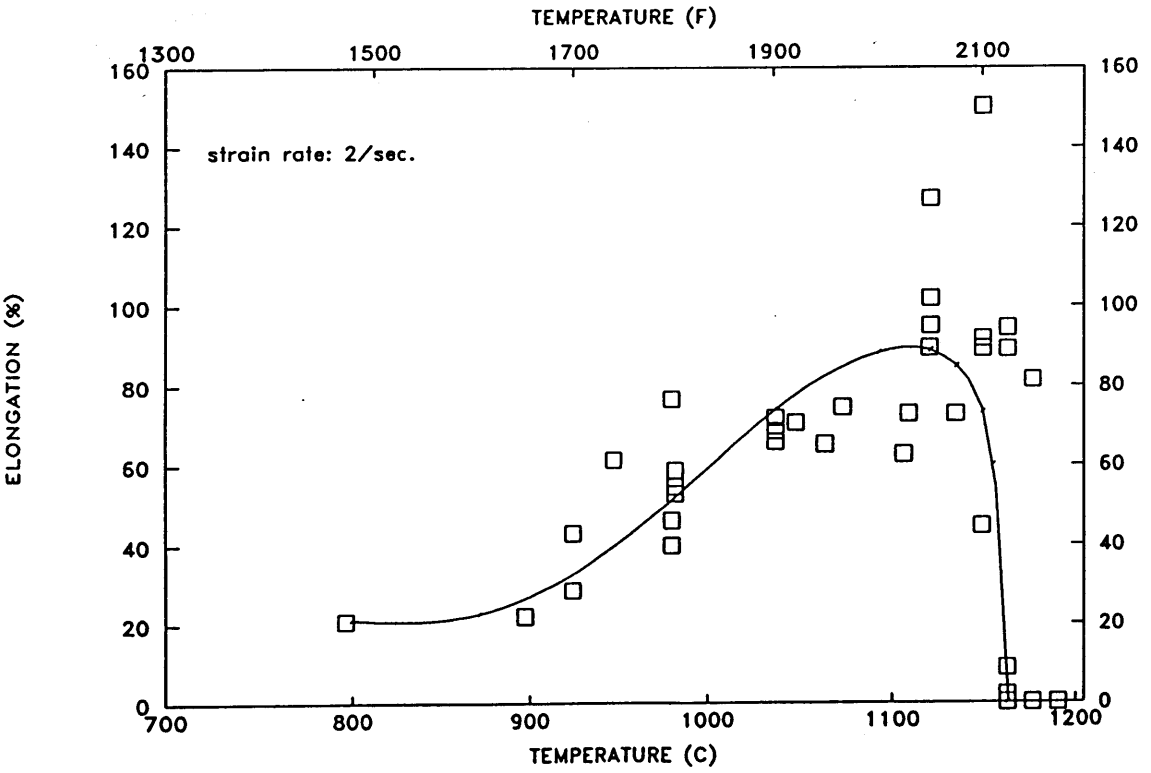


Figure 4.3. UDIMET ALLOY 720 HOT WORKABILITY

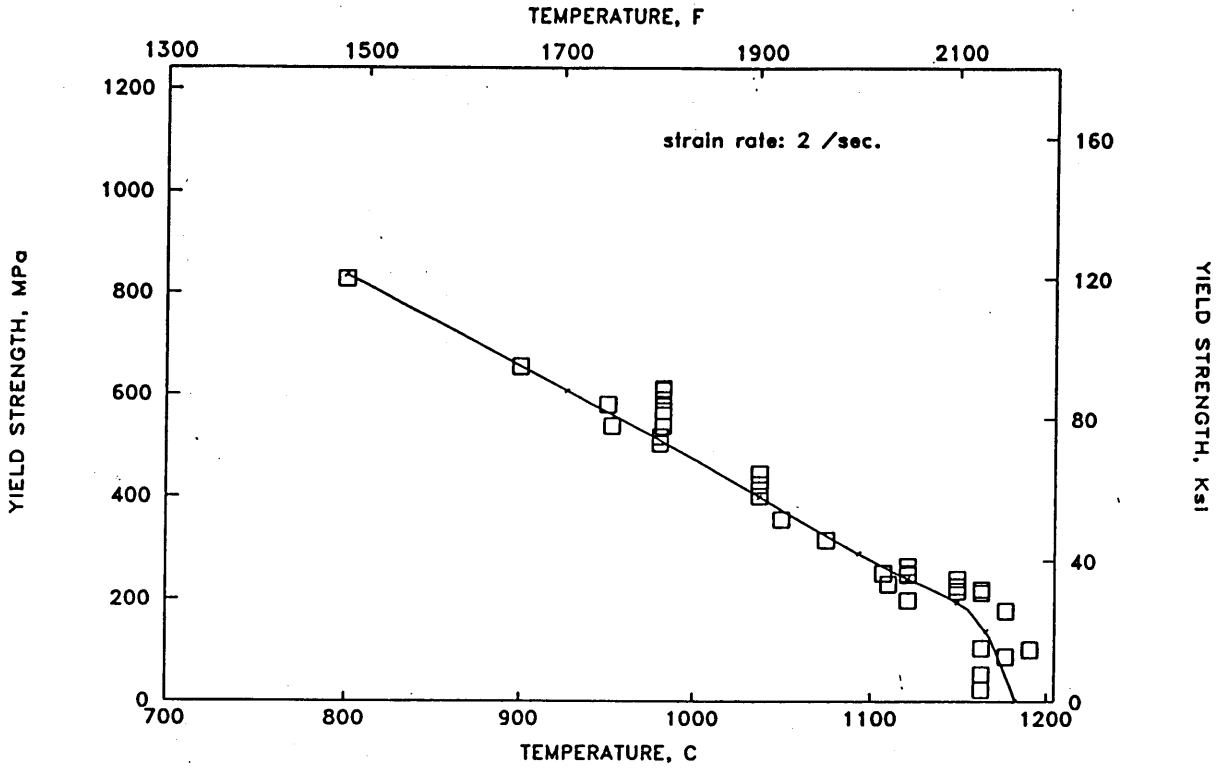
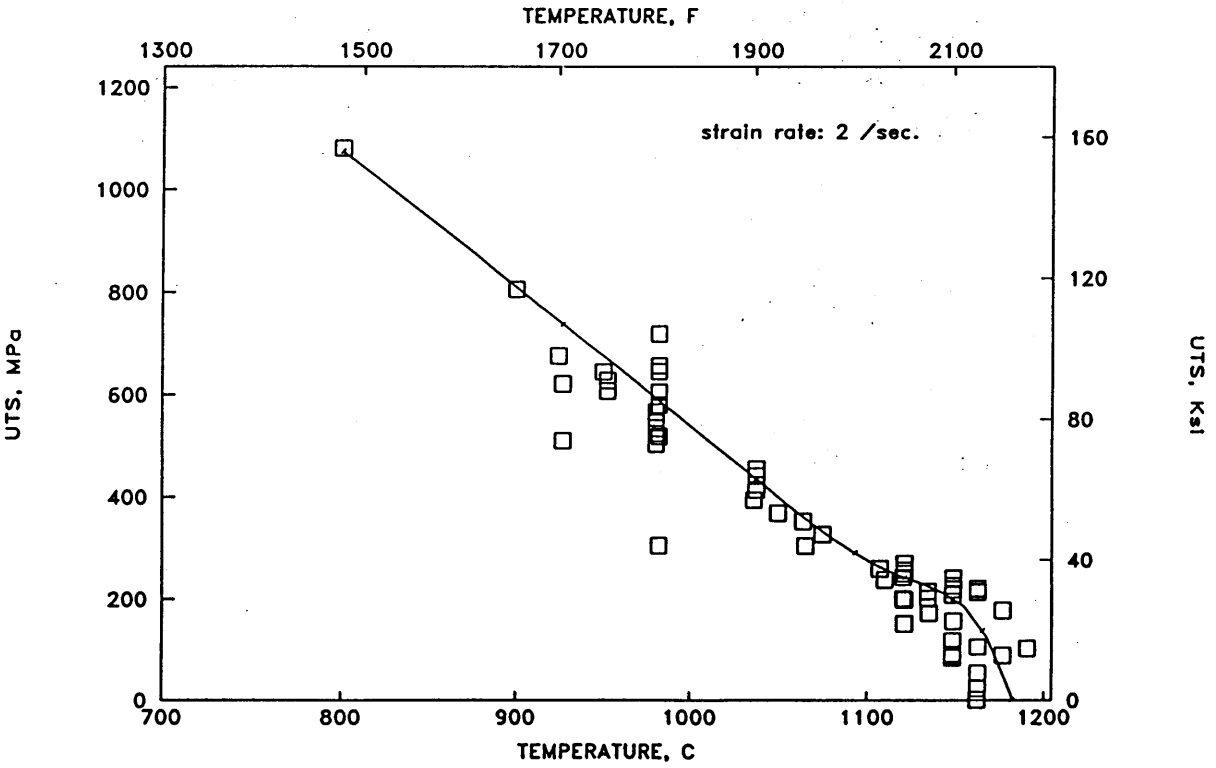


Figure 4.4. UDIMET ALLOY 720 HOT WORKABILITY



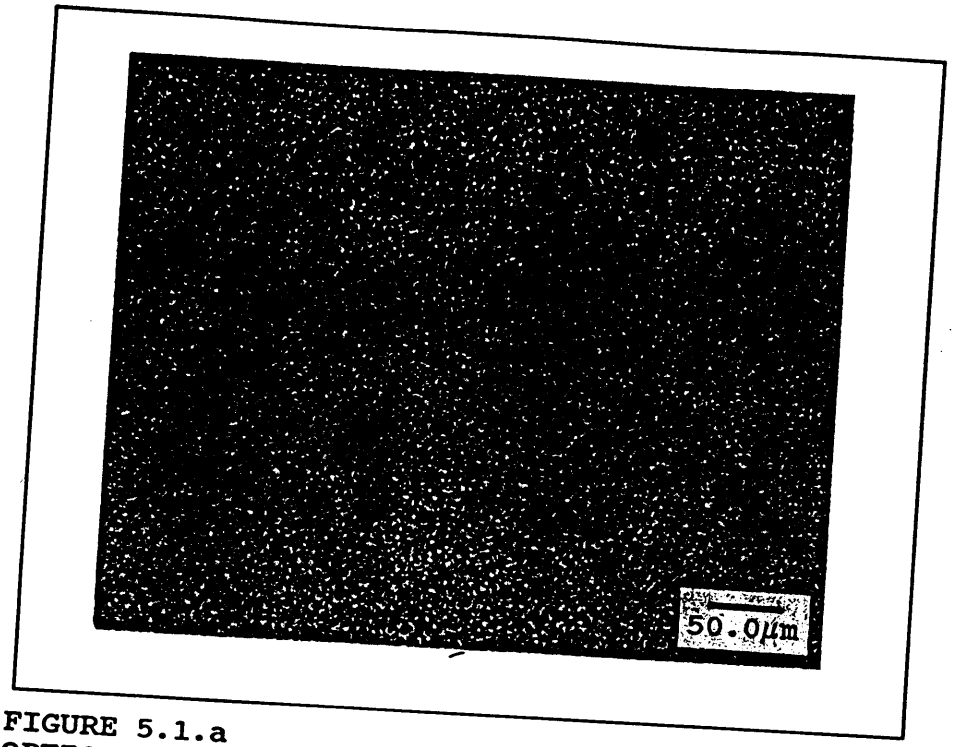


FIGURE 5.1.a
OPTICAL

AS ROLLED
ETCHANT "C"

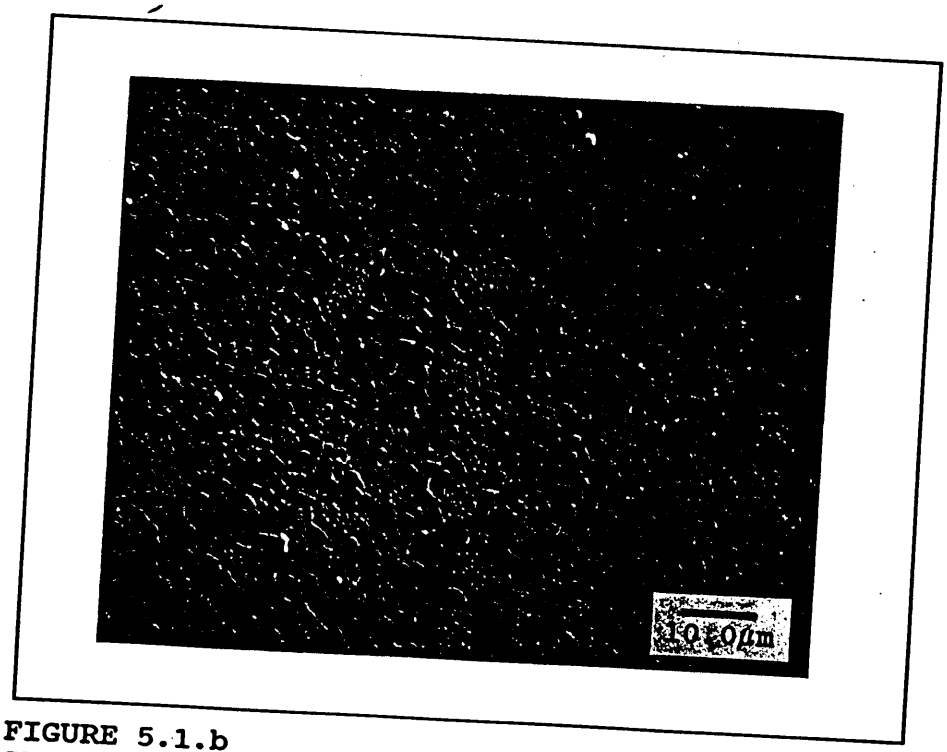


FIGURE 5.1.b
SEM

AS ROLLED
ETCHANT "A"

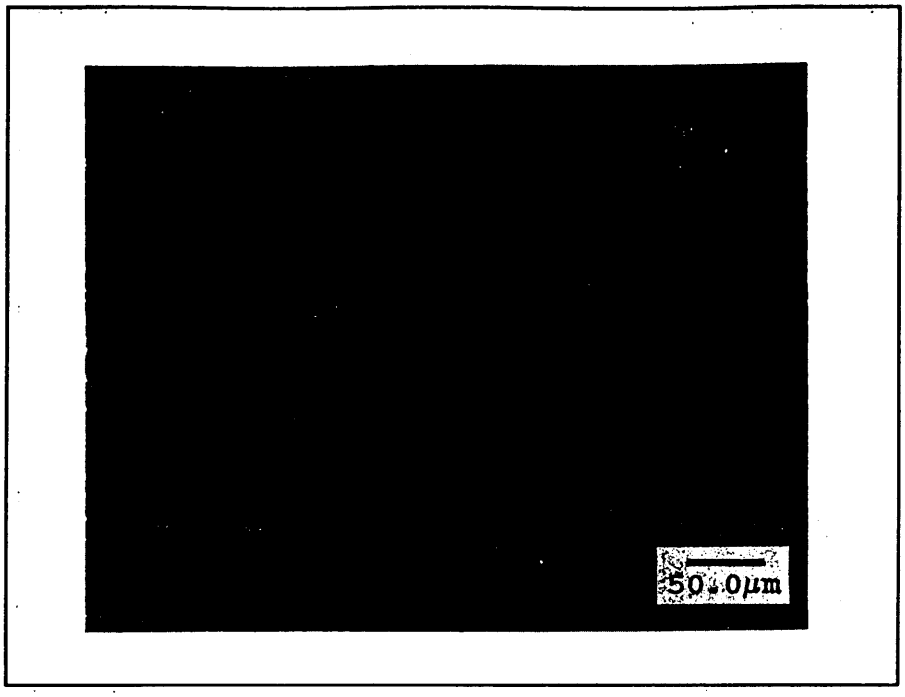


FIGURE 5.2.a CR HEAT TREATMENT
OPTICAL ETCHANT "C"

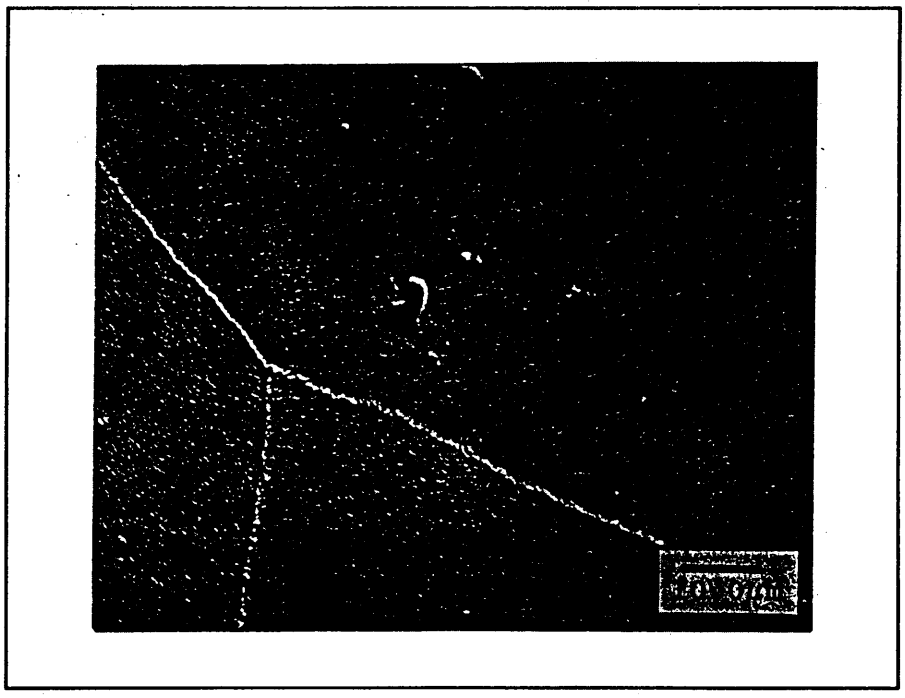


FIGURE 5.2.b CR HEAT TREATMENT
SEM ETCHANT "A"

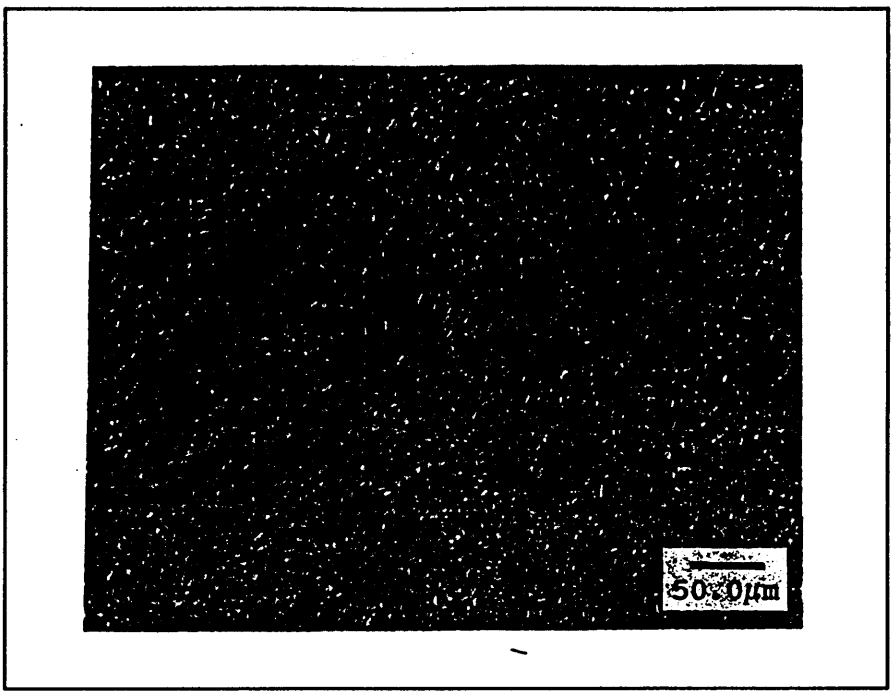


FIGURE 5.3.a HS1 HEAT TREATMENT
OPTICAL ETCHANT "C"

FIGURE 5.3.b HS1 HEAT TREATMENT
SEM ETCHANT "A"

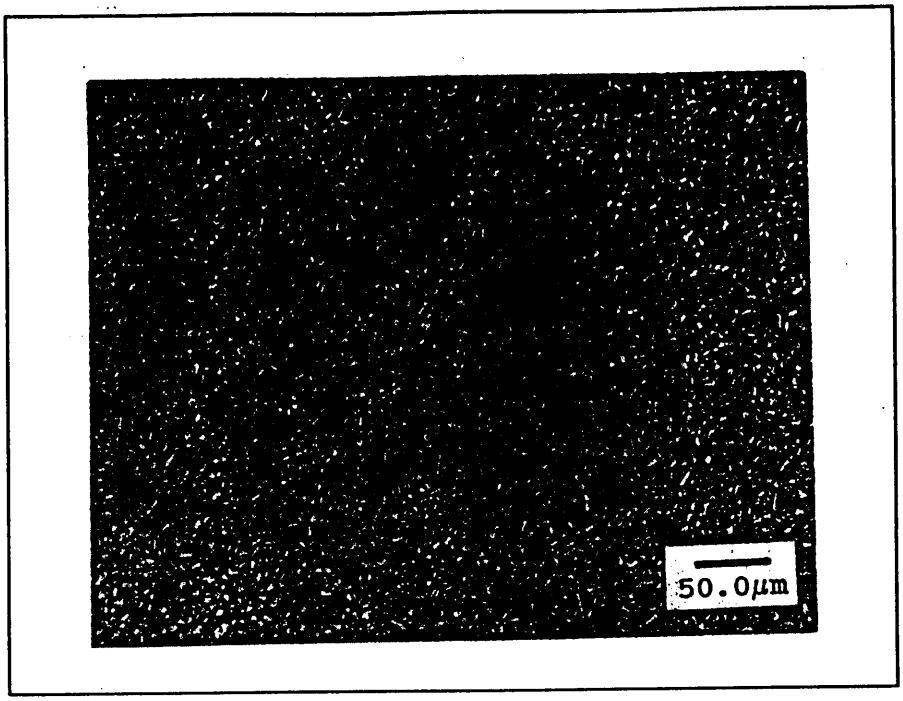


FIGURE 5.4.a
OPTICAL

HS2 HEAT TREATMENT
ETCHANT "C"

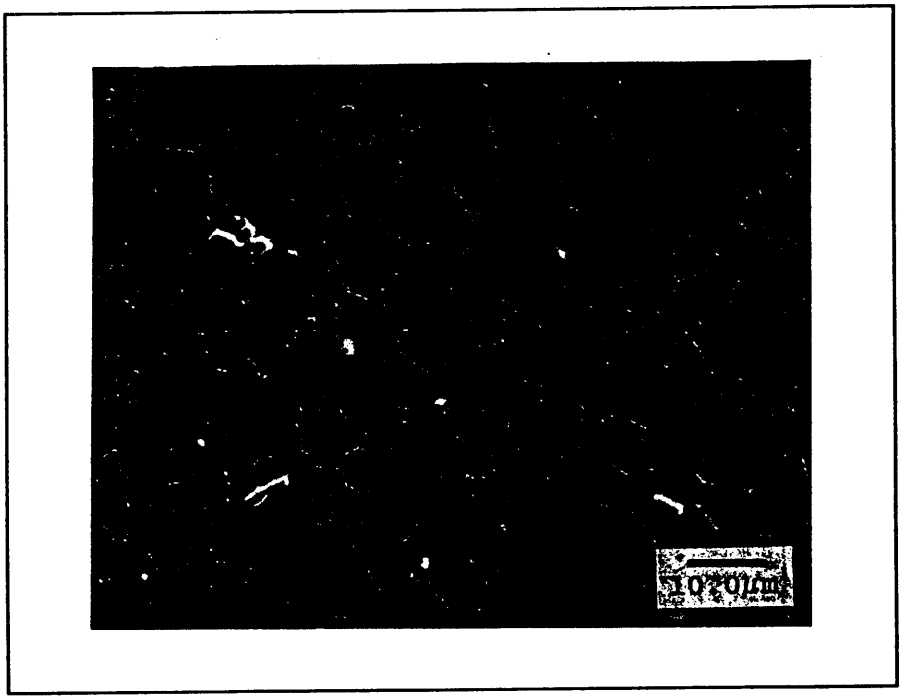


FIGURE 5.4.b
SEM

HS2 HEAT TREATMENT
ETCHANT "A"

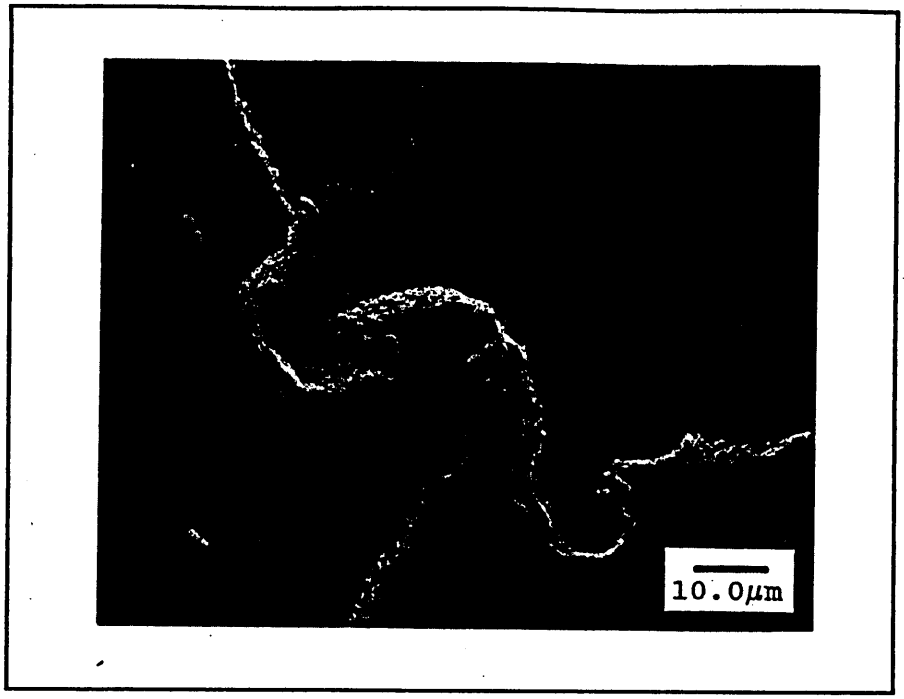


FIGURE 5.5 SLOW COOLING 100°C/min. (180°F/MIN.)
SEM ETCHANT "B"

Figure 8.1 - UDIMET Alloy 720 CR Creep Rupture Properties

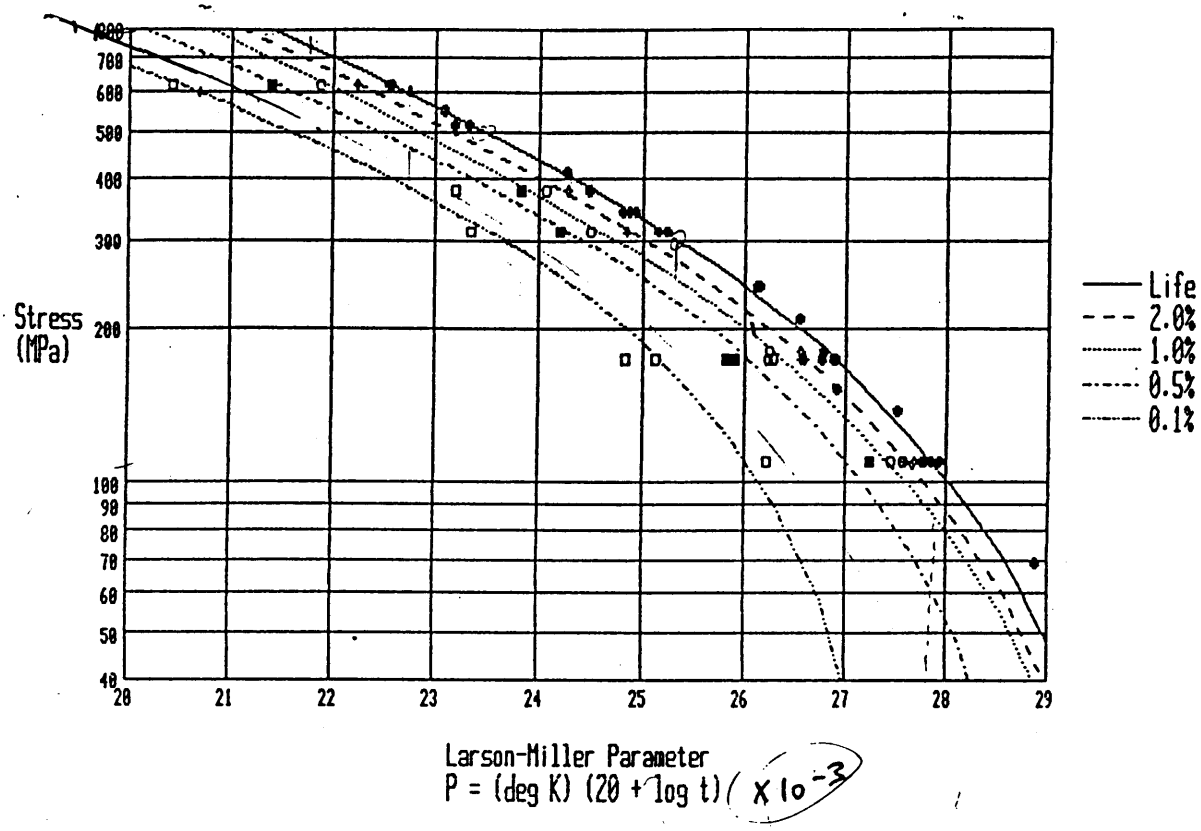


Figure 8.2 - UDIMET Alloy 720 HS Creep Rupture Properties

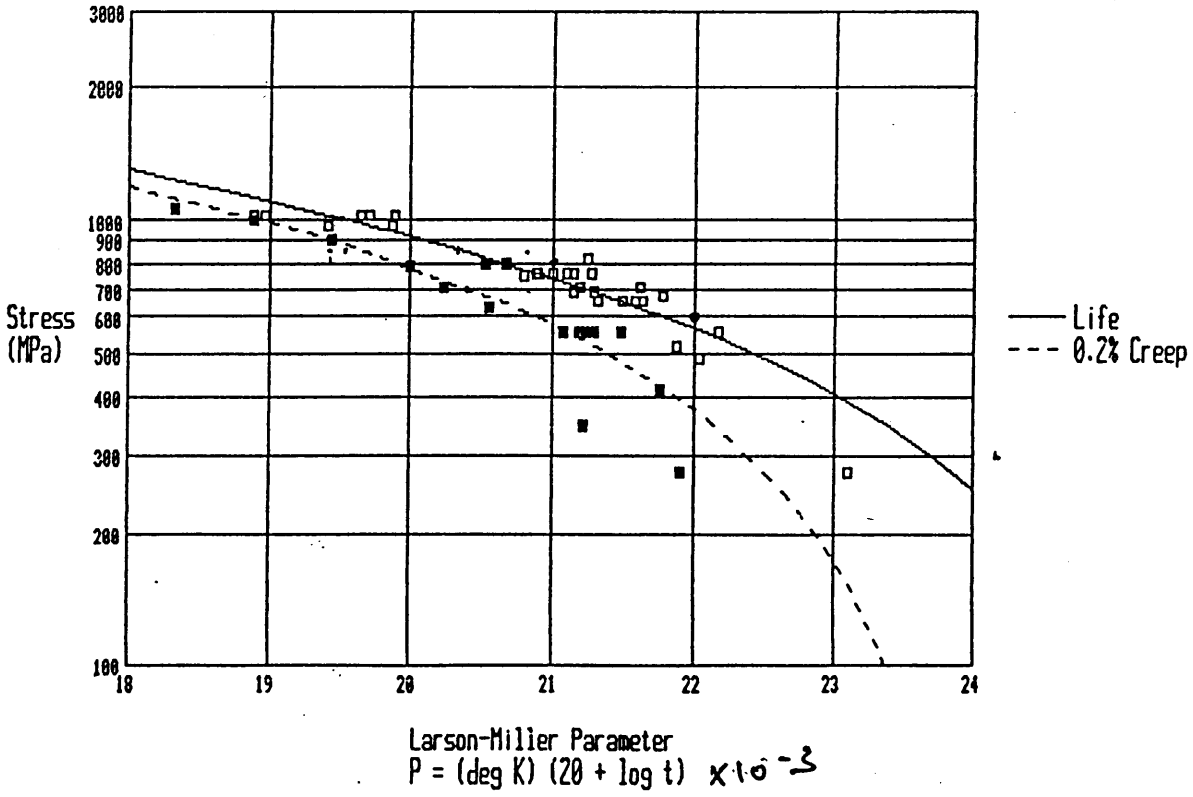


Figure 8.3 - UDIMET Alloy 720 CR Tensile Properties

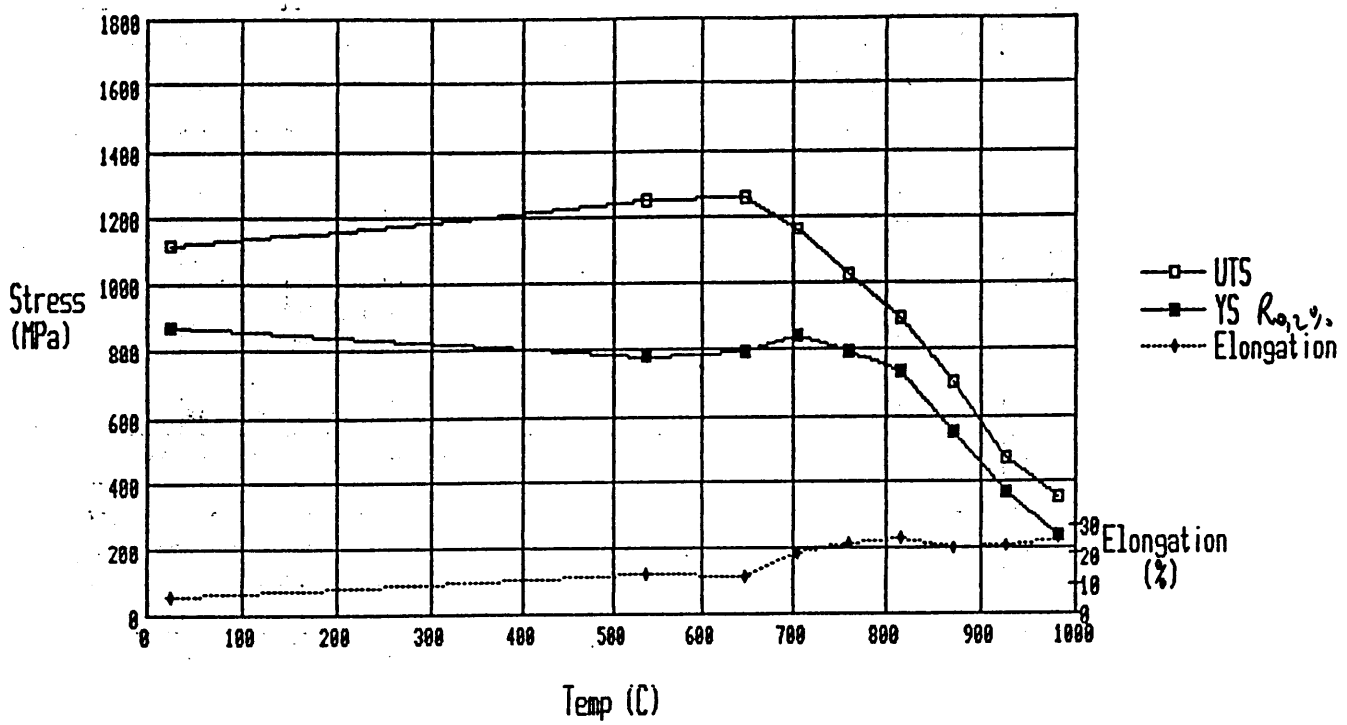
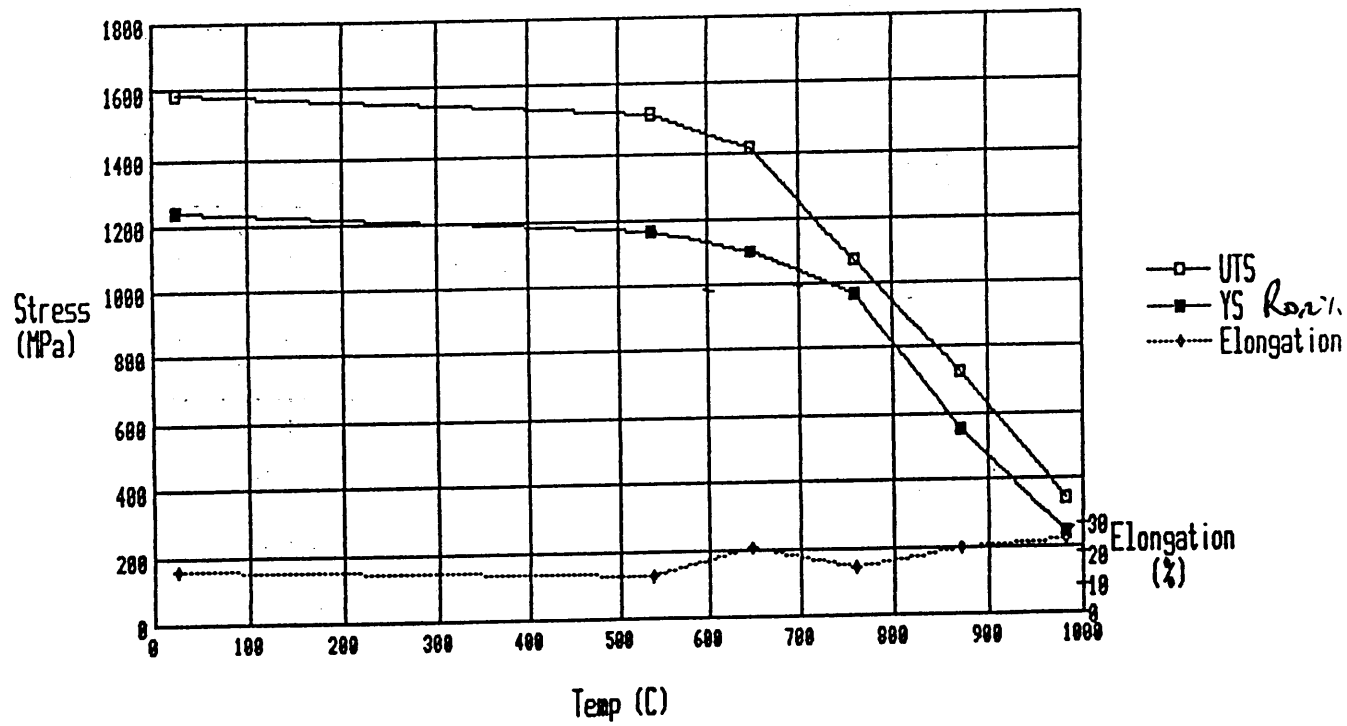


Figure 8.4 - UDIMET Alloy 720 HS Tensile Properties



[redacted]

Figure 8.5 - Comparison of Ultimate Tensile Strength for creep resistant and high strength UDIMET Alloy 720

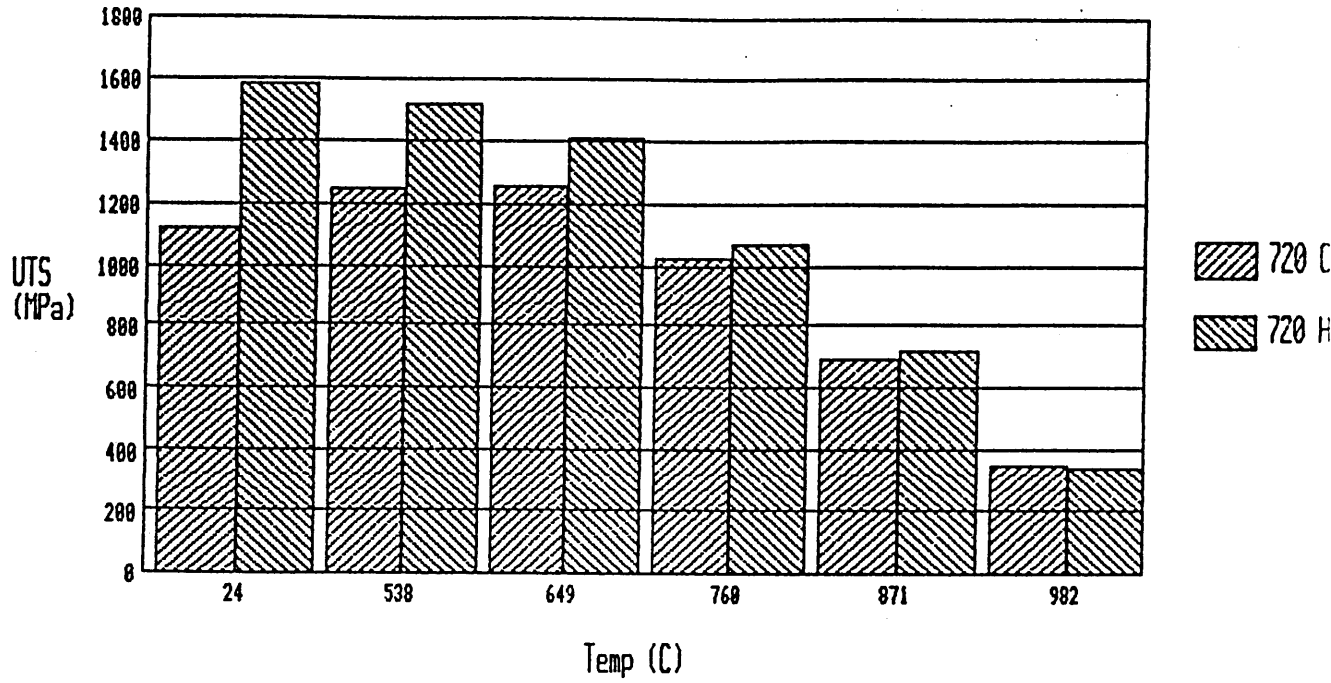


Figure 8.6 - Comparison of Ultimate Tensile Strength for UDIMET Alloy 720 and other wrought superalloys

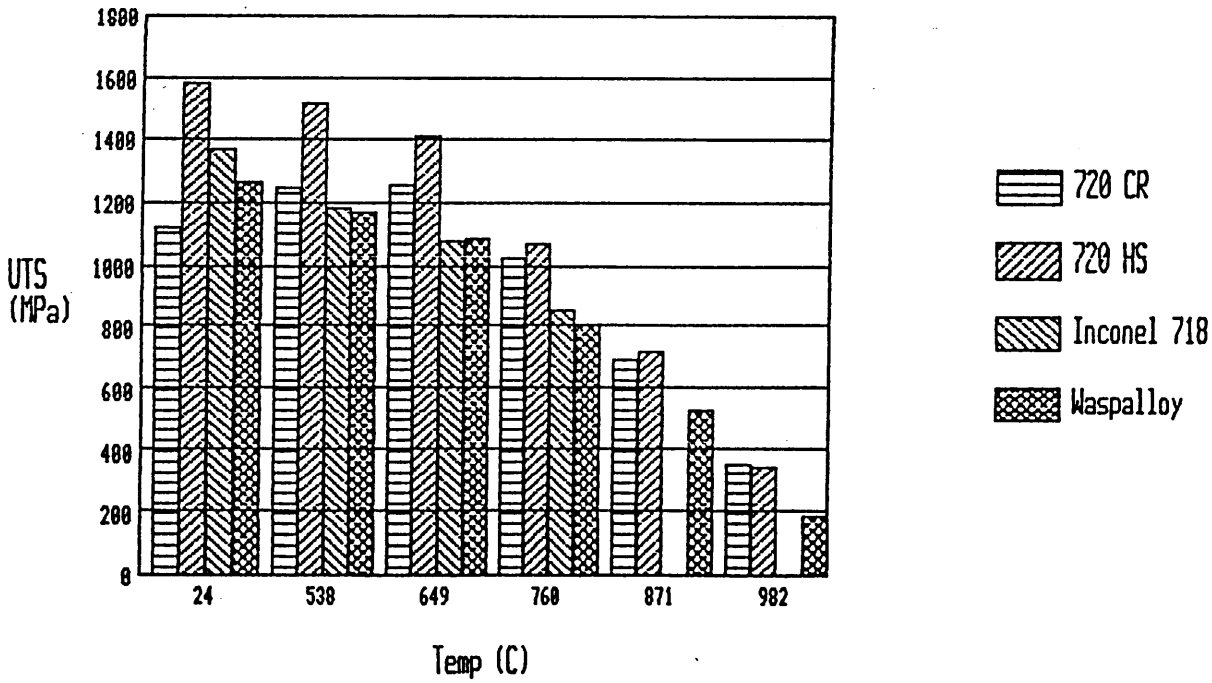


Figure 8.7 - Load Controlled LCF
540 deg C, R=0.0, F=0.33 Hz, Kt=3, HS2

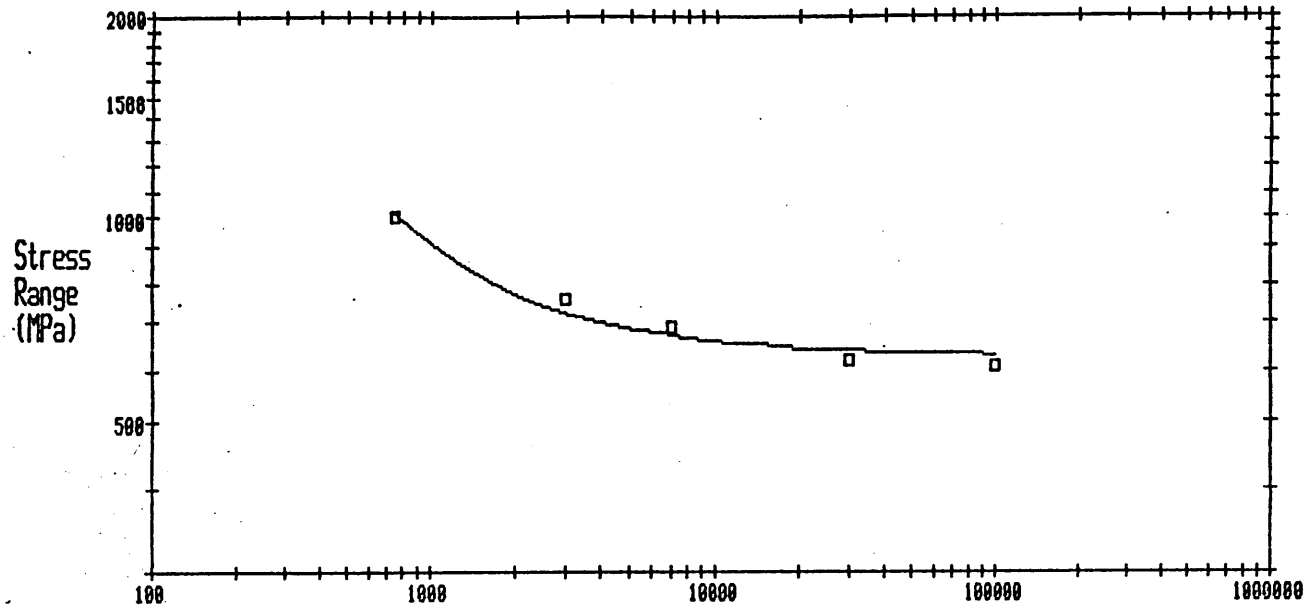


Figure 8.8 - Load Controlled LCF
620 deg C, R=0.0, F=0.33 Hz, HS2 (Kt = 0)

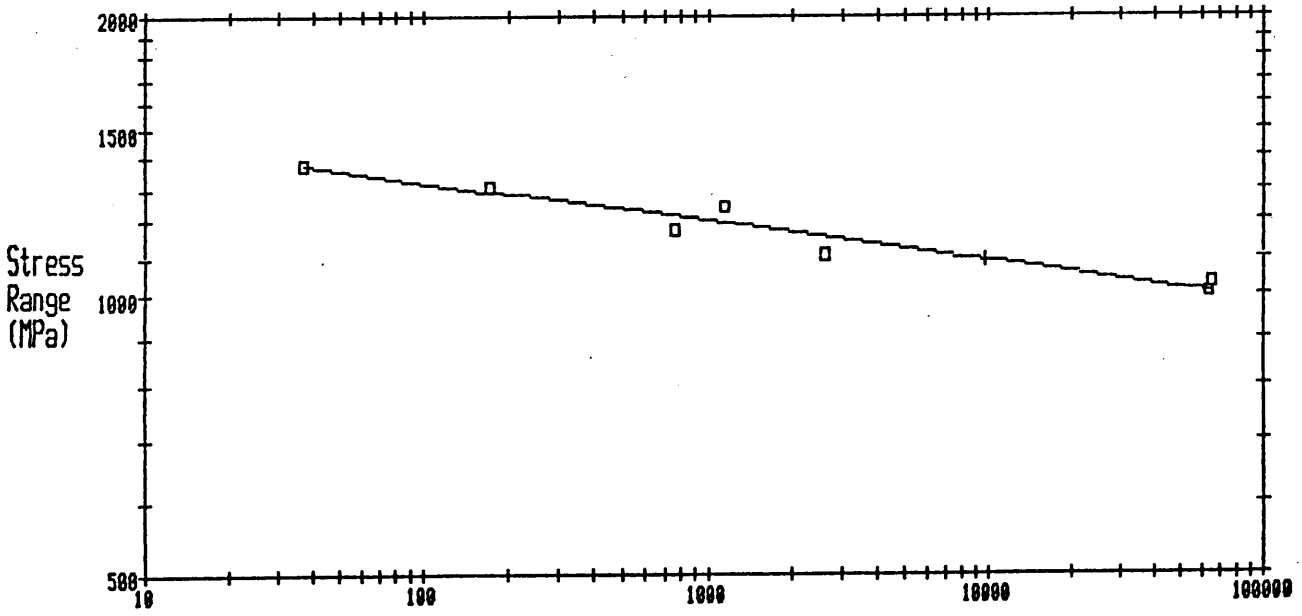


Figure 8.9 - Strain Controlled LCF
540 deg C, R=-1.0, F=0.33 Hz, Kt=1, HS2

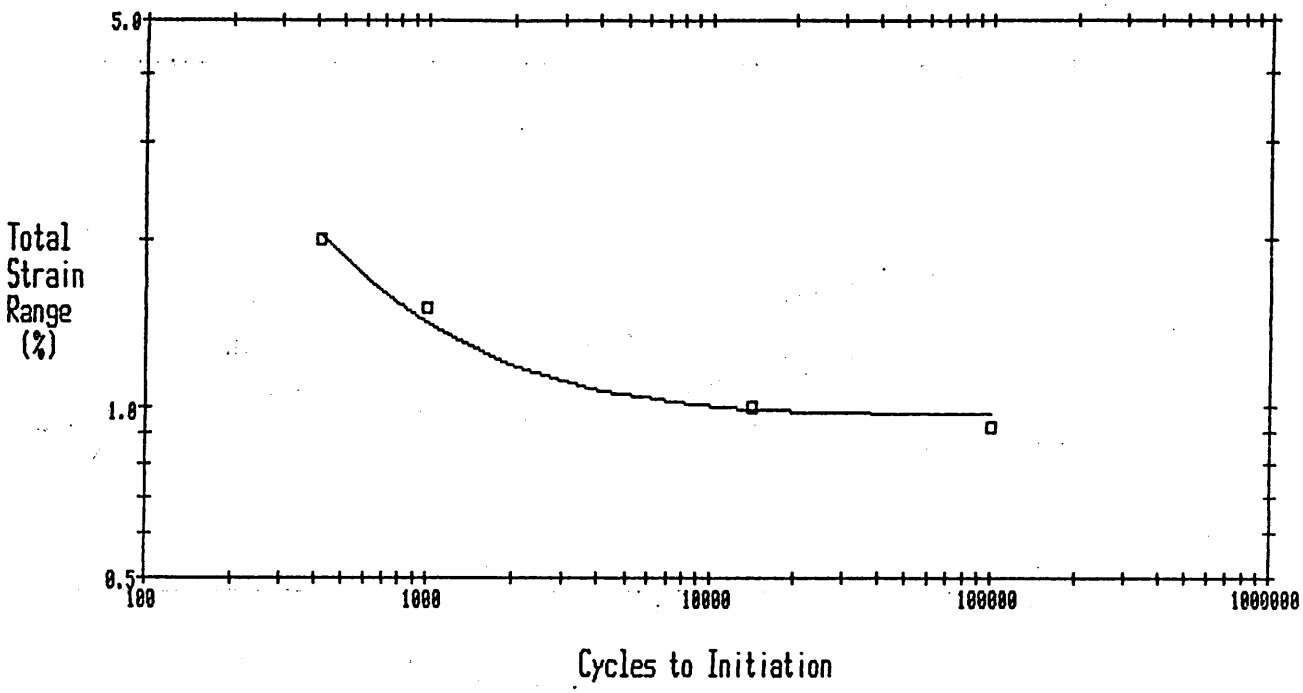


Figure 8.10 - Strain Controlled LCF
540 deg C, R=0.0, F=0.33 Hz, Kt=1, HS2

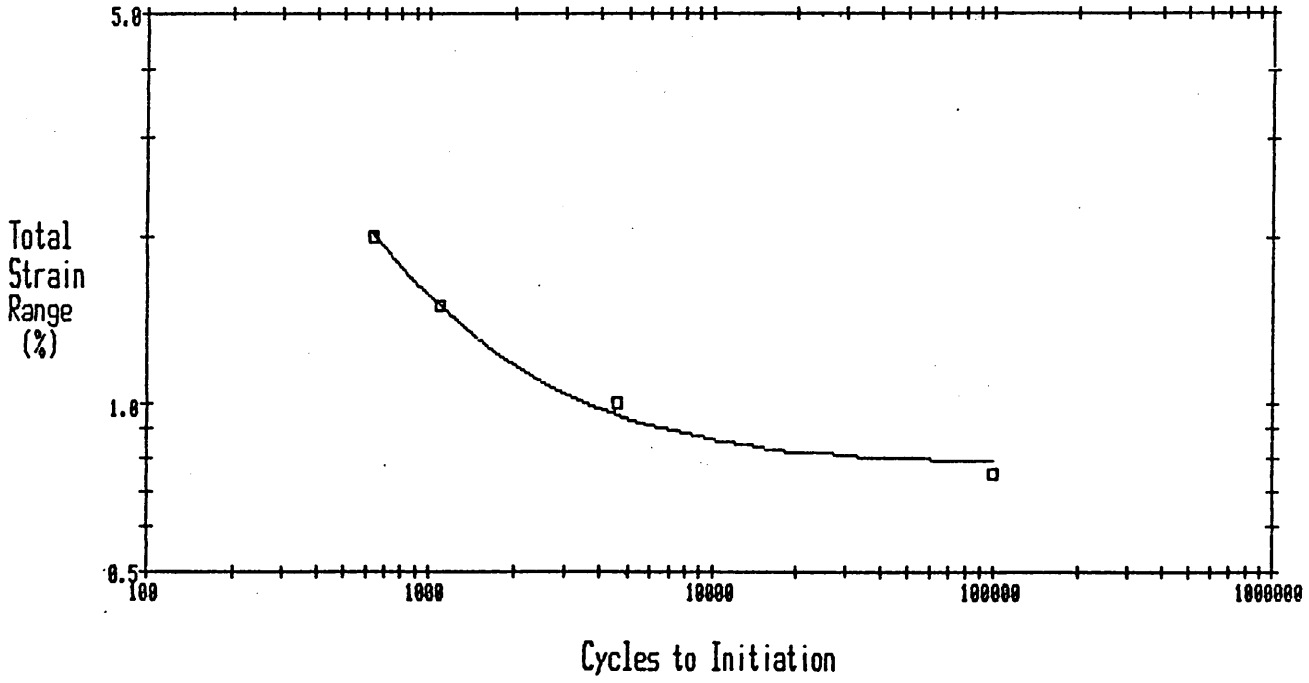


Figure 8.11 - Strain Controlled LCF
R=-1.0, F=0.33 Hz, Kt=0, HS2

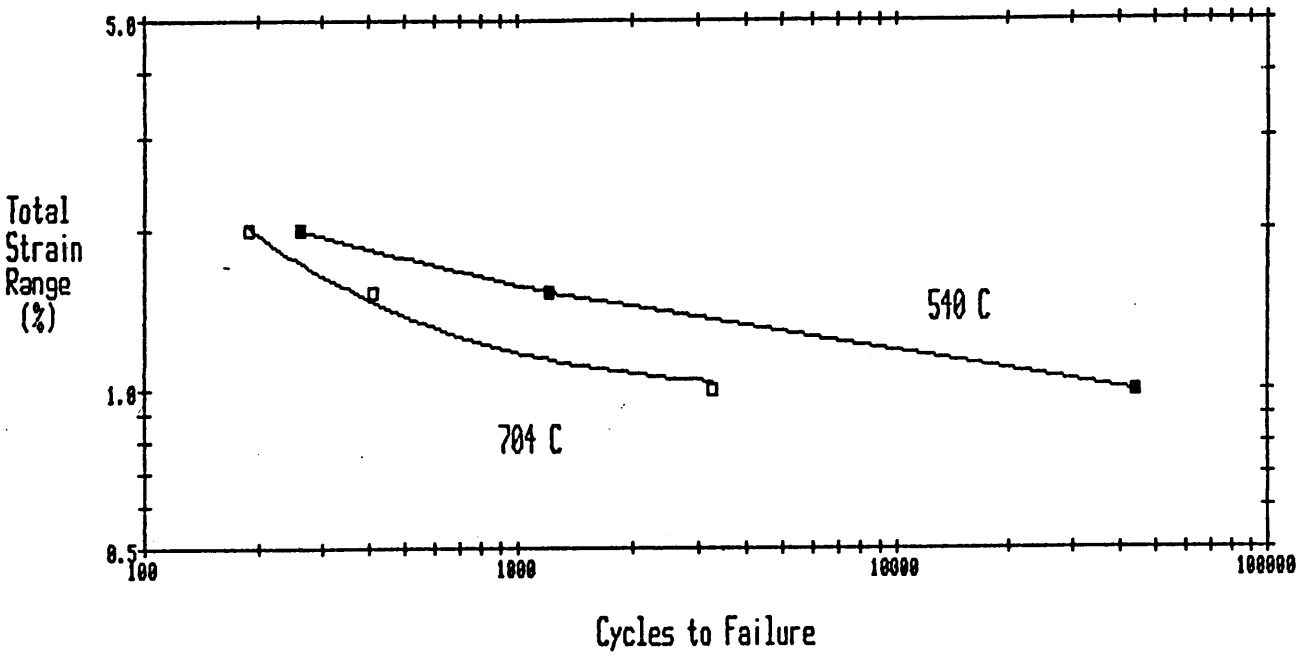
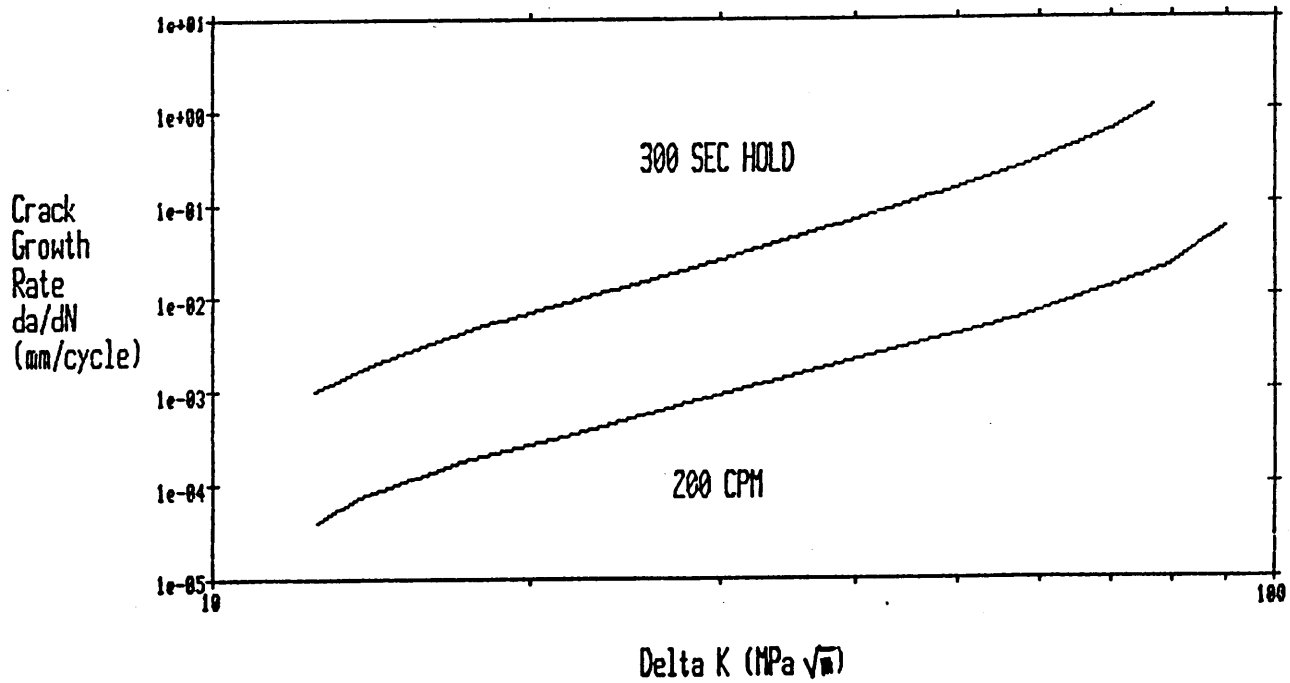


Figure 8.12 - Fatigue Crack Growth Rate of UDIMET Alloy 720
650 deg C, R=0.05



APPENDIX I

METALLOGRAPHIC PREPARATION OF UDIMET ALLOY 720

There are three major procedures used for the metallography of **UDIMET Alloy 720** at Special Metals Corporation. Each procedure has advantages and disadvantages for revealing microstructures of the alloy depending upon the thermomechanical history of the material and the type of metallography being used (optical or scanning electron microscopy). No one etch is effective in revealing all the microstructural features found in the various heat treat conditions. The following information was compiled to determine the best choice of procedure for each metallographic examination.

Some of the procedures described below are electrolytic immersion methods. These procedures employ the use of a stainless steel beaker (250ml) as the cathode and a pair of stainless steel laboratory tongs to hold the specimen, which is the anode. The electrolyte is poured into the beaker and the specimen is immersed in the solution by means of the tongs. The negative lead from a DC power supply is connected to the beaker and the positive lead is connected to the tongs. Particular care should be taken with this apparatus, as contact of the specimen or the tongs with the beaker may cause a spark, igniting the alcohol in the electrolyte. Persons using these etches must be thoroughly familiar with superalloy metallography and safe handling of the chemicals and equipment described below, as well as the proper procedures for mixing and disposing of these chemicals.[1]

Review of the ASTM Procedure E407-70, "Standard Methods for Microetching Metals and Alloys," is advised before attempting any of these procedures.

---

[1] ASTM, Metals - Mechanical Testing; Elevated and Low-Temperature Tests; Metallography, Volume 3.01 of Annual Book of ASTM Standards, ASTM, Philadelphia, 1987.

ETCHANT "A"

This etch procedure is a modified transmission electron microscope etch for producing extraction replicas. It is used here to reveal the gamma prime morphology. Because it etches the gamma prime in relief, it is an excellent etch for delineating the gamma prime at the grain boundary where normal "etch-out" structures from other etchants exhibit confusing images. Envelopment of grain boundaries, carbides and borides by gamma prime is revealed to show close contact of the adjoining phases. The procedure is actually three steps: electropolish, electroetch, and final rinse.

1.	Specimen size:	1-10 cm^3
2.	Metallographically prepare to 600 grit finish with SiC papers.	
3.	Electropolish	Electrolytic immersion
	Cathode:	Stainless steel beaker
	Electrolyte:	20% H_2SO_4 in Methanol 200ml H_2SO_4 Reagent Grade 800ml Absolute Methanol Add acid to alcohol slowly (10ml/min.) with continuous stirring. Store in glass or plastic container.
	Voltage:	15V
	Current Density:	0.6 - 1.2 A/cm^2 (Solution should be room temperature or cooler. Warming of the solution will cause current density to increase, resulting in pitting of the specimen.)
	Time:	1 min.
	Agitation:	Gentle
	Rinse:	Hot running water; dry with compressed air.

4. Electroetch

Cathode:	Stainless steel beaker
Electrolyte:	ASTM E-407 ETCHANT No. 111 460ml H_3PO_4 Reagent Grade 25ml H_2SO_4 Reagent Grade 50g CrO_3 Reagent Grade Store in glass or teflon container.
Voltage:	3V
Current Density:	10-100 mA/cm^2
Time:	2.5 - 10 seconds (Generally: the larger the gamma prime, the longer the etch time.)
Agitation:	Gentle
Rinse:	Hot running water; dry with compressed air.

5. Final rinse (Rinsing clears sub micron particles extracted from the material in the electroetch step.)

Container:	Plastic beaker
Solution:	ASTM E-407 ETCHANT No. 186 14ml HF Reagent Grade 6ml HNO_3 Reagent Grade 60ml H_2O Store in plastic container.
Time:	8 - 10 seconds
Agitation:	Ultrasonic
Rinse:	Hot running water; dry with compressed air.

ETCHANT "B"

This etchant is used to delineate dense intricate carbide and boride structure in the grain boundaries and around primary carbides and borides. This etch procedure deeply etches the gamma matrix to reveal other structures. The etch is performed by an electrolytic immersion method, but the amount of agitation is critical to the results. The longer the etch is applied, the deeper the matrix is removed. Particles can be lost by polishing too deeply.

1. Specimen size: $1\text{-}10cm^3$

2. Metallographically prepare to a 600 grit finish with SiC paper.

3. Electropolish

   Electrolyte: 10% HCl - Methanol
   100ml Hydrochloric acid
   900ml Absolute Methanol
   Add acid to the alcohol slowly (10ml/min)

   Store in glass or plastic container.

   Voltage: 18 - 20V

   Current Density: $1 - 1.2A/cm^2$

   Agitation: Very Gently

   Time: 30 - 60 seconds

4. Etch

   Solution: 10% HCl - Methanol as above

   Voltage: 0 (power off)

   Time: 1 minute

   Agitation: Very Gently

   Rinse: Hot running water; dry with compressed air.

ETCHANT "C"

This is a Kalling's-2 etchant. It has been used for most superalloys for many years. It is a suitable and reproducible etch for optical metallography. Kalling's-2 etch leaves a deposit on the surface of the metal which becomes contaminated under an electron beam. Its primary mechanism for generating structure is the different rates at which the grains are chemically attacked due to their crystallographic orientation. The large disparity in the height of each grain makes the structure suitable for optical metallography.

1. Grind with 120 grit with SiC paper, petrodisc to 9μm diamond.
2. Polish with 1μm diamond.
3. Polish with 0.05μm alumina just prior to etching.
4. Immersion etch:

Reagent:	ASTM VOL 3.01 E407 ETCHANT No. 94 1000ml Ethanol 50g $CuCl_2$ H_2O Reagent Grade 1000ml Hydrochloric acid
Time:	20 seconds
Agitation:	Ultrasonic
Rinse:	Hot running water; dry with compressed air.

The following tables list the heat treatments for **UDIMET Alloy 720** and the response of the alloy to the etchants used at each stage of the heat treatments. Below each stage of heat treatment, described in Table A.I.2, are the structures revealed by each etchant.

Table A.I.1. **UDIMET Alloy 720 Heat Treatments**

STAGE	HEAT TREATMENT
0	As Rolled, 1100°C (2012°F)-2 hrs-furnace cool, 1040°C (1904°F)-2 hrs-fan cool.
1	1170°C (2138°F)-4 hrs-air cool.
2	1170°C (2138°F)-4 hrs-air cool, 1080°C (1976°F)-4 hrs-air cool.
3	1170°C (2138°F)-4 hrs-air cool, 1080°C (1976°F)-4 hrs-air cool, 845°C (1553°F)-24 hrs-air cool.
4	**Creep Resistant (CR)** 1170°C (2138°F)-4 hrs-air cool, 1080°C (1976°F)-4 hrs-air cool, 845°C (1553°F)-24 hrs-air cool, 760°C (1400°F)-16 hrs-air cool.
5	1105°C (2021°F)-2 hrs-oil quench.
6	1105°C (2021°F)-2 hrs-oil quench, 760°C (1400°F)-8 hrs-air cool.
7	**High Strength-1 (HS1)** 1105°C (2021°F)-2 hrs-oil quench, 760°C (1400°F)-8 hrs-air cool, 650°C (1202°F)-24 hrs-air cool.
8	1120°C (2048°F)-4 hrs-oil quench.
9	1120°C (2048°F)-4 hrs-oil quench, 650°C (1202°F)-24 hrs-air cool.
10	**High Strength-2 (HS2)** 1115°C (2048°F)-4 hrs-oil quench, 650°C (1202°F)-24 hrs-air cool, 760°C (1400°F)-8 hrs-air cool.

Table A.I.2. **UDIMET Alloy 720 Microstructures Revealed by Etchants for Various Heat Treatments**

	Heat Treatment Stage										
Etchant	0	1	2	3	4	5	6	7	8	9	10
"A"	MC MB gp gb GS gen SEM opt	MC MB gp gen SEM opt	MC MB gp gb GS gen SEM opt	MC MB gp gb GS gen SEM opt	MC MB gp gb GS gen SEM opt	MC MB gp gen SEM opt	MC MB gp gb GS gen SEM opt	MC MB gp gb GS gen SEM opt	MC MB gp gen SEM opt	MC MB gp gb GS gen SEM opt	MC MB gp gb GS gen SEM opt
"B"	MC MB S gb GS SEM	MC MB SEM	MC MB gb GS SEM	MC MB gb GS SEM	MC MB S gb GS SEM	MC MB SEM	MC MB gb GS SEM	MC MB gb GS SEM	MC MB SEM	MC MB gb GS SEM	MC MB gb GS SEM
"C"	MC MB gb GS gen opt SEM	MC MB gen opt SEM	MC MB gb GS gen opt SEM	MC MB gb GS gen opt SEM	MC MB gb GS gen opt SEM	MC MB gen opt SEM	MC MB gb GS gen opt SEM	MC MB gb GS gen opt SEM	MC MB gen opt SEM	MC MB gb GS gen opt SEM	MC MB gb GS gen opt SEM

ETCH COMMENTS:

gb . . . . grain boundary precipitate, $M_{23}(C,B)_6$
GS . . . . grain size
MC . . . . primary carbides, Mc-type
MB . . . . primary borides
gp . . . . gamma prime precipitate
S . . . . sigma phase precipitate
gen. . . . general microstructure
SEM. . . . secondary election image scanning electron microscopy
opt. . . . optical microscopy

APPENDIX II

DIFFERENTIAL THERMAL ANALYSIS (DTA) OF UDIMET Alloy U720

Typical differential thermal analysis curves are presented in Figures A.II.1. to A.II.4. These curves are representative of annealed bar and other materials given the CR, HS1 and HS2 heat treatments. The observable reactions of interest are the liquidus temperature (T_l), solidus temperature (T_s), incipient melting point (I.M.) and the gamma prime solvus. The liquidus temperature is determined by the peak of the melting curve. The solidus temperature is the first point of deviation from the baseline of the heating curve. Incipient melting is the result of minor phase liquation prior to the onset of major melting at T_s. This point is defined as the first point of deviation from the baseline of the minor melting portion of the curve analogous to T_s. The gamma prime solvus is determined by the intersection of tangents drawn along the baseline of the curve prior to the reaction, and along the point of maximum slope during the reaction. It should be noted that the accepted method of gamma prime solvus calculation via DTA is to determine the peak temperature of the derivative of the differential curve. Since this temperature is not easily determined on the differential curve the intersection method is used. In general, the intersection method yields values slightly below true solvus temperatures; however, the temperature does correlate well with structural changes, such as grain growth, which accompany gamma prime solutioning.

Table A.II.1. Differential Thermal Analysis of UDIMET Alloy 720

	°C	(°F)	CONDITION
Liquidus	1335 ± 3	(2435 ± 5)	Typical
Solidus	1238 ± 3	(2260 ± 5)	All
Incipient Melting	1195 ± 2	(2138 ± 3)	Conditions
Gamma Prime Solv.	1147	(2097)	CR
"	1097	(2007)	HS 1
"	1145 - 1190	(2093 - 2174)	HS 1
"	1111	(2032)	HS 2
"	1150 - 1190	(2102 - 2174)	HS 2
"	1032	(1890)	As-Worked
"	1145 - 1190	(2093 - 2174)	As-Worked

As expected, the liquidus, solidus and incipient melting reactions were not noticeably affected by heat treatment; however, gamma prime reactions changed considerably. The as-worked material shows two distinct gamma prime solvus temperatures: a low temperature, fine gamma prime and a high temperature, very coarse gamma prime precipitate. The latter structure produces a broad gamma prime solutioning curve, which is typical of large precipitates. Following the CR heat treatment, a uniform, coarse gamma prime precipitate is formed which is much finer than the as-worked structure. This structure is observed as a fairly sharp reaction at 1147°C (2097°F). The ultrafine gamma prime precipitated at the lower temperature ages were not observed on the trace. Following the HS heat treatment, the low temperature gamma prime phase has been solutioned and re-precipitated as a higher solvus phase, while the very coarse gamma prime was essentially unaffected.

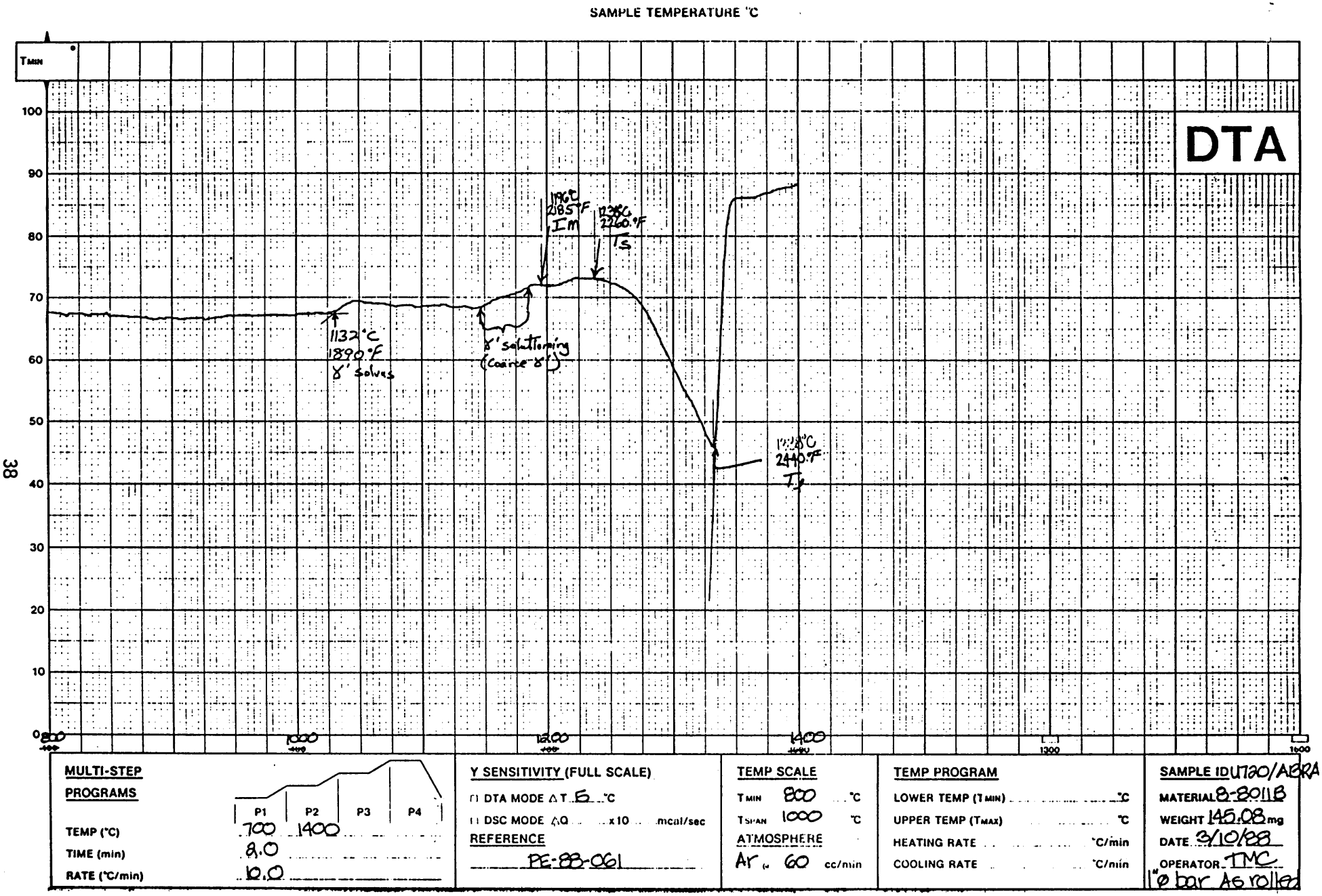


Figure II-1. DIFFERENTIAL THERMAL ANALYSIS OF UDIMET ALLOY 720 IN THE AS-WORKED CONDITION

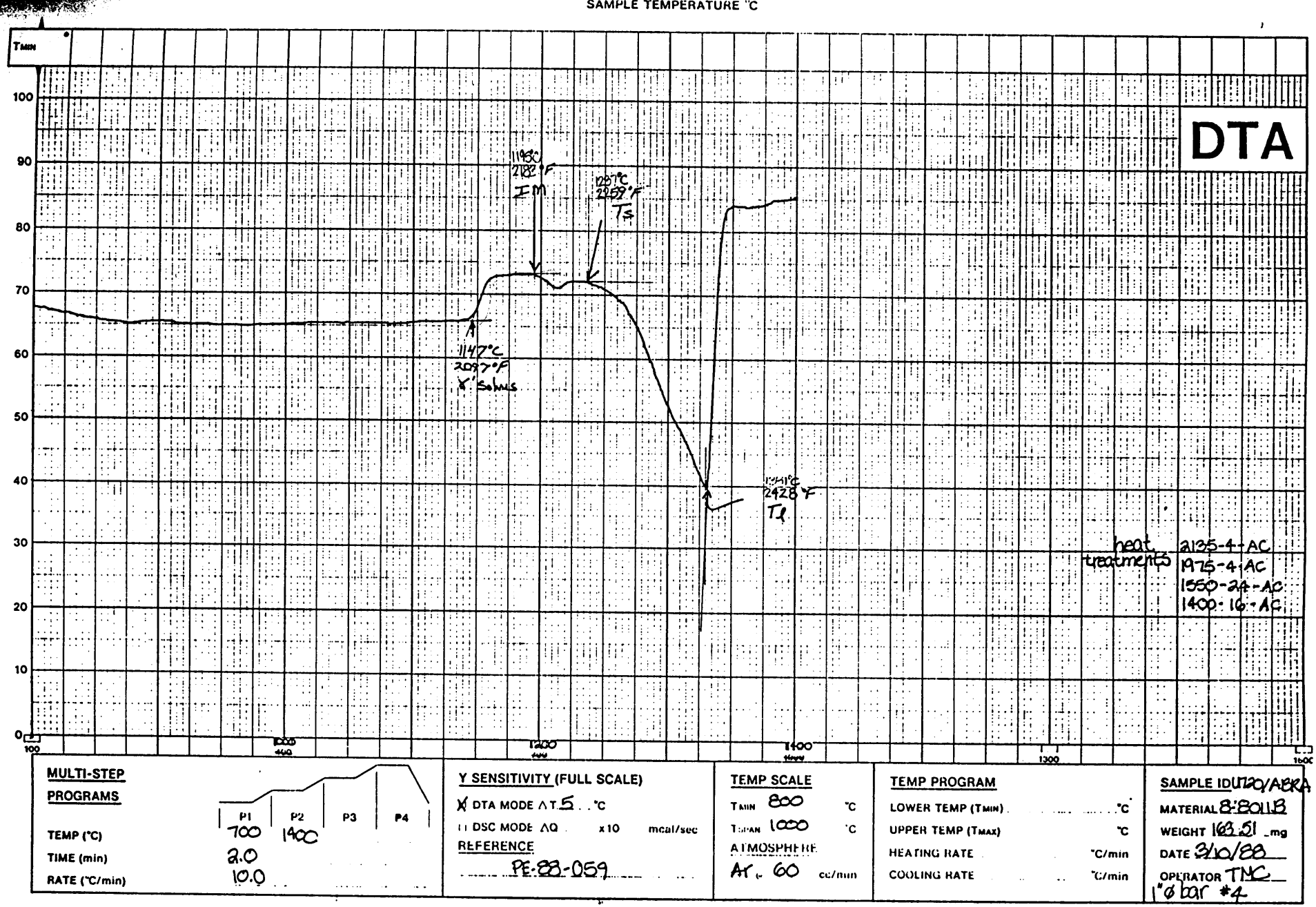


Figure II-2. DIFFERENTIAL THERMAL ANALYSIS OF UDIMET ALLOY 720 WITH THE CREEP RESISTANT (CR) HEAT TREATMENT

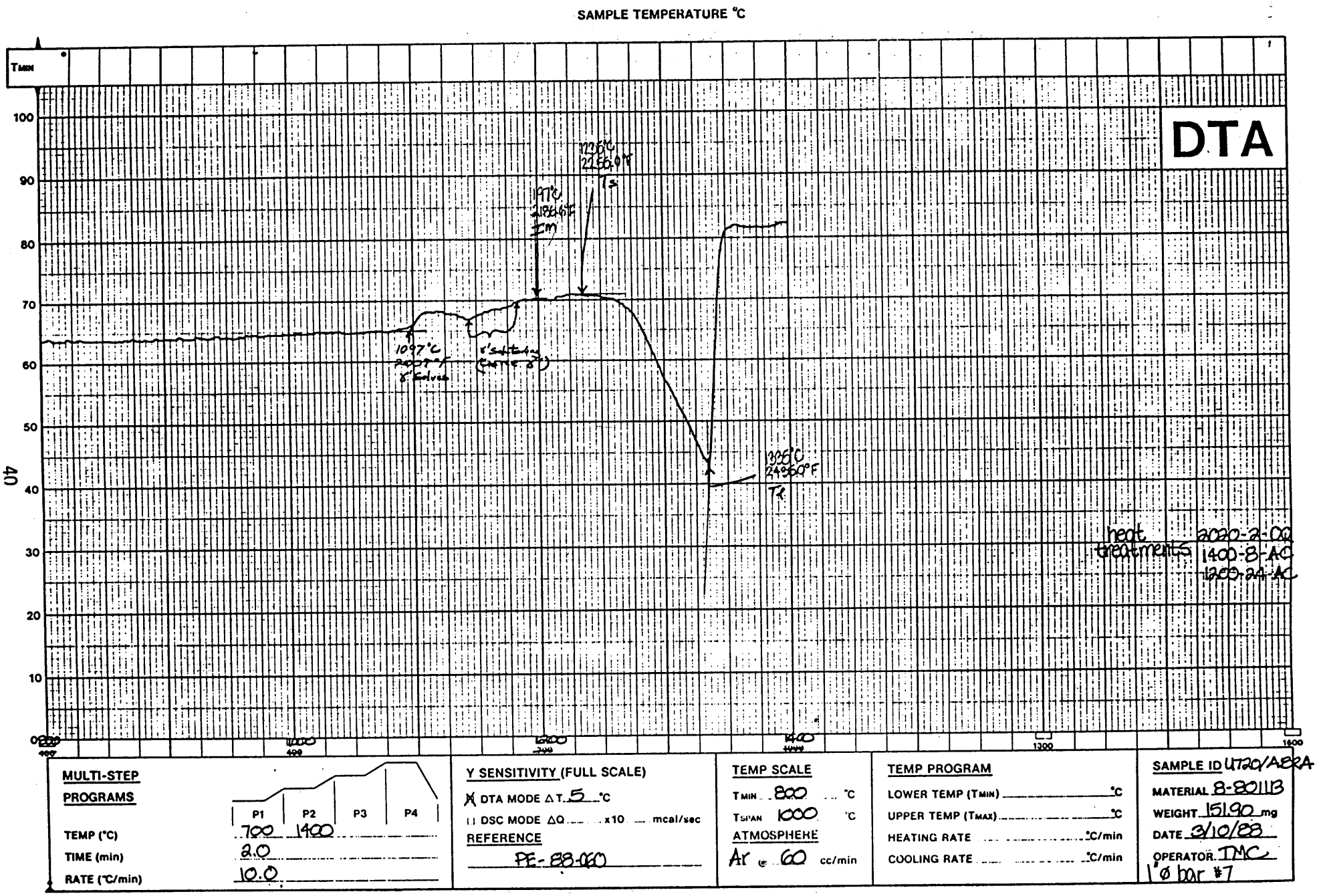


Figure II-3. DIFFERENTIAL THERMAL ANALYSIS OF UDIMET ALLOY 720 WITH THE HIGH STRENGTH-1 (HS1) HEAT TREATMENT

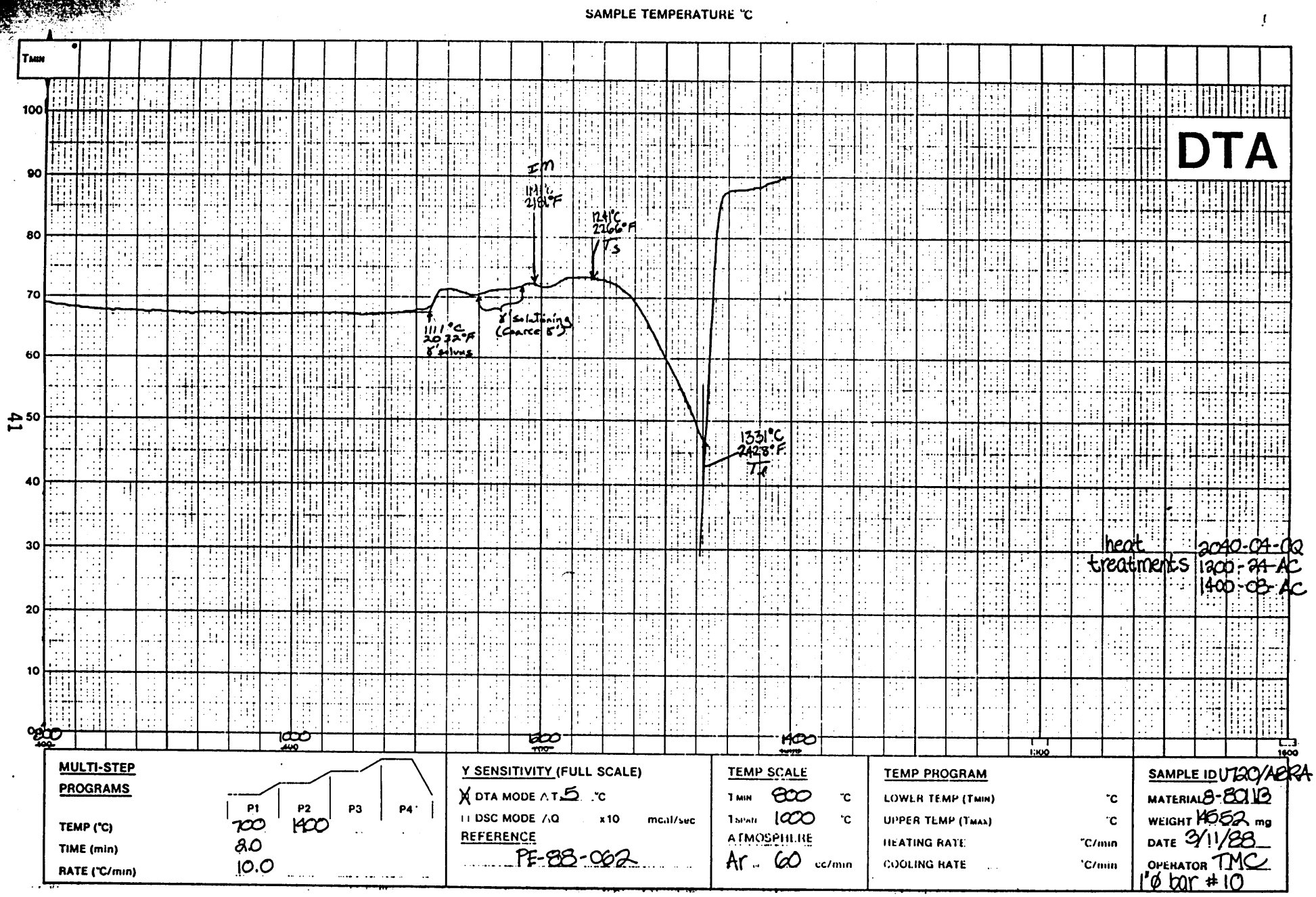


Figure II-4. DIFFERENTIAL THERMAL ANALYSIS OF UDIMET ALLOY 720 WITH THE HIGH STRENGTH-2 (HS2) HEAT TREATMENT