Load and strain were monitored and recorded continuously throughout the duration of each test. Load was measured with a 55 kip MTS load cell. Strain was measured using a MTS extensometer with 0.5 inch of available travel. The final diameter of each specimen was measured using a dial caliper to determine material fracture properties. The tension test data was analyzed using the B&W NESI certified computer program MTADS. This program uses the load and strain data in conjunction with various specimen and testing parameters to perform a standard ASTM E8-94a analysis. Reported values for each test include yield and ultimate tensile strength, uniform and total elongation, reduction in area, fracture load, fracture stress, fracture strength, and the Ramberg-Osgood strain hardening parameters. Data analysis results are reported in Table 1. All test parameters are shown in Appendix A along with test reports, realtime data plots, and data analysis reports for each specimen.

Table 1. – Summary of Tension Test Results – Advanced Test Reactor Surveillance Program

Specimen ID	Test Temp. (°F)	Strength (ksi) Yield	Strength (ksi) Ultimate	Fracture Load (lb)	Fracture Stress (ksi)	Fracture Strength (ksi)	Elongation (%) Uniform	Elongation (%) Total	Reduction in area (%)	Ramberg–Osgood Parameters Alpha	Ramberg–Osgood Parameters n
PM1	125	60.8	94.1	2649	291.0	54.0	>43	N/A	81.5		
PM2	125	51.0	91.4	2884	306.2	58.7	>44	N/A	80.8		
PM4	125	54.4	91.6	2245	270.5	45.7	>44	N/A	83.1		
PM5	125	61.7	96.5	2838	301.3	57.8	>44	N/A	80.8		
PM6	125	52.2	88.5	2553	293.5	52.0	>43	N/A	82.3		
PM7	125	45.9	88.8	2599	311.0	53.0	>44	N/A	83.0		
W1	125	99.2	110.3	4847	203.8	98.7	17.7	32.1	51.6	5.45	8.43
W2	125	80.6	102.9	4333	207.8	88.3	22.9	35.5	57.5	5.52	5.92
HAZ1	125	79.3	98.6	2996	294.1	61.0	>44	N/A	79.2		
HAZ2	125	74.3	97.8	2907	316.4	59.2	>44	N/A	81.3		
HAZ3	125	81.0	98.1	2999	346.3	61.0	>44	N/A	82.4		
HAZ4	125	71.6	87.0**	2819**	319.4**	57.4**	>44	N/A	82.0**		
W5	125	80.4	110.8	1992	159.4	99.0	4.75*	8.44*	38.0		
W6	125	114.4	119.3	2120	152.6	105.5	5.33*	6.71*	30.9		
W7	125	116.8	121.8	2046	180.9	101.7	3.37*	6.08*	43.8		
W8	NOT TESTED										

*Results not valid – specimen necked and fractured outside the extensometer gage length.
**Test disturbed by a thunderstorm.

4.0 FRACTURE TOUGHNESS TEST RESULTS

4.1 Test Procedures

Several mock-up specimens were received from ATR. These specimens were used to verify the MTS test system, MTS software, and the fixture which provides support during the test. Also, control parameters used in the actual testing were obtained from these mock-up tests.

Two unnotched Charpy bars (one for each specimen geometry) were provided by ATR and loaded to 10,000 and 4,000 pounds for large and small bend specimens, respectively, to determine the machine/fixture compliance. These results were then used in correcting load-line displacements during actual testing by subtracting the displacement caused by machine/fixture compliance from measured test displacement as specified in ASTM E813-89 Annex A1.4 [4].

The J-integral fracture toughness testing was performed in accordance with Babcock & Wilcox LTC Technical Procedure TP-177, Revision 5. This procedure is in compliance with ASTM standards E813-89 and E1152-87.

The tests were performed in position control mode on a servohydraulic test machine equipped with a 55 kip load cell. The three-point bending fixture used in this project is in compliance with ASTM E813-89. Load and displacement were monitored continuously through loading and unloading cycles with a load cell and a clip gage interfaced to a personnel computer. Crack lengths were calculated based on material compliance relationships using load and displacement data collected during the unloading portion of each cycle in conjunction with specimen geometry information. These tests were performed in an ATS split type furnace and temperature was controlled to within $\pm$ 5 °F of the test temperature.[2] The specimen was heated to test temperature (usually it took 20 to 25 minutes) and soaked in the furnace for 20 minutes for the small bend specimens and 30 minutes for large bend specimens to assure uniform specimen temperature.

Test machine control and data analysis was performed using the computer program "JTEST.R01". This program was developed by MTS Systems Corporation for both elastic-plastic fracture toughness J_{IC} test per ASTM E813-89 and ASTM E1152-87 and plane strain fracture toughness K_{IC} test per ASTM E399-90. The portion involving the J_{IC} testing was

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[2]Since the radiation levels for the specimens were high, no thermocouple wire was attached onto the specimen surface for temperature measurement. Mock-up specimens (unirradiated) supplied by ATR were placed in the oven and heated up to 115, 120, and 125°F, respectively. The temperature measurements on the specimen surface and those from furnace thermocouple wire were compared. It was found that the difference between these two readings are within 1°F.

certified per B&W NESI Nuclear Materials Engineering Implementing Procedure NME-QIP-10 "Software Development, Procurement, and Utilization Controls". The details of the certification documents can be found in Reference [1].

4.2 Input Data

The values for yield strength and tensile strength used for calculations during test were based on the tension test results (Table 1). Note that for the weld metals, the average values of W1 and W2 were used. Test results from W5, W6, and W7 were not used since these results were questionable. Specimen dimensions specified in the report provided by ATR [2] were used as the input parameters for software JTEST.R01. The percent unloading parameter specifies the amount of unload for each unloading cycle during the test. An unloading value of 20% from the current load was specified for each specimen.

The force and the crack mouth opening (COD) displacement of the unload were used to calculate the crack length using compliance method. Because the extreme high and low ends of the unload process are relatively noisy, only the middle portion of the unload process is used to calculate the crack length to achieve higher accuracy. The operator specifies the portion of the load- displacement curve to be used for compliance measurements. For these tests, 15% and 85% of the unload was specified for the lower and upper limits, respectively.

Loading rate is specified in inches of displacement per second. Appropriate loading displacement rates were used depending on the specimen geometries. The test parameters used for each specimen are reported in Appendices B and C.

4.3 Program Execution

Initially, upon program execution, the specimen was loaded to approximately 30% of the limit load to determine the initial crack length using the compliance method. The measured crack length was used to compared with the final precrack crack length (provided by ATR) for consistency. This process was then repeated for several times. If the results were consistent, the crack length checking process was complete. If results were not consistent, the test system was checked and the clip gage was examined for proper seating. This process was continued until reproducible results were obtained. Since the load applied to the specimen was significantly lower than the yield and the loads used in the precracking process, no impact to the test results was expected.

Following the initial crack length measurement cycling, the actual test begins. The specimen is loaded and unloaded in accordance with the parameters entered prior to the test. Load, COD, and load-line displcement (LLD) data are collected continuously. Compliance (load vs. COD) data collected during each unloading is used for a crack length calculation. Crack length is calculated using the following equations.

SE(B) specimen

$$a/w = 0.999748-3.9504u_{LL}+2.9821u_{LL}^2-3.21408u_{LL}^3+51.51654u_{LL}^4-113.031u_{LL}^5$$

where: $u_{LL} = 1/[[B_eEC_c/(S/4)]^{1/2}+1]$

$$B_e = B - \frac{(B-B_N)^2}{B}$$

B = specimen thickness
B_N = net specimen thickness
C_c = specimen crack opening compliance on an unloading/reloading sequence
S = span

In this manner, real time load versus COD and load versus LLD curves are generated. These curves are monitored during each test and test control parameters may be changed if necessary based on material response.

4.4 Data Analysis

4.4.1 Calculation of J-R Curves

The data analysis program offers three optional routines:

1. Effective Yield Strength - Effective yield strength is the average of the yield strength and the ultimate strength input by the operator. This option was selected.

2. Rotation Correction - This option allows the software to implement a geometry-based rotational correction when calculating the crack length from specimen compliance. This option was not selected since no compact tension specimens were involved.

3. ASTM E813-89 Criteria or ASTM E813-81 Criteria - the operator has the choice of using the data analysis method described in ASTM E813-89 or ASTM E813-81 to analyze the data. ASTM E813-89 was selected for data analysis.

Using the load versus LLD data, the J-R curve is calculated using the following equations.

$$J = J_e + J_p$$

where:
J_e = the elastic component

J_p = the plastic component

- The elastic component is calculated per ASTM E1152-87:

$$J_e = \frac{K^2(1-\nu^2)}{E}$$

$$K = \left[\frac{PS}{(BB_N)^{1/2}W^{3/2}}\right] f\left(\frac{a}{W}\right)$$

$$f\left(\frac{a}{W}\right) = \frac{3(a/w)^{1/2}[1.99-(a/w)(1-a/W)(2.15-3.93(a/w)+2.7(a/w)^2]}{2(1+2a/W)(1-a/w)^{3/2}}$$

where: ν = Poisson's ratio

- The plastic component for the ith loading step is calculated as follows:

$$J_{p(i)} = \left[J_{p(i-1)} + \frac{\eta_i}{b_i}\left(\frac{A_{p(i)} - A_{p(i-1)}}{B_N}\right)\right]\left[1-\gamma_i\left(\frac{a_{(i)} - a_{(i-1)}}{b_i}\right)\right]$$

where $\eta_i = 2.0$
$\gamma_i = 1.0$
$b_i = W - a_i$

and

$$A_{p(i)} = A_{p(i-1)} + \frac{[P_{(i)} + P_{(i-1)}][\Delta_{p(i)} - \Delta_{p(i-1)}]}{2}$$

where: A_p = the plastic portion of the area under the load versus displacement (LLD) curve.

and Δ_p = the plastic portion of the LLD
$(\Delta_{p(I)} = \Delta_{total(I)} - P_iC_i)$

$\Delta_{total(i)}$ = total LLD after the ith step

P_i = i^{th} step end load

C_i = i^{th} step compliance

4.4.2 Calculation of J

In the calculation of J, the data that lie between the 0.006" and 0.060" inch exclusion lines are numerically fit to a power law expression:

$$J = C_1(\Delta a)^{C2}$$

where C1 and C2 are constants.

The intersection of the power law curve and a 0.008" offset line is then determined. The 0.008" offset line has the slope of the theoretical blunting line and is described by the following equation[3]:

$$J = 2\sigma_f\,(\Delta a\text{-}0.008)$$

where σ_f = material flow strength. (effective yield strength was used in this project)

The value of Δa is then varied until the following relationship is satisfied:

$$C_1(\Delta a)^{C_2} = 2\sigma_f\,(\Delta a\text{-}0.008)$$

The resulting value of Δa is then used to calculate J using both the power law expression and the 0.008" offset relationship. If the two J values agree within 2%, then the power law value is taken as J_Q. If the two values do not agree, then the iteration stepsize for Δa is decreased and the process is repeated until the 2% criteria is met.

4.4.3 Calculation of Tearing Modulus

Attempts are being made to describe stable crack growth under elastic-plastic conditions. Several attempts have received notable attention. One is the tearing modulus concept

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[3]For ductile material such as stainless steel, slopes larger than $2\sigma_f$ are used by some researchers. In this project, $2\sigma_f$ was used as defined in ASTM E813-89.

developed by Paris et al. [3]. Paris has suggested calculating the slope of the curve, dJ/da. However, this slope is temperature dependent for most materials. Paris found that dividing J by σ_f results in a reasonably temperature independent parameter:

$$[\frac{dJ}{da}][\frac{1}{\sigma_f}]=C_1$$

Since the J-Δa diagram and σ_f are material characteristics, this parameter has a unique value for a given material and therefore fully describes its stable tearing behavior. Paris further introduced the parameter

$$T_{mat}=(\frac{dJ}{da})(\frac{E}{\sigma_f^2})$$

where T stands for "tearing modulus". This value of T_{mat} has to be compared to a similar expression, T_{app}, which is the tearing modulus applied to a known cracked body by the loading system:

$$T_{app}=(\frac{dJ}{da})_{app}(\frac{E}{\sigma_f^2})$$

As soon as $T_{app} > T_{mat}$ the occurrence of instability must be expected.

dJ/da can be calculated from the power-law curve fit of the R-curve data presented in Appendices B and C for each test. The values seen in Appendices B and C were calculated at the point where the J_{1C} or J_Q values were determined.

4.4.4 Calculation of K_j and $K_{j(max)}$

The K_j fracture toughness is calculated from the J_{IC} value calculated above. This calculation is performed according to the following equation:

$$K_j=[\frac{J_{1C}E}{(1-\nu^2)}]^{1/2}$$

4.5 Crack Length Measurement

After the test, the specimens were heat-tinted in a furnace at 650 °F for 15 minutes. The

specimens were then removed from the furnace and placed back onto the bend fixture and fatigue-cycled to failure. For small band specimens, the crack length was measured in the Fatigue and Fracture Laboratory (outside our hot cell facility) using a video micrometer system due to their lower radiation levels. This system was calibrated prior to and after the measurements were made. For the larger bend specimens, the specimens were transferred into our hot cell facility due to their high radiation levels and the crack length was measured using the same video micrometer system. Again, the video micrometer system was calibrated. All specimens were photographed for their fracture surface appearance in the hot cell facility.

The cracks were measured at nine locations across the crack front spanning the specimen thickness. These nine measurements were used to determine an average initial and final crack length as follows:

$$a_{AVG} = \frac{1}{8}\left[\frac{(a_1+a_9)}{2} + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 + a_8\right]$$

where

a_{AVE} is the average crack length from nine measurements
a_n is nine point measured crack length

These values were later used as references to verify the accuracy of the crack length determined from the compliance method.

4.6 Test Results

The results for all tests are summarized in Table 2. A J_{IC} or a J_Q is reported for each specimen. If this value is reported as J_Q, then an explanation of the J_{IC} criteria violated is also included. All weld metal specimens (small bend specimens) had J_{1C} or J_Q values while the base metal and HAZ specimens (large bend specimens) were very ductile and the specimen size requirement were violated. B&W NESI currently cannot analyze the data since the J value is larger than the allowable J_{max} defined in the ASTM E1152-87. However, the calculated J_{max} values ($J_{max} = B\sigma_y/20$) were reported in Table 2.

The test results, test parameters, and the J- R curve are shown in Appendices B and C.

Table 2 Fracture Toughness Test Results

Specimen Identification	Test Temperature (°F)	J_{1C}, or J_Q (in-lb/in^2)	K_j (ksi-in$^{1/2}$)	J_{1C} Criteria Violations
W-7 (weld)	125	668	148	none, J_{1c}
W-6 (weld)	125	658	148	none, J_{1c}
W-5 (weld)	125	312	93	J_Q, 9.4.1.7
W-1 (weld)	125	668	150	none, J_{1c}
W-2 (weld)	125	525	130	none, J_{1c}
W-9 (weld)	125	362	110	none, J_{1c}
W-10 (weld)	125	763	151	none, J_{1c}
W-11 (weld)	125	672	142	none, J_{1c}
PM-1	125	>1800*	N/A	N/A
PM-2	125	>1800*	N/A	N/A
PM-3	125	>1800*	N/A	N/A
PM-5	125	>1800*	N/A	N/A
PM-6	125	>1800*	N/A	N/A
HAZ-1	125	>2350*	N/A	N/A
HAZ-2	125	>2350*	N/A	N/A
HAZ-3	125	>2350*	N/A	N/A
HAZ-5	125	>2350*	N/A	N/A
HAZ-7	125	>2350*	N/A	N/A

*Calculated based on $J_{max} = B\sigma_y/20$. HAZ metal had higher values because it has higher yield stress.

4.7 HAZ Tension Specimens Metallography

Four broken HAZ tension specimens were transferred into LTC hot cell facilities for

sectioning. The fracture surface was removed from the broken specimens first, then a 0.2 inch long sample was sectioned from each specimen. These samples were then transferred out of cell to Failure Analysis Laboratory where specimens were mounted, polished, and etched to reveal the weld metal. The etchant used was 15 ml HCl and 5 ml HNO_3 and the specimens were swabbed in the etchant for 10 to 12 second. The photograph (magnification factor: 16X) of the specimens can be found in Appendix F. No definite line to separate weld metal and HAZ/base metals was observed on any of the specimens. However, a combination of larger and smaller grains in the same specimen was observed. This was an indication that the specimen was not totally made of base metal. The amount of large grains that could be find in the specimen has good correlation with the mechanical test results. For example, HAZ-3 which has more large grains has higher yield strength than HAZ-4 which has limited large grain.

5.0 DISCUSSION

Based on the test results shown in Table 2, the weld metal (type 308 stainless steel) is the limiting material for the ATR reactor vessel. The J_{Ic} (or J_Q) values range from 312 in-lb/in^2 to 763 in-lb/in^2. The value that was used in the original assessment performed by ATR was 464 in-lb/in^2 [2]. The average of the J_{Ic} (or J_Q) values of these eight specimens is higher than 464 in-lb/in^2. However, the J_{Ic} (or J_Q) values of two specimens fall below 464 in-lb/in^2. Comparison of test results between the irradiated and unirradiated specimens since the specimen orientation (e.g. T-L) was not provided for the irradiated specimens.

All large bend specimens were made of base or HAZ metals. All base metal specimens show significant ductility. This can be observed from the J-a plot where the crack grew along the blunting line (with a slope of $2\sigma_f$). No standard E-813 and E1152 analysis was performed since the interception of the 0008" offset line and the 0.006" and 0.60" exclusion line (described in 4.4.2) was above the allowable J_{max} specified in E1152.

In general, HAZ specimens also showed good ductility but was less compared to the base metals. No standard E-813 and E1152 analysis was performed since the interception of the 0.008" offset line and the 0.006" and 0.60" exclusion line (described in 4.4.2) was above the allowable J_{max} specified in E1152.

One observation made on testing the irradiated specimens was that the specimen dimensions (measurements made when the specimens were machined) provided by ATR were not appropriate since the specimen could not be centered by a fixture designed based on ATR's information[4]. This fixture was designed based on the fact that the distance from one

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[4]Several bend specimens were measured for specimen thickness and specimens width in the hot cell facility after testing. All measurements were consistent with the specifications

referenced end to the center of the specimen was fixed. The fixture also acted as a specimen stopper and provided the alignment for the second direction (specimens thickness direction) as shown in Figure 2. Therefore, the specimens should have been centered and aligned using the fixture. However, after the specimen was placed on the fixture, the center of the specimen was not aligned with the loading fixture. The reason for the misalignment is unknown. In any case, the specimens were centered by operator through the lead glass window (~ 24 inches from the specimen). Through the help from specimen notch and marker on the loading fixture, the center of the specimen was aligned with the center of the loading fixture within 1/32" (This was verified with the mock-up specimens). This was within the allowable 1% deviation of the span length specified in the ASTM standard.

There were several specimens with noisier data. This was because of the fact that for the first several specimens only 9 data points were collected during the unloading process for the determination of the crack length. These data points did not provide good statistical basis for the determination of crack length. This problem was identified and corrected by using collecting 50 data points during the unloading process. Optimal testing parameters were established and therefore better experimental results were obtained for specimens tested later.

6.0 SUMMARY

1. Fifteen tension and eighteen bend irradiated specimens have been tested in compliance with ASTM standard E8-94 and ASTM E813-89, respectively at 125°F.

2. Radiation embrittlement was observed in both tension and fracture toughness test results on weld metal.

3. Significant ductility was observed in base and HAZ metal specimens. No comparison was made to unirradiated specimens due to insufficient data. However, radiation embrittlement was observed in tension test results for both metals.

7.0 REFERENCES

1. K.Y. Hour, "Software Certification Report- Automated Single Specimen J-Test per ASTM E813-89 and E1152-87", B&W NESI Software Certification NES-005, dated November 16, 1993.

2. S.M Graham, WR. Lyoyd, W.G Reuter, "Fracture Toughness and Tensile Test Results

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described in specimen drawings.

for Unirradiated Weldment of Type 304 stainless Steel" INEL Internal Report No. PG-T-89-001, dated May, 1989.

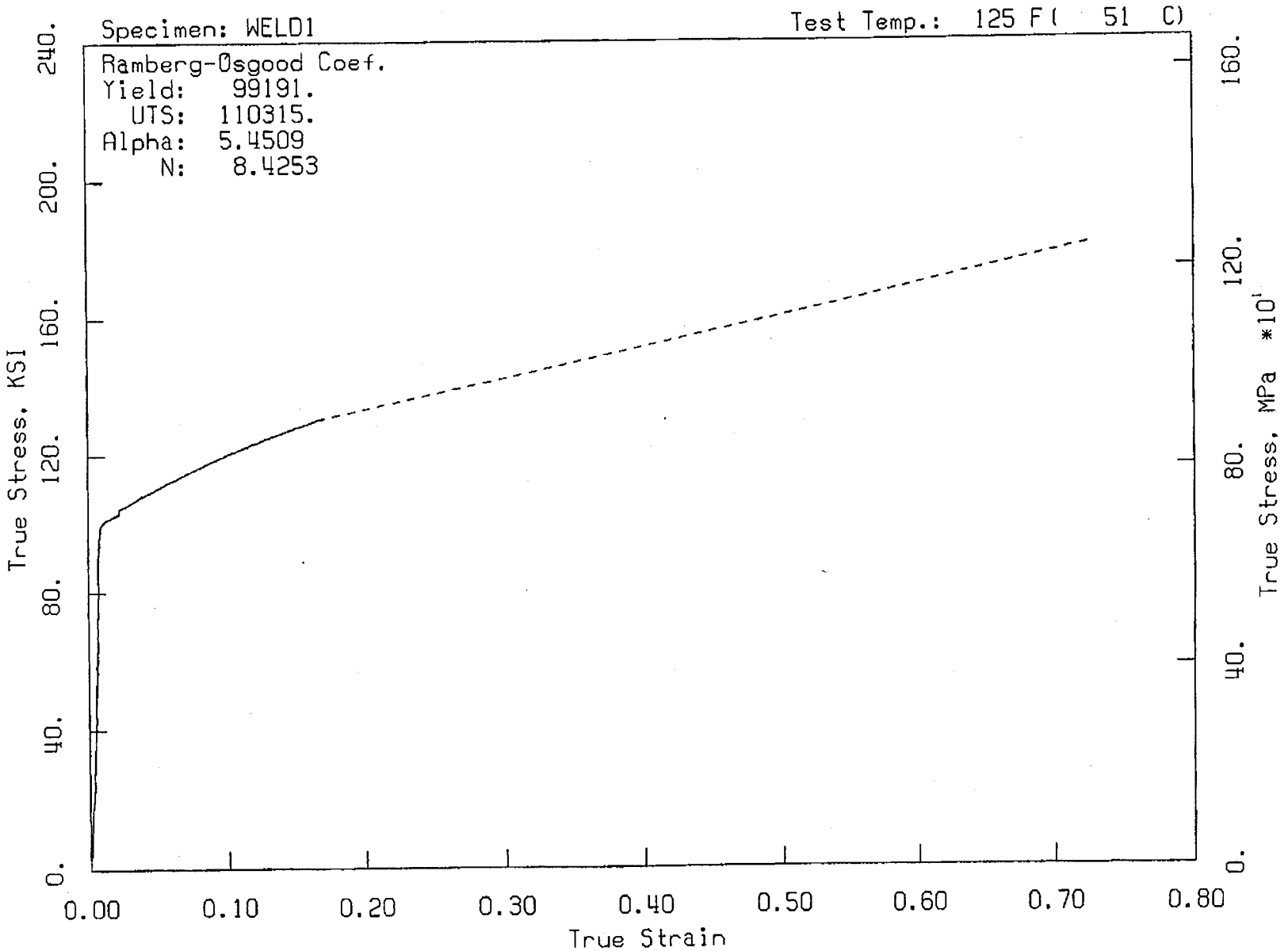
3. Paris, P.C., Tada H., Zahoor, A. and Ernst, H. "The Theory of Instability of the Tearing Mode of Elastic Plastic Crack Growth", *Elastic-Plastic Fracture*, ASTM STP 668, American Society for Testing and Materials, Philadelphia, pp. 5-36 (1979).

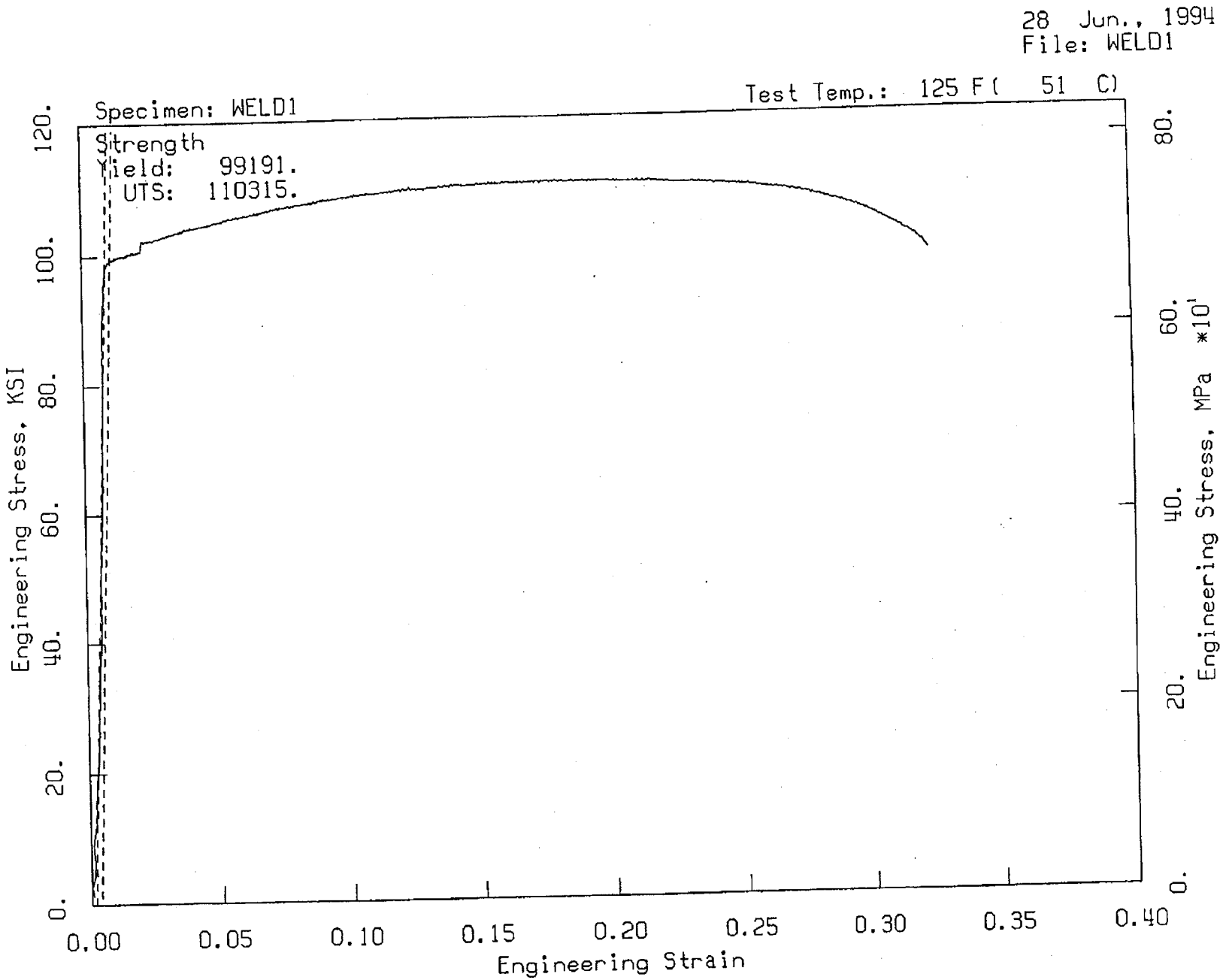
4. "Standard Test Method for J_{IC}, A Measure of Fracture Toughness", American Society for Testing and Materials Standards E813-89, Vol. 3.01, pp. 646-660 (1995).

APPENDIX A

Tension Test Results Record

28 Jun., 1994
File: WELD1




28 Jun., 1994
File: WELD1
Test Temp.: 125 F (51 C)
Specimen: WELD1
Strength
Yield: 99191.
UTS: 110315.
Engineering Stress, KSI
Engineering Stress, MPa *10¹
Engineering Strain
0.
20.
40.
60.
80.
100.
120.
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40

TADS
<890928.1259> TENSILE DATA ANALYSIS

28 Jun., 1994
File: WELD2

SPECIMEN ID PARAMETERS

Date of test	6/24/94	
Operator	BJV	
Project number	0135	
Specimen	WELD2	
Test temperature	125 F	52. C
Material	WELD	
Modulus	29575. ksi	203920. MPa
Cross Section type	CIRC	
Fluence	0.0000E+00	
Technical Specification . .	TP-78-12	

SET UP PARAMETERS

Initial disp rate	.0100 in/min	.254 mm/min
Second. disp rate	.0400 in/min	1.02 mm/min
Gauge length (Ext)	1.000 in	25.40 mm

DIMENSIONAL

Diameter INITIAL	.2500 in	6.35 mm
FINAL	.1629 in	4.14 mm
Axial Fidical INITIAL . .	1.0000 in	25.40 mm
FINAL . .	.0000 in	.00 mm

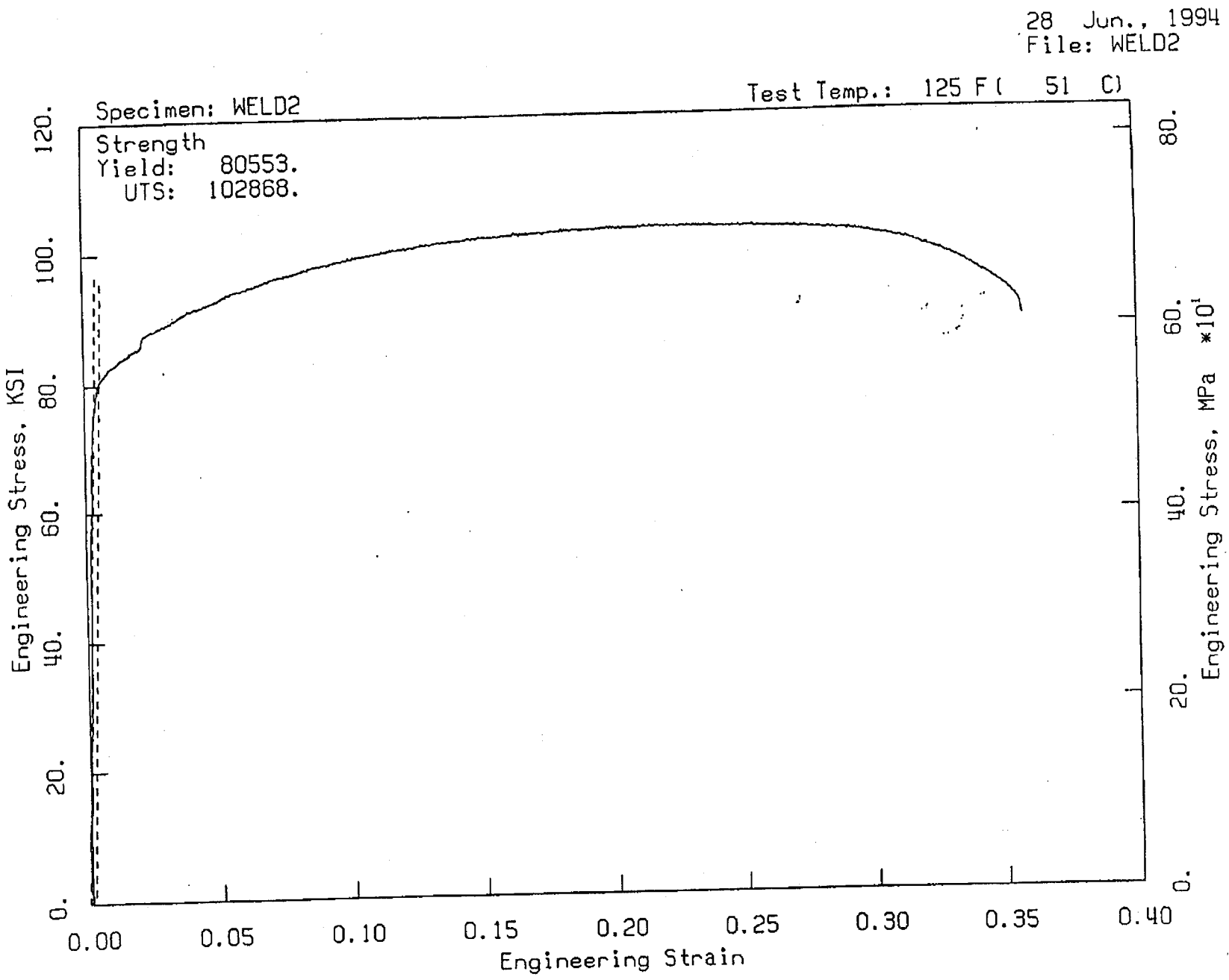
TEST RESULTS

Yield Strength	80553. psi	555.4 MPa
Tensile Strength	102868. psi	709.3 MPa
Fracture Load	4333. lb	19273. N
Fracture Stress	207777. psi	1432.6 MPa
Fracture Strength	88272. psi	608.6 MPa
Young's Modulus	1.72E+07 psi	1.19E+05 MPa
Elongation (fiducial). . .	-1.0000	
Uniform Elongation (Ext) .	.2288	
Total Elongation (Ext) . .	.3546	
Reduction in Diameter. . .	34.8 %	
Reduction in Area	57.5 %	

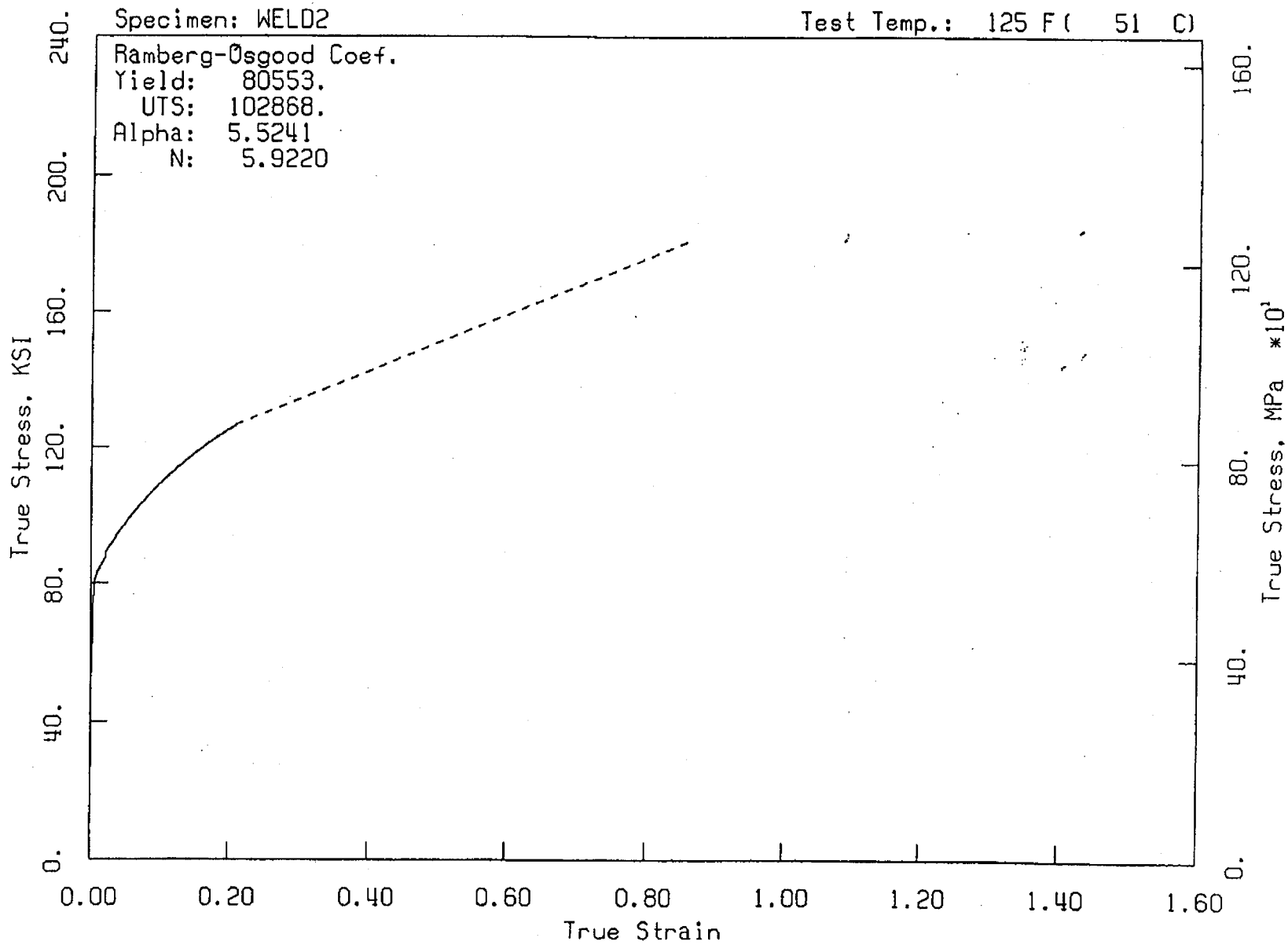
CURVE FIT

Ramberg-Osgood Equation

		Fit Std Dev
Alpha	5.524	.010
N	5.922	.029


28 Jun., 1994
File: WELD2
Test Temp.: 125 F (51 C)
Specimen: WELD2
Strength
Yield: 80553.
UTS: 102868.
Engineering Stress, KSI
0.
20.
40.
60.
80.
100.
120.
Engineering Stress, MPa *10¹
0.
20.
40.
60.
80.
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Engineering Strain

28 Jun., 1994
File: WELD2



TADS
<890928.1259> TENSILE DATA ANALYSIS

1 Jul., 1994
File: PM1

SPECIMEN ID PARAMETERS

Date of test	7/1/94	
Operator	BJV	
Project number	0135	
Specimen	PM1	
Test temperature	125 F	52. C
Material	BASE	
Modulus	29575. ksi	203920. MPa
Cross Section type	CIRC	
Fluence	0.0000E+00	
Technical Specification . .	TP-78-12	

SET UP PARAMETERS

Initial disp rate	.0075 in/min	.190 mm/min
Second. disp rate	.0600 in/min	1.52 mm/min
Gauge length (Ext)	1.000 in	25.40 mm

DIMENSIONAL

Diameter INITIAL	.2500 in	6.35 mm
FINAL	.1076 in	2.73 mm
Axial Fidical INITIAL . .	1.0000 in	25.40 mm
FINAL . .	.0000 in	.00 mm

TEST RESULTS

Yield Strength	60800. psi	419.2 MPa
Tensile Strength	87704. psi	604.7 MPa
Fracture Load	4299. lb	19123. N
Fracture Stress	472366. psi	3257.0 MPa
Fracture Strength	87584. psi	603.9 MPa
Young's Modulus	7.68E+06 psi	5.30E+04 MPa
Elongation (fiducial). . .	-1.0000	
Uniform Elongation (Ext) .	.4393	
Total Elongation (Ext) . .	.4437	
Reduction in Diameter. . .	56.9 %	
Reduction in Area	81.5 %	

CURVE FIT

Ramberg-Osgood Equation

		Fit Std Dev
Alpha	22.189	.019
N	3.033	.038