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Temperature Effects on the Mechanical Properties of Annealed and HERF 304L Stainless Steel

B.R. Antoun

Prepared by Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Temperature Effects on the Mechanical Properties of Annealed and HERF 304L Stainless Steel

B.R. Antoun

Sandia National Laboratories
P.O. Box 969
Livermore, CA 94551

Abstract

The effect of temperature on the tensile properties of annealed 304L stainless steel and HERF 304L stainless steel forgings was determined by completing experiments over the moderate range of –40°F to 160°F. Temperature effects were more significant in the annealed material than the HERF material. The tensile yield strength of the annealed material at –40°F averaged twenty two percent above the room temperature value and at 160°F averaged thirteen percent below. The tensile yield strength for the three different geometry HERF forgings at –40°F and 160°F changed less than ten percent from room temperature. The ultimate tensile strength was more temperature dependent than the yield strength. The annealed material averaged thirty six percent above and fourteen percent below the room temperature ultimate strength at –40°F and 160°F, respectively. The HERF forgings exhibited similar, slightly lower changes in ultimate strength with temperature. For completeness and illustrative purposes, the stress-strain curves are included for each of the tensile experiments conducted. The results of this study prompted a continuation study to determine tensile property changes of welded 304L stainless steel material with temperature, documented separately.

Keywords: 304L, stainless steel, HERF, forging, tensile properties, temperature effect

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Introduction

This report describes an experimental study that was completed for the Gas Transfer Systems (GTS) department. The study was prompted by the need for accurate tensile properties for 304L stainless steel in both the annealed and heavily worked HERF (High Energy Rate Forged) conditions over a specific temperature range –40°F to 160°F. Only limited tensile data for the annealed condition as a function of temperature is available from the literature [1-6], none that targeted this temperature range in detail. Room temperature tensile data for the HERF material exists from ongoing GTS related research at Sandia National Laboratories [7,8], but not at the limits of the temperature range of interest.

The tensile properties were needed as a function of temperature so the variation from room temperature properties could be considered in safety calculations routinely performed for GTS reservoirs. The results reported within quantify these variations.

Material

The 304L stainless steel material used for the annealed tensile property measurements was 2.5 inch diameter bar stock, material control number 116131-07. The quality acceptance certification report for this material is included in the appendix. Tensile specimens were prepared by EDM removal of 0.280 inch diameter cylinders from the bar stock, machining the cylinders into 0.125 inch diameter specimens, then annealing the specimens at 1000°C for 40 minutes. The EDM cylinder removal drawings and a photograph of the bar stock after EDM machining are shown in Figures 1 and 2. The tensile specimen dimensions are shown in Figure 3.

The HERF 304L stainless steel material was provided by the GTS department in the form of five reservoir forgings shown in Figure 4, labeled C, D, E, F, and G for this study. Similar to the steps followed for the annealed bar stock material, 0.280 inch diameter cylinders were removed from the forgings that were subsequently machined into 0.125 inch diameter specimens with dimensions shown in Figure 3. The EDM cylinder removal drawings and post-EDM machining photographs are shown in Figures 5-9 for forgings C, D, E, F, and G, respectively.

Forgings C and D were identical reservoir cup forgings (without stems). Forging C was used to determine the variability of HERF tensile properties at 160°F within a single forging. Forging D was used to determine the tensile property variation between three temperatures (-40°F, 70°F, 160°F). Forgings E and F were used similarly. Forgings E and F were identical reservoir cup forgings (with stems), forging E was used to determine the variability of HERF tensile properties at 160°F and forging F was used to determine the tensile property variation between three temperatures (-40°F, 70°F, 160°F). Forging G had a unique geometry with a straight wall section that allowed twice as many tensile specimens to be machined from the material as the other forgings. Forging G was used to determine the variation of tensile properties for four temperatures (-40°F, 70°F, 115°F, 160°F). The variation of tensile properties with temperature in the annealed bar stock material was determined for the same four temperatures. Note that the tensile specimen dimensions were identical for all materials and were chosen based on the maximum size specimen that could be accommodated in all of the forgings.

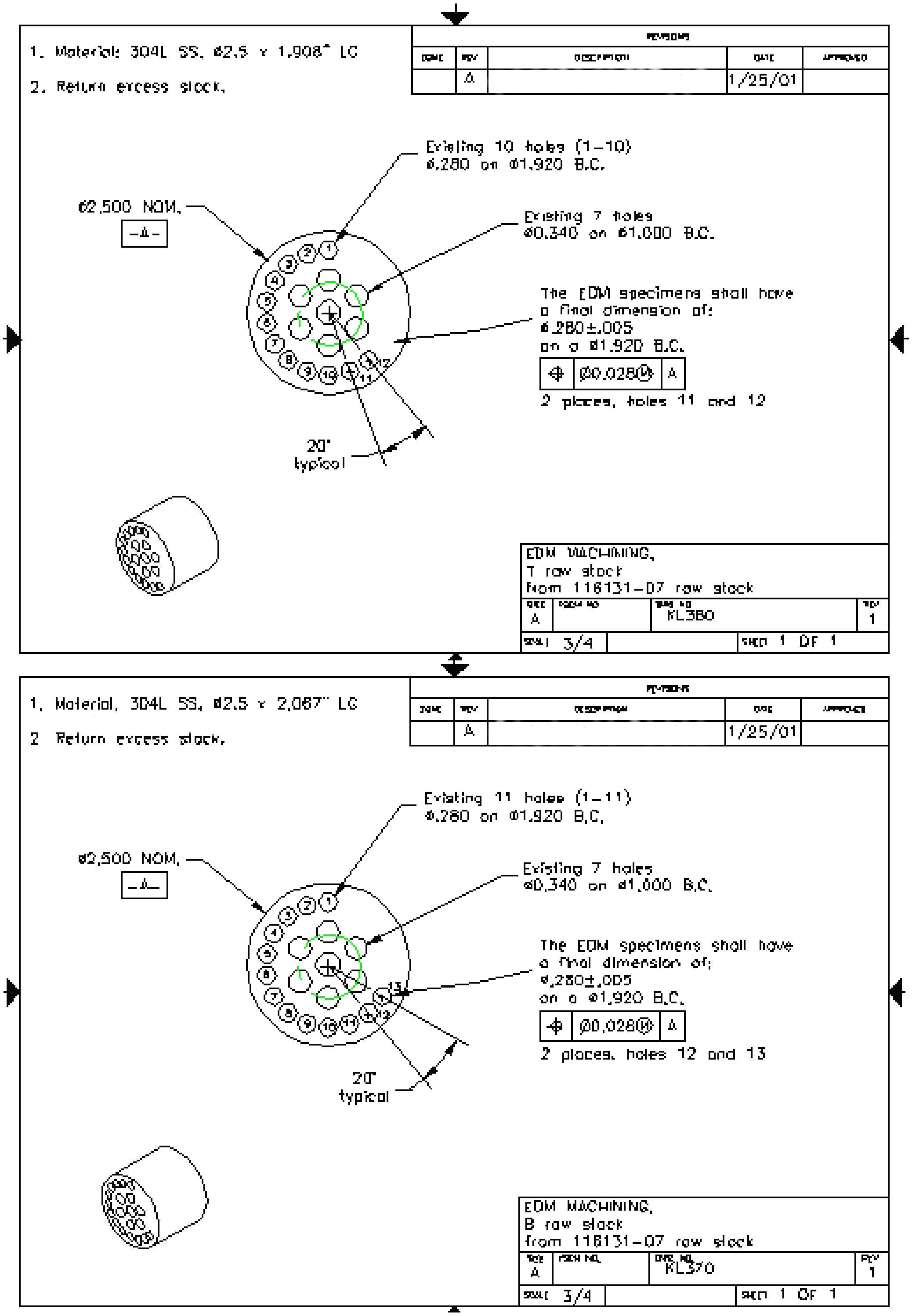

Figure 1. EDM cylinder removal drawings from 2.5 inch diameter 304L bar stock.

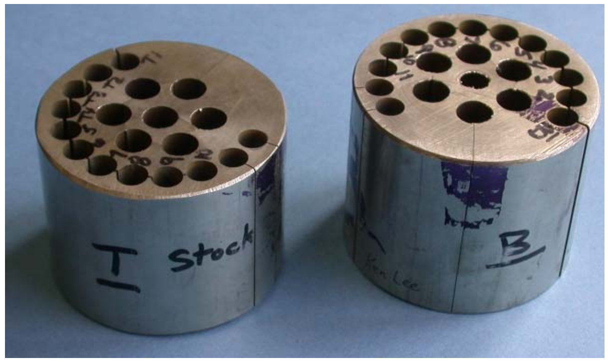

Figure 2. 304L stainless steel bar stock after specimen cylinder blank removal.

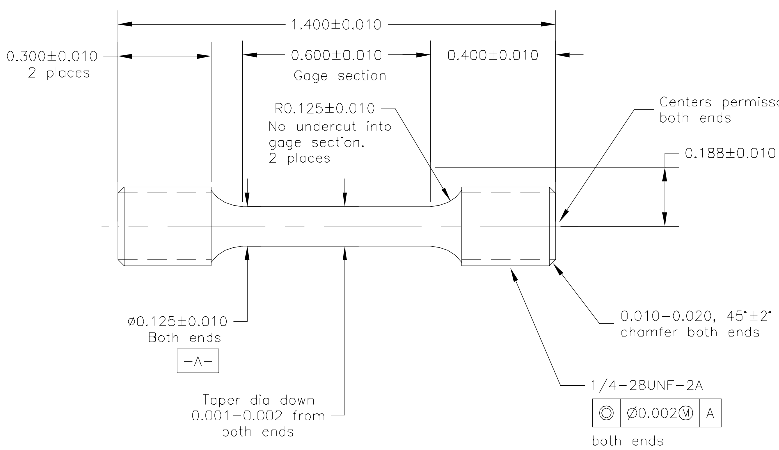

Figure 3. Dimensions of the 0.125 inch gage diameter tensile specimens.

Figure 4. 304L stainless steel HERF reservoir forgings C, D, E, F, and G.

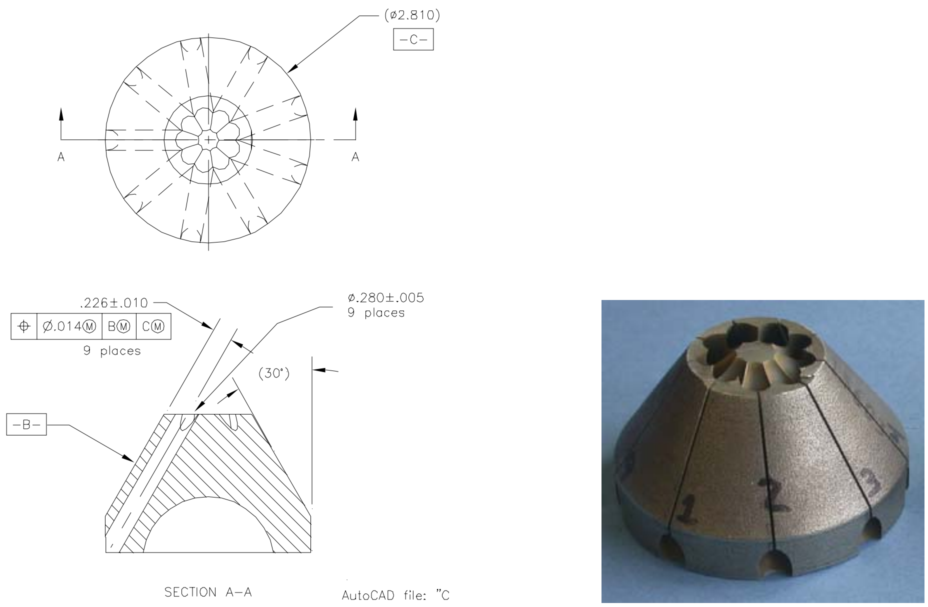

Figure 5. Tensile specimen cylinder removal plan and post-EDM photograph for HERF reservoir forging C.

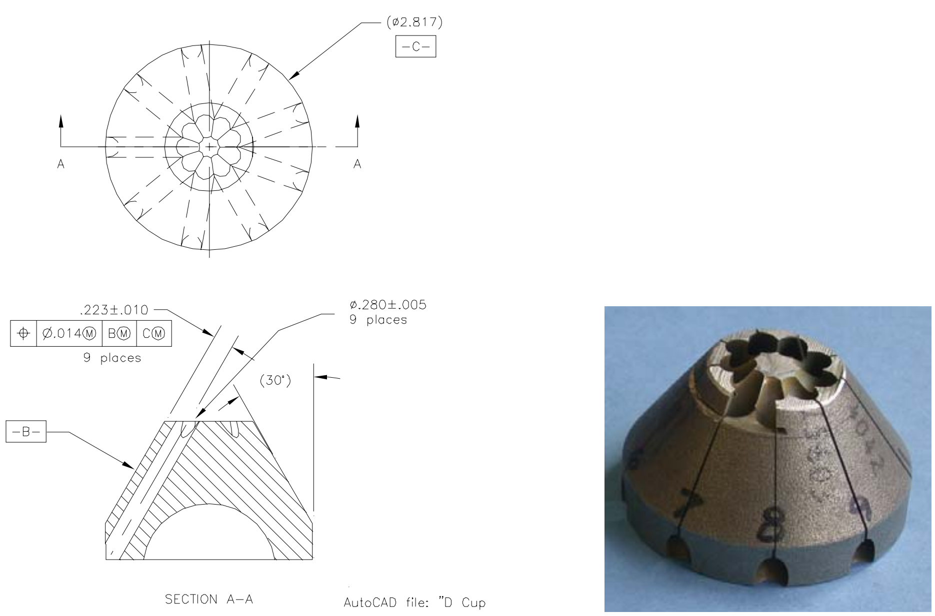

Figure 6. Tensile specimen cylinder removal plan and post-EDM photograph for HERF reservoir forging D.

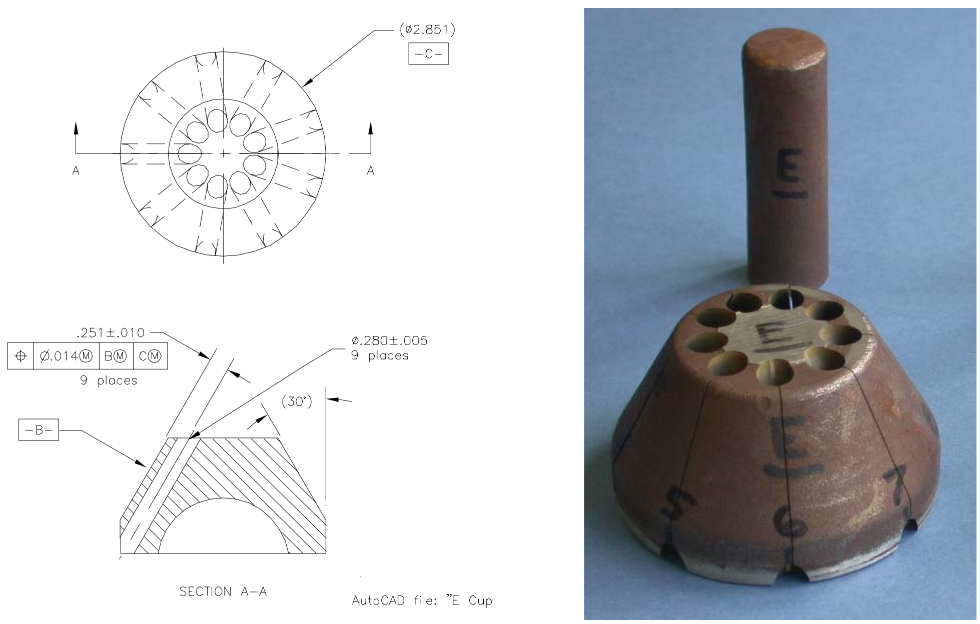

Figure 7. Tensile specimen cylinder removal plan and post-EDM photograph for HERF reservoir forging E.

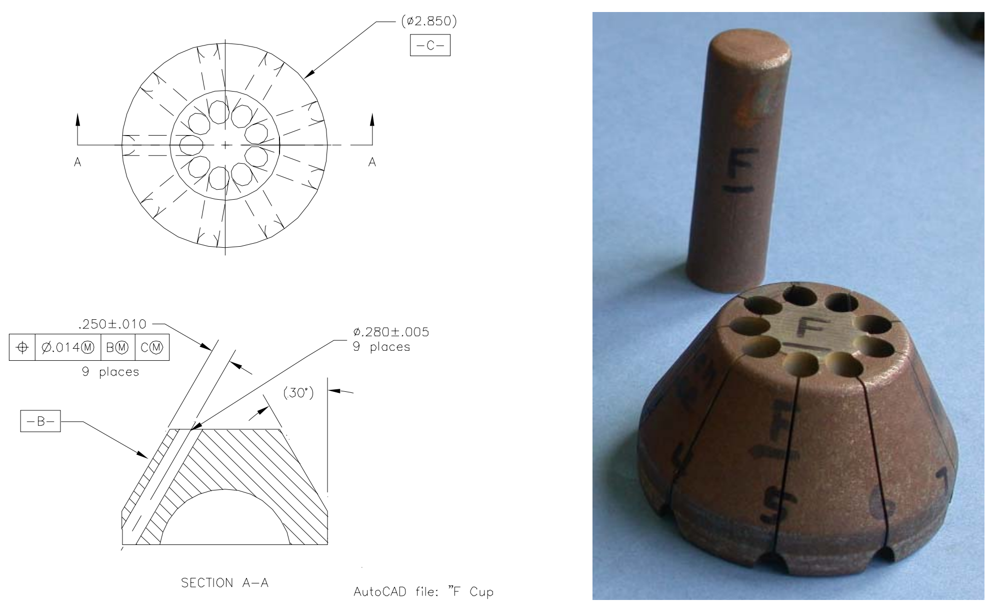

Figure 8. Tensile specimen cylinder removal plan and post-EDM photograph for HERF reservoir forging F.

Figure 9. Tensile specimen cylinder removal plan and post-EDM photograph for HERF reservoir forging G.

Experimental Method

The tensile specimens were tested on an MTS 880 20,000 pound load frame, which was controlled by an MTS TestStar 790.00 controller. The test frame and associated computer-controlled operating system are shown in Figure 10.

The loading fixtures and specimens were located within a Thermotron temperature chamber, FR-3-CH, which is controlled by an MTS 409.80 controller. This system provided convection heating for test temperatures above room temperature and provided convection cooling for the lower temperatures by blowing chilled air via liquid nitrogen input from a cryogenic dewar metered by a solenoid switch. A total of four type K thermocouples were used to ensure accurate temperature control. Thermocouples were not directly attached to the tensile specimens to avoid possibility of premature failure. Rather, one thermocouple was spot welded to each grip to measure the temperature across each specimen, one thermocouple was used to monitor the chamber air temperature and another thermocouple was used to control the chamber air temperature. An MTS extensometer, 632.138-20 S/N 411, was used for strain measurement and control. This extensometer had a gage length of 0.500" with a total travel of 0.075". Figure 11 shows a close up photograph of a failed tensile specimen following testing at –40°F with the extensometer located across the failed gage section. All transducers that were used were calibrated and are traceable to Lockheed Martin Standards Laboratory according to ASTM E4 [9] standard.

Figure 10. MTS 880 load frame and control system used for tensile experiments.

Figure 11. Failed tensile specimen tested at –40°F.

Experimental Results

A total of seventy-four tensile tests were conducted to evaluate temperature effects: twenty from the annealed 304L 2.5 inch diameter bar stock, nine each from forgings C, D, E and F, and eighteen from forging G. Tables 1 and 2 show the test matrix, including test temperature, specimen dimensions and test order for the annealed and HERF specimens, respectively. All tests were conducted according to ASTM E8 [10] tensile test standard. Tests were initiated in strain control at a strain rate of 1×10^{-5}/s to at least 1.1% strain, followed by 1×10^{-4}/s to the extensometer limit of 15% strain, then continuing at a strain rate of about 1×10^{-4}/s by controlling in stroke control at 0.0005 in/s to failure.

For each of the six types of materials (annealed, forgings C, D, E, F and G) there are three data plots shown. Each plot includes all specimens tested of that particular material. For each material, the first plot is engineering stress versus engineering strain to failure, the second plot is engineering stress versus engineering strain in the low strain region to better illustrate yield dependency, and the third plot is true stress versus true strain. The standard definitions of stresses and strains were used in the calculations to produce these plots. Note that the true stress is valid only until maximum stress is reached, after that specimen necking results in invalid calculated true strain values. The curves are shown until failure for illustration, with a reminder of this caveat. For all materials at all temperatures, an elastic modulus of 29×10^6 psi was used to determine the 0.2% offset yield strength. Additionally, for each of the six materials a summary table of the measured tensile properties is included following the stress versus strain curves.

SPECIMEN NUMBER	MATERIAL	TEST TEMPERATURE (°F)	DIA (IN)	TEST ORDER #
T1	annealed	-40	0.1254	65
T2	annealed	-40	0.1257	67
T3	annealed	-40	0.1256	71
T4	annealed	-40	0.1254	68
T5	annealed	-40	0.1253	66
T6	annealed	70	0.1254	15
T7	annealed	70	0.1255	8
T8	annealed	70	0.1255	4
T9	annealed	70	0.1256	7
T10	annealed	70	0.1255	9
B1	annealed	115	0.1255	55
B2	annealed	115	0.1255	57
B3	annealed	115	0.1255	51
B4	annealed	115	0.1256	58
B5	annealed	115	0.1256	53
B6	annealed	160	0.1255	22
B7	annealed	160	0.1257	49
B8	annealed	160	0.1256	21
B9	annealed	160	0.1257	40
B10	annealed	160	0.1256	34

Table 1. Test matrix for annealed 304L stainless steel tensile specimens.

SPECIMEN NUMBER	MATERIAL	TEST TEMPERATURE (°F)	DIA (IN)	TEST ORDER #
C1	Forging C	160	0.1236	38
C2	Forging C	160	0.1237	23
C3	Forging C	160	0.1237	28
C4	Forging C	160	0.1237	30
C5	Forging C	160	0.1236	18
C6	Forging C	160	0.1236	17
C7	Forging C	160	0.1237	44
C8	Forging C	160	0.1236	24
C9	Forging C	160	0.1237	33
D1	Forging D	-40	0.1236	60
D2	Forging D	70	0.1236	10
D3	Forging D	160	0.1236	25
D4	Forging D	-40	0.1236	59
D5	Forging D	70	0.1235	11
D6	Forging D	160	0.1235	19
D7	Forging D	-40	0.1235	64
D8	Forging D	70	0.1237	5
D9	Forging D	160	0.1236	36
E1	Forging E	160	0.1225	31
E2	Forging E	160	0.1219	39
E3	Forging E	160	0.1235	16
E4	Forging E	160	0.1235	35
E5	Forging E	160	0.1236	48
E6	Forging E	160	0.1235	47
E7	Forging E	160	0.1237	45
E8	Forging E	160	0.1236	20
E9	Forging E	160	0.1222	27
F1	Forging F	-40	0.1238	70
F2	Forging F	70	0.1236	12
F3	Forging F	160	0.1235	42
F4	Forging F	-40	0.1235	63
F5	Forging F	70	0.1237	3
F6	Forging F	160	0.1234	26
F7	Forging F	-40	0.1235	69
F8	Forging F	70	0.1236	1
F9	Forging F	160	0.1234	41
G1	Forging G	-40	0.1232	74
G2	Forging G	-40	0.1233	73
G3	Forging G	70	0.1235	2
G4	Forging G	115	0.1233	54
G5	Forging G	160	0.1233	43
G6	Forging G	160	0.1234	29
G7	Forging G	-40	0.1233	62
G8	Forging G	70	0.1234	14
G9	Forging G	70	0.1236	6
G10	Forging G	115	0.1233	56
G11	Forging G	160	0.1233	50
G12	Forging G	160	0.1235	37
G13	Forging G	-40	0.1234	61
G14	Forging G	-40	0.1234	72
G15	Forging G	70	0.1233	13
G16	Forging G	115	0.1234	52
G17	Forging G	160	0.1233	46
G18	Forging G	160	0.1234	32

Table 2. Test matrix for HERF stainless steel tensile specimens.

The results for the annealed 304L material are shown in Figures 12, 13 and 14 and summarized in Table 3 for each of the four test temperatures. The scatter between the five tests at each temperature is low. The dependency of the yield and ultimate strengths on temperature is apparent in the plots, with a monotonic decrease in strength with temperature. However, the strain to failure decreases from its room temperature value for temperatures both above and below room temperature. This behavior of 304L has been observed in other works [11].

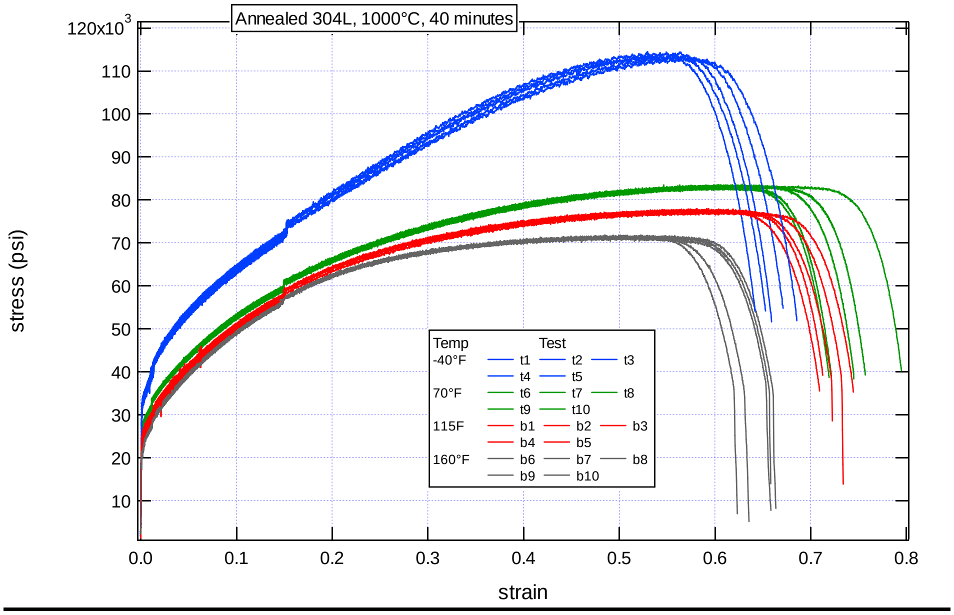

Figure 12. Engineering stress versus engineering strain for annealed 304L specimens.

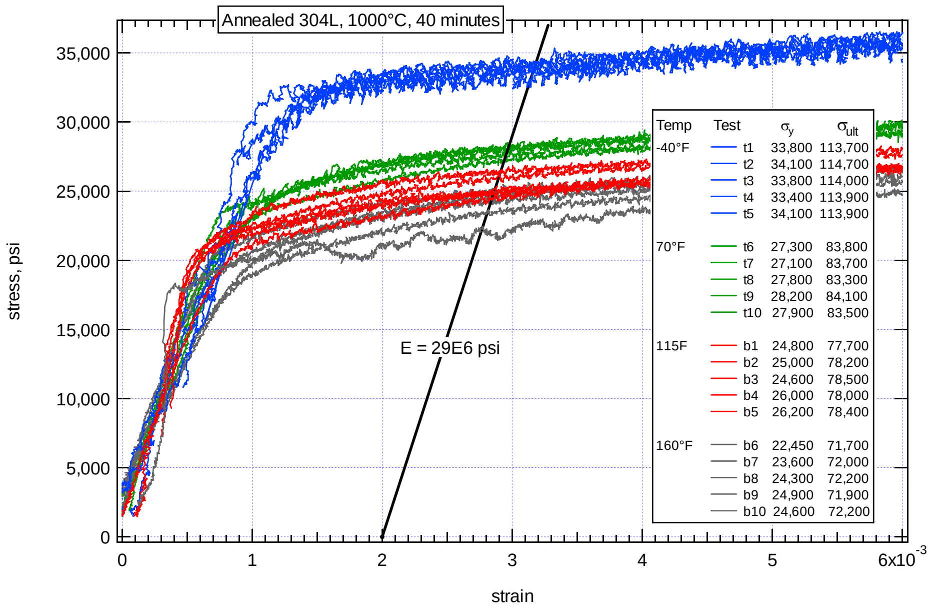

Figure 13. Engineering stress versus engineering strain at low strain for annealed 304L specimens.

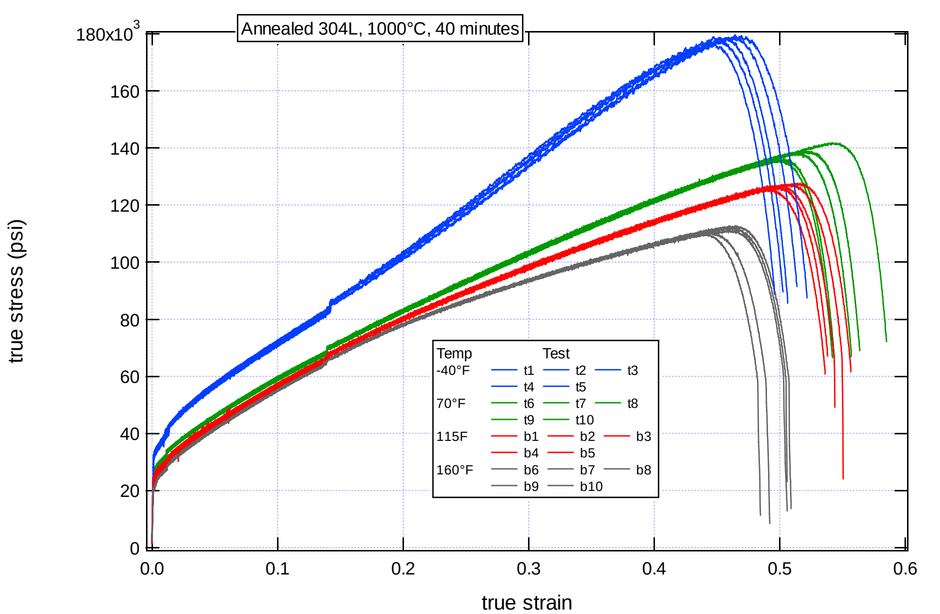

Figure 14. True stress versus true strain for annealed 304L specimens.

Test Temperature (°F)	Specimen Number	0.2% Yield Stress (psi)	Ultimate Stress (psi)	engineering strain to failure
-40	T1	33,800	113,700	0.687
-40	T2	34,100	114,700	0.659
-40	T3	33,800	114,000	0.653
-40	T4	33,400	113,900	0.671
-40	T5	34,100	113,900	0.642
-40	AVERAGE	33,840	114,040	0.662
70	T6	27,300	83,800	0.795
70	T7	27,100	83,700	0.757
70	T8	27,800	83,300	0.722
70	T9	28,200	84,100	0.745
70	T10	27,900	83,500	0.719
70	AVERAGE	27,660	83,680	0.748
115	B1	24,800	77,700	0.744
115	B2	25,000	78,200	0.709
115	B3	24,600	78,500	0.723
115	B4	26,000	78,000	0.734
115	B5	26,200	78,400	0.713
115	AVERAGE	25,320	78,160	0.725
160	B6	22,450	71,700	0.658
160	B7	23,600	72,000	0.636
160	B8	24,300	72,200	0.623
160	B9	24,900	71,900	0.658
160	B10	24,600	72,200	0.664
160	AVERAGE	23,970	72,000	0.648

Table 3. Measured tensile properties of annealed 304L at –40°F, 70°F, 115°F and 160°F.

The results for the HERF material from forging C are shown in Figures 15, 16 and 17 and summarized in Table 4. All tests were conducted at 160°F. The average tensile yield strength for forging C at 160°F is 65,675 psi and the average ultimate strength at 160°F is 87,370 psi. Although there is scatter between tests in the strain to failure, the data and strengths show very little variability within the forging. Note that test C2 was not completed due to equipment malfunction, however the test was valid past yield.

The results for the HERF material from forging D are shown in Figures 18, 19 and 20 and summarized in Table 5. Tests were conducted at three temperatures: –40°F, 70°F, and 160°F. As in the annealed material, the dependency of yield and ultimate strength is apparent, but not as significant. The average yield and ultimate strengths from the three experiments at 160°F are 66,167 psi and 87,933 psi and compare extremely well to the measured values in forging C, which is identical to forging D. Again, scatter between tests at a given temperature is mostly exhibited in the strain to failure values. Unlike the annealed 304L behavior, the strain to failure decreases monotonically with temperature in this heavily worked 304L.

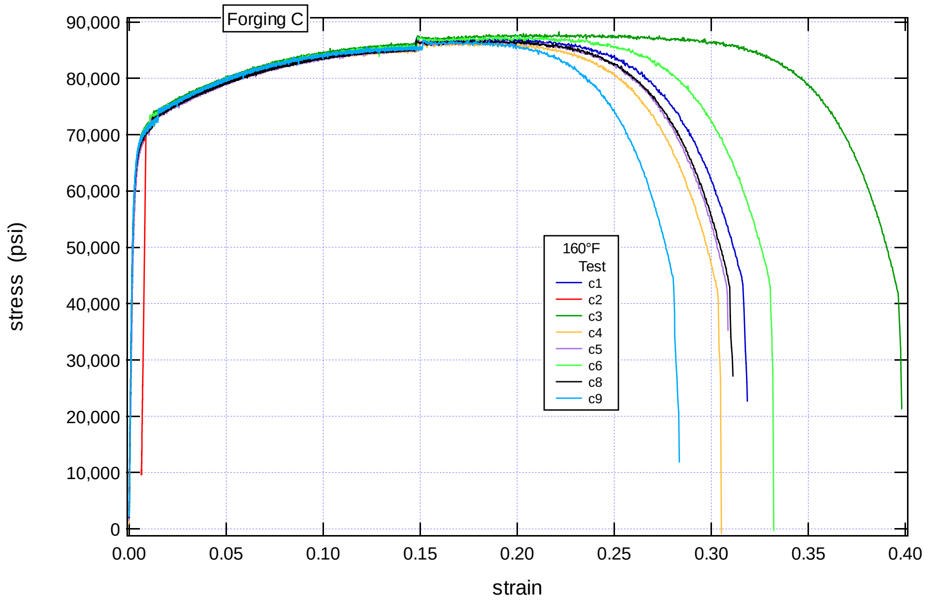

Figure 15. Engineering stress versus engineering strain for Forging C specimens.

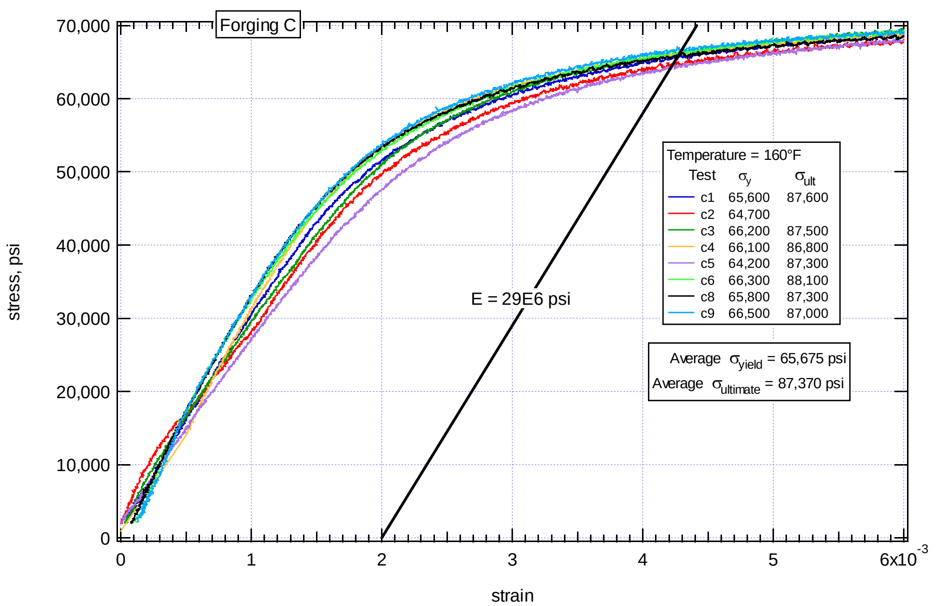

Figure 16. Engineering stress versus engineering strain at low strain for Forging C specimens.

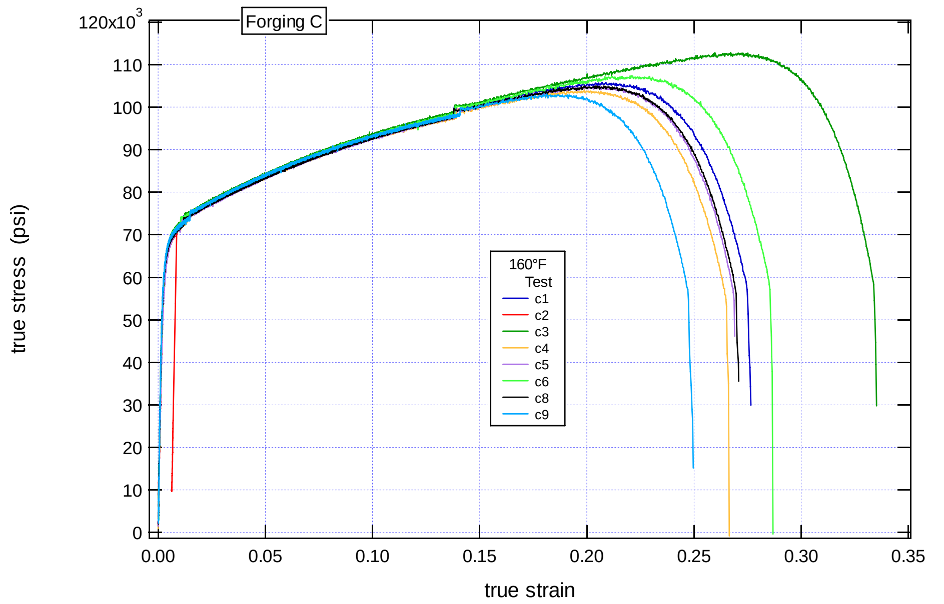

Figure 17. True stress versus true strain for Forging C specimens.

Test Temperature (°F)	Specimen Number	0.2% Yield Stress (psi)	Ultimate Stress (psi)	engineering strain to failure
160	C1	65,600	87,600	0.319
160	C2	64,700		
160	C3	66,200	87,500	0.398
160	C4	66,100	86,800	0.305
160	C5	64,200	87,300	0.309
160	C6	66,300	88,100	0.332
160	C8	65,800	87,300	0.311
160	C9	66,500	87,000	0.283
160	Average	65,675	87,370	0.322
	Standard Deviation	817	423	0.036

Table 4. Measured tensile properties of Forging C at 160°F.

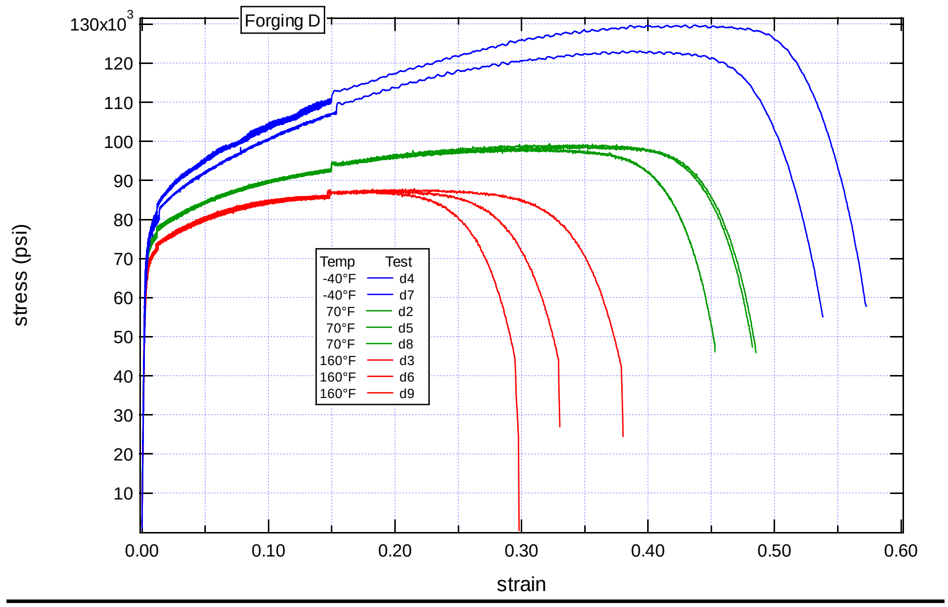

Figure 18. Engineering stress versus engineering strain for Forging D specimens.

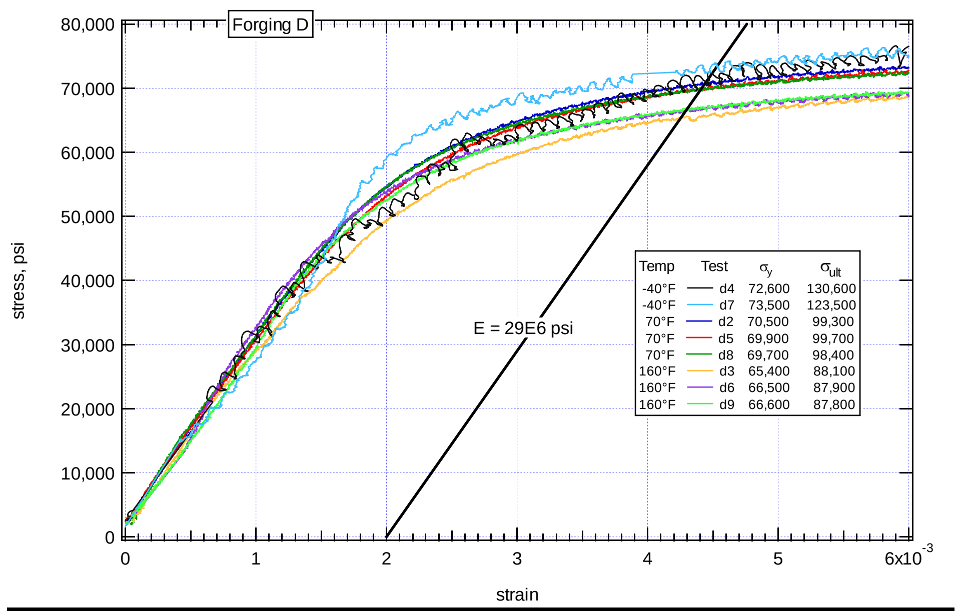

Figure 19. Engineering stress versus engineering strain at low strain for Forging D specimens.

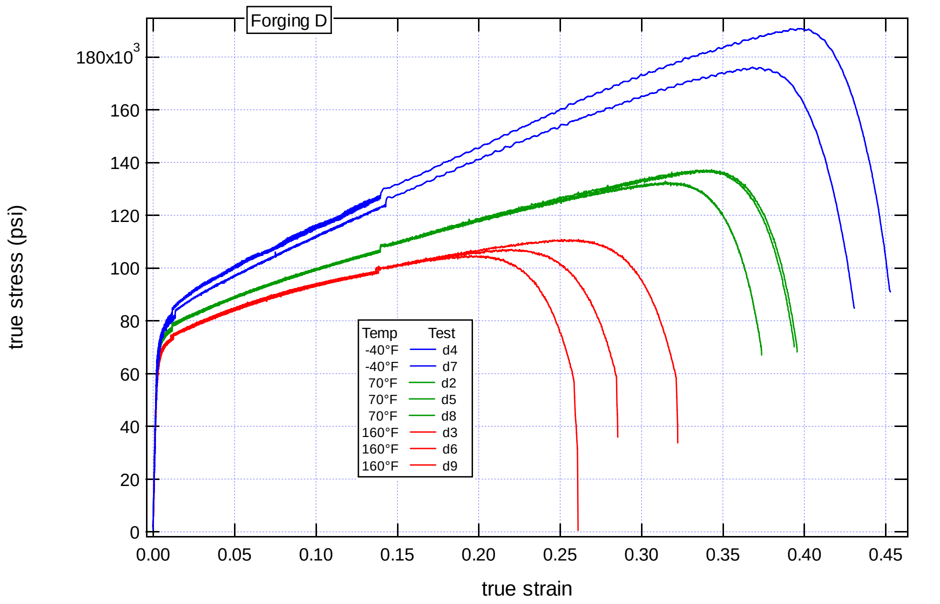

Figure 20. True stress versus true strain for Forging D specimens.

Test Temperature (°F)	Specimen Number	0.2% Yield Stress (psi)	Ultimate Stress (psi)	engineering strain to failure
-40	D4	72,600	130,600	0.572
-40	D7	73,500	123,500	0.538
-40	AVERAGE	73,050	127,050	0.555
70	D2	70,500	99,300	0.485
70	D5	69,900	99,700	0.483
70	D8	69,700	98,400	0.453
70	AVERAGE	70,033	99,133	0.474
160	D3	65,400	88,100	0.380
160	D6	66,500	87,900	0.298
160	D9	66,600	87,800	0.330
160	AVERAGE	66,167	87,933	0.336

Table 5. Measured tensile properties of Forging D at –40°F, 70°F and 160°F.

The results for the HERF material from forging E are shown in Figures 21, 22 and 23 and summarized in Table 6. All tests were conducted at 160°F. The average tensile yield strength for forging E at 160°F is 53,590 psi and the average ultimate strength at 160°F is 81,956 psi, with little variation noted within the forging. The strength of forging E at 160°F is lower than the similar forging C (no stem), likely due to less energy introduced during the forging process with the stem present. Strain to failure values ranged from 0.419 to 0.480.

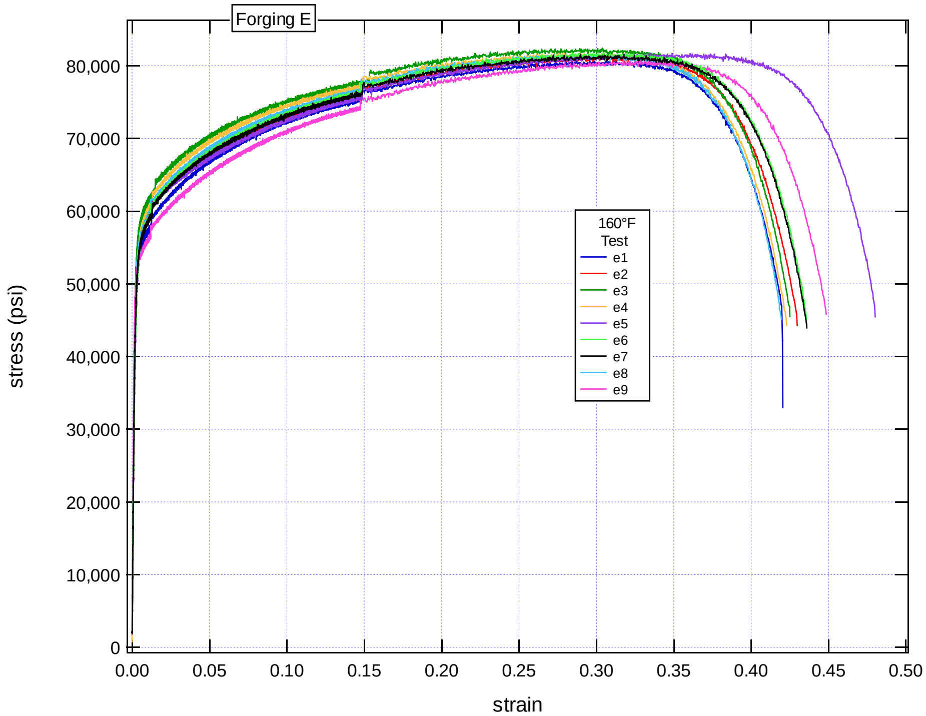

Figure 21. Engineering stress versus engineering strain for Forging E specimens.

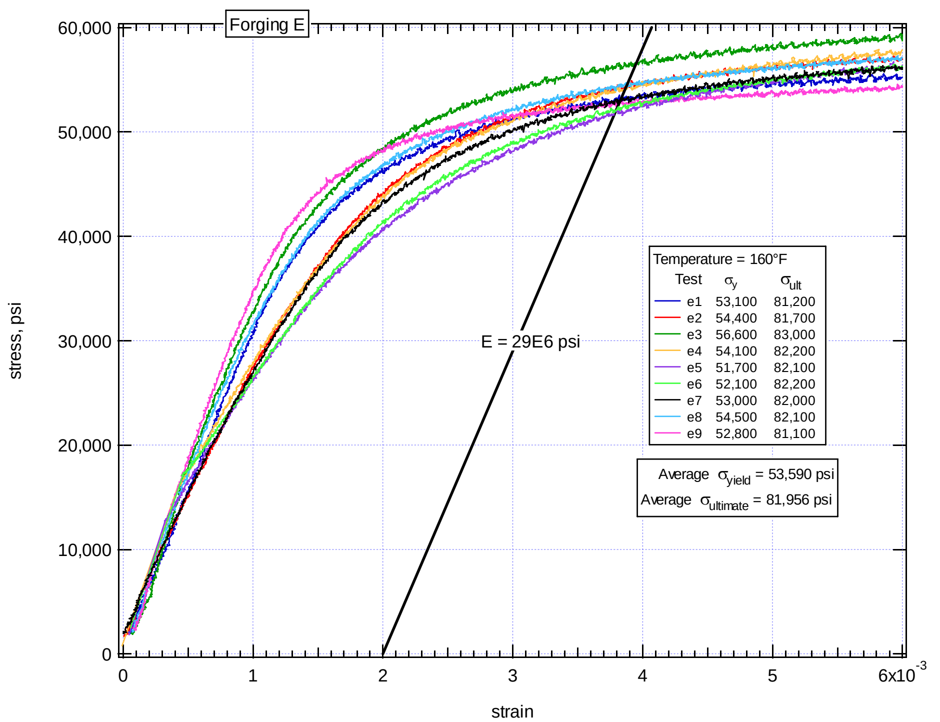

Figure 22. Engineering stress versus engineering strain at low strain for Forging E specimens.

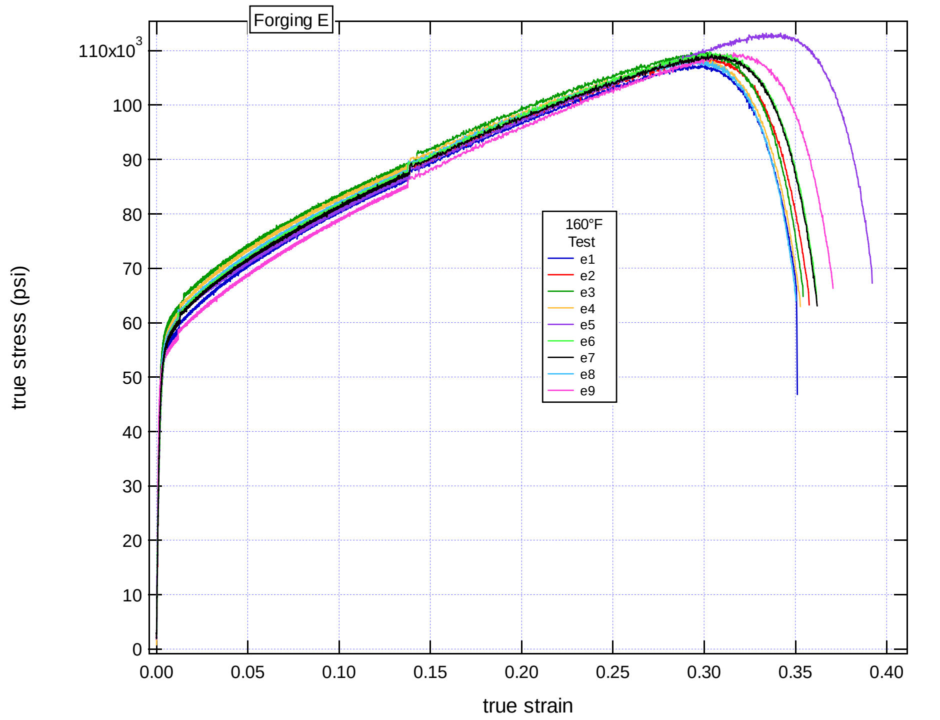

Figure 23. True stress versus true strain for Forging E specimens.

Test Temperature (°F)	Specimen Number	0.2% Yield Stress (psi)	Ultimate Stress (psi)	engineering strain to failure
160	E1	53,100	81,200	0.420
160	E2	54,400	81,700	0.430
160	E3	56,600	83,000	0.425
160	E4	54,100	82,200	0.423
160	E5	51,700	82,100	0.480
160	E6	52,100	82,200	0.434
160	E7	53,000	82,000	0.436
160	E8	54,500	82,100	0.419
160	E9	52,800	81,100	0.448
160	Average	53,590	81,956	0.435
	Standard Deviation	1,492	573	0.019

Table 6. Measured tensile properties of Forging E at 160°F.

The results for the HERF material from forging F are shown in Figures 24, 25 and 26 and summarized in Table 7. Tests were conducted at three temperatures: –40°F, 70°F, and 160°F. The average yield and ultimate strengths from the two experiments at 160°F are 55,850 psi and 84,215 psi and compare well to the measured values in forging E, which is identical to forging F. As noted for forging D, the heavily worked material has strain to failure values that decrease monotonically with temperature. Also, a similar reduction in strength is noted between forgings F and D, as between forgings E and C due to the stem presence.

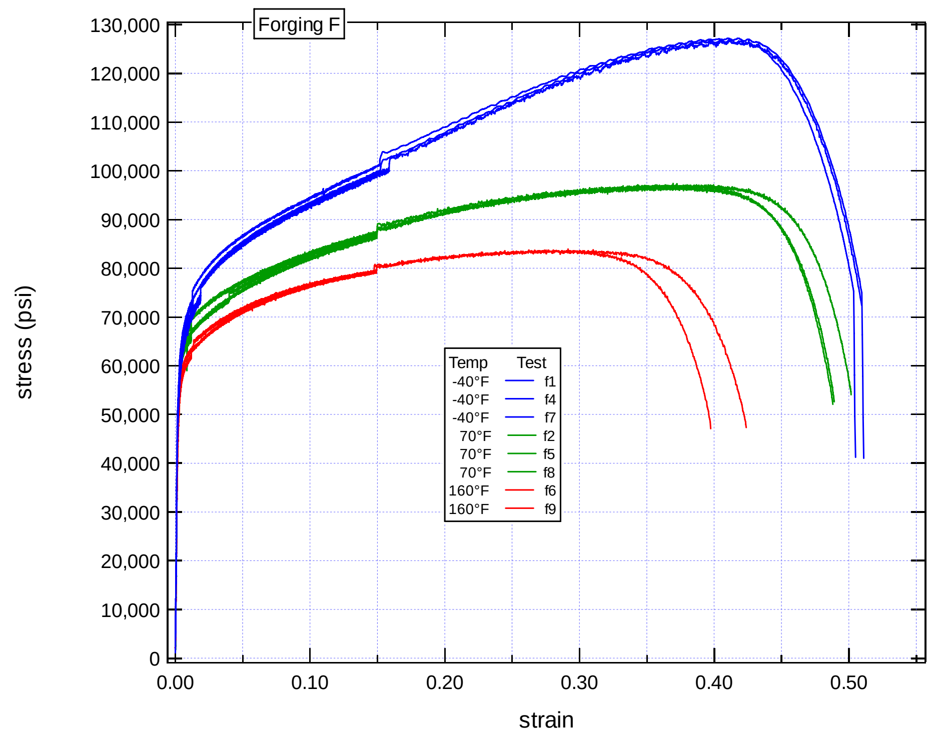

Figure 24. Engineering stress versus engineering strain for Forging F specimens.

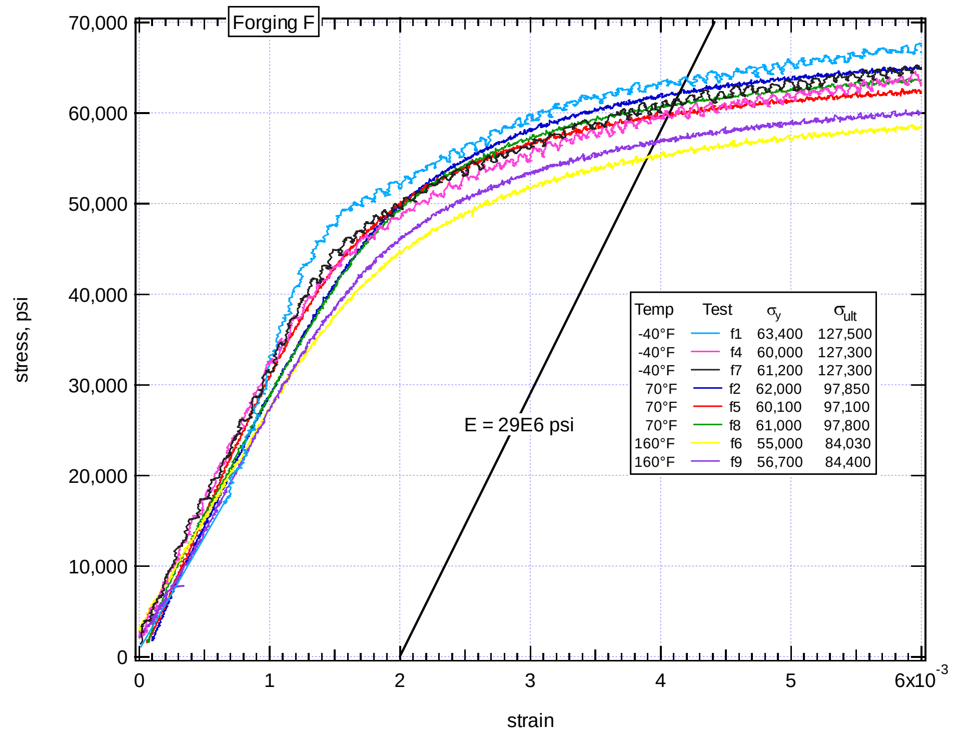

Figure 25. Engineering stress versus engineering strain at low strain for Forging F specimens.

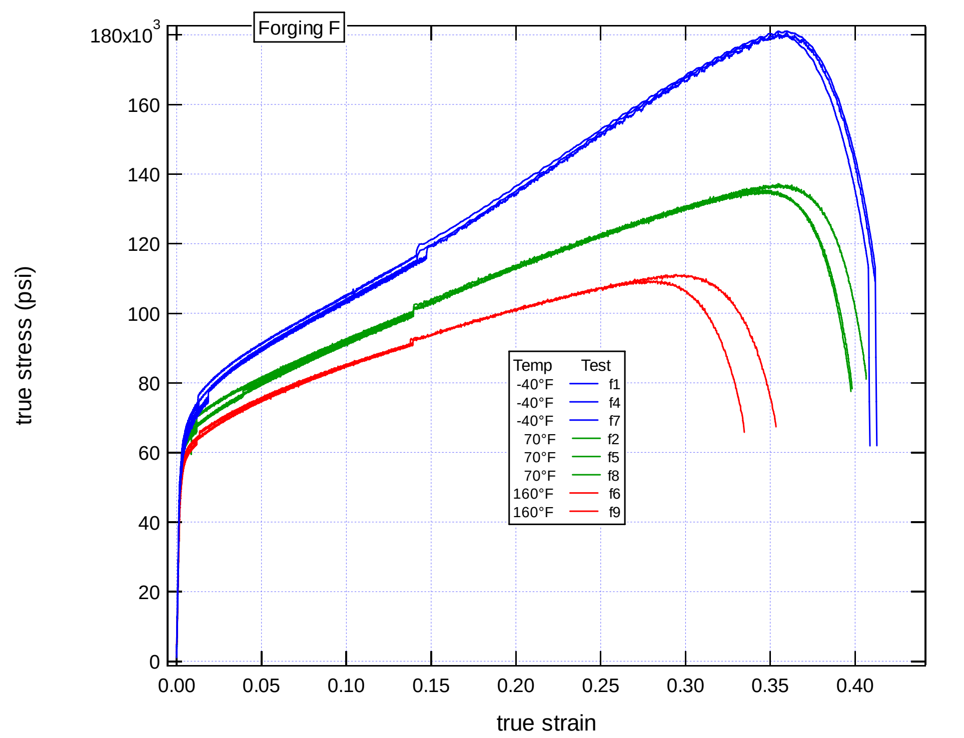

Figure 26. True stress versus true strain for Forging F specimens.

Test Temperature (°F)	Specimen Number	0.2% Yield Stress (psi)	Ultimate Stress (psi)	engineering strain to failure
-40	F1	63,400	127,500	0.511
-40	F4	60,000	127,300	0.509
-40	F7	61,200	127,300	0.505
-40	AVERAGE	61,533	127,367	0.508
70	F2	62,000	97,850	0.488
70	F5	60,100	97,100	0.489
70	F8	61,000	97,800	0.501
70	AVERAGE	61,033	97,583	0.493
160	F6	55,000	84,030	0.397
160	F9	56,700	84,400	0.424
160	AVERAGE	55,850	84,215	0.411

Table 7. Measured tensile properties of Forging F at –40°F, 70°F and 160°F.

The results for the HERF material from forging G are shown in Figures 27, 28 and 29 and summarized in Table 8. Tests were conducted at four temperatures: –40°F, 70°F, 115°F and 160°F. The average yield and ultimate strengths from the six experiments at 160°F are 49,533 psi and 76,850 psi, lowest of all of the forging designs. For each test temperature, very little scatter is observed in the measured strength values. Once again, the strain to failure values decrease monotonically with temperature in this HERF material.

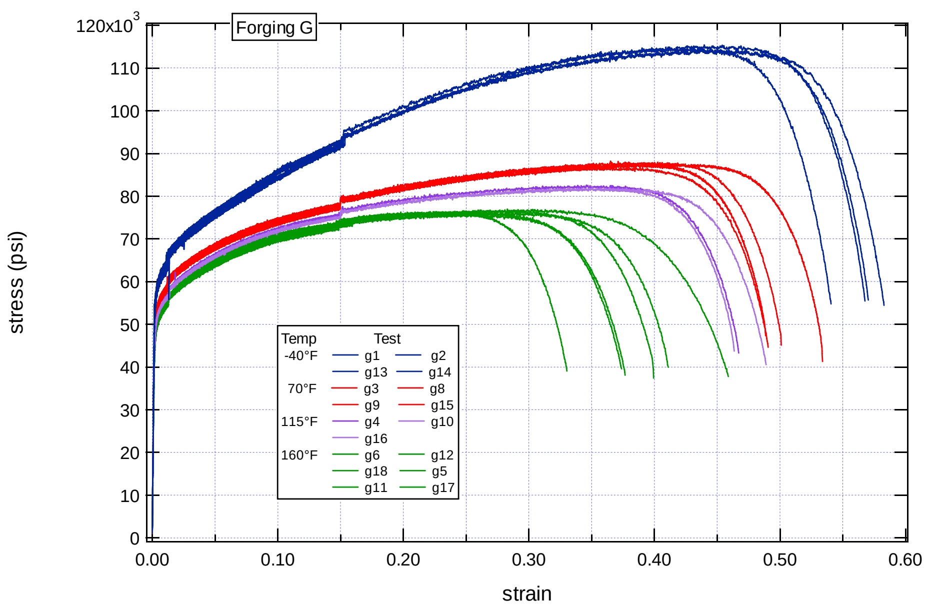

Figure 27. Engineering stress versus engineering strain for Forging G specimens.

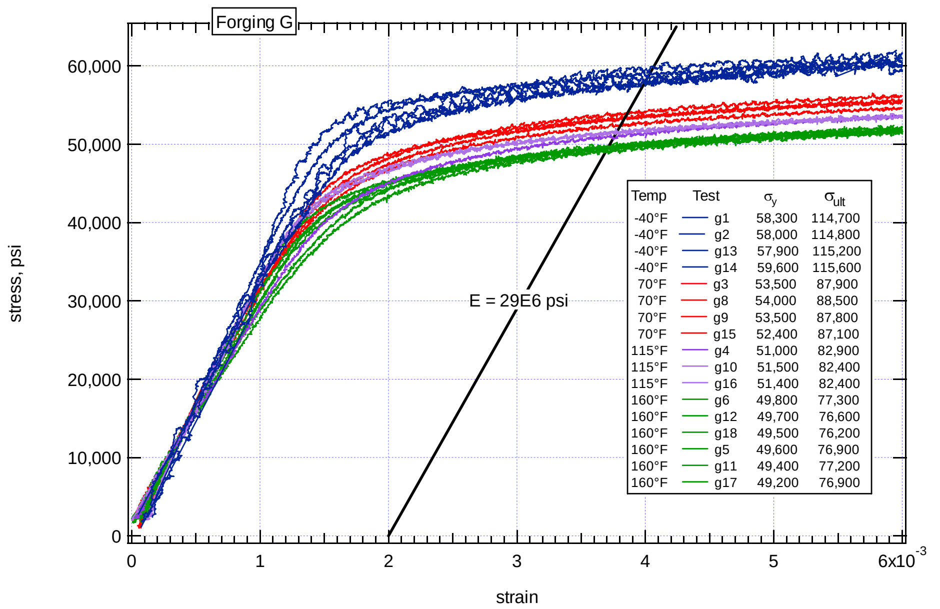

Figure 28. Engineering stress versus engineering strain at low strain for Forging G specimens.

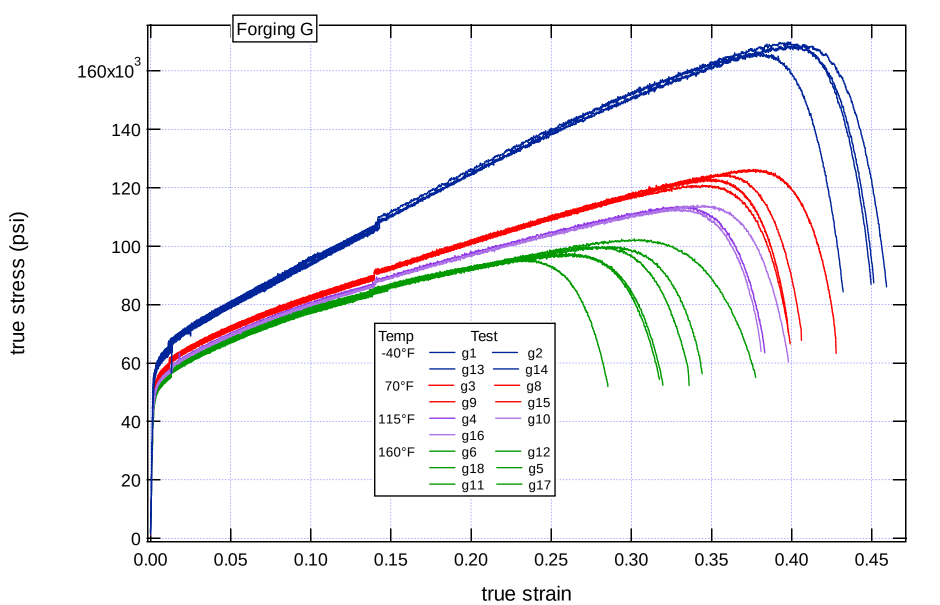

Figure 29. True stress versus true strain for Forging G specimens.

Test Temperature (°F)	Specimen Number	0.2% Yield Stress (psi)	Ultimate Stress (psi)	engineering strain to failure
-40	G1	58,300	114,700	0.583
-40	G2	58,000	114,800	0.570
-40	G13	57,900	115,200	0.541
-40	G14	59,600	115,500	0.568
-40	AVERAGE	58,450	115,050	0.566
70	G3	53,500	87,900	0.534
70	G8	54,000	88,500	0.501
70	G9	53,500	87,800	0.489
70	G15	52,400	87,100	0.491
70	AVERAGE	53,350	87,825	0.504
115	G4	51,000	82,900	0.467
115	G10	51,500	82,400	0.464
115	G16	51,400	82,400	0.489
115	AVERAGE	51,300	82,567	0.473
160	G6	49,800	77,300	0.458
160	G12	49,700	76,600	0.410
160	G18	49,500	76,200	0.377
160	G5	49,600	76,900	0.330
160	G11	49,400	77,200	0.399
160	G17	49,200	76,900	0.373
160	Average	49,533	76,850	0.391
	Standard Deviation	216	404	0.043

Table 8. Tensile yield stress and ultimate strength of Forging G at –40°F, 70°F, 115°F and 160°F.

To allow easy comparison between the materials, the average tensile yield strength of the annealed bar stock and four forgings as a function of test temperature is shown in Figure 30. The strength that the HERF process imparts to the 304L material is obvious in this figure. The same data is plotted in Figure 31 as the change in value from the room temperature value. This figure illustrates the lower temperature dependence of 304L noted after the HERF forging process. A plot of the annealed 304L yield strength as a function of temperature from MIL handbook 5 is included in Figure 32 for comparison to this study. This data shows a similar decrease in yield strength at 160°F, about 10%, and a lower increase in yield strength at –40°F, about 10%, than the >20% observed in the current study.

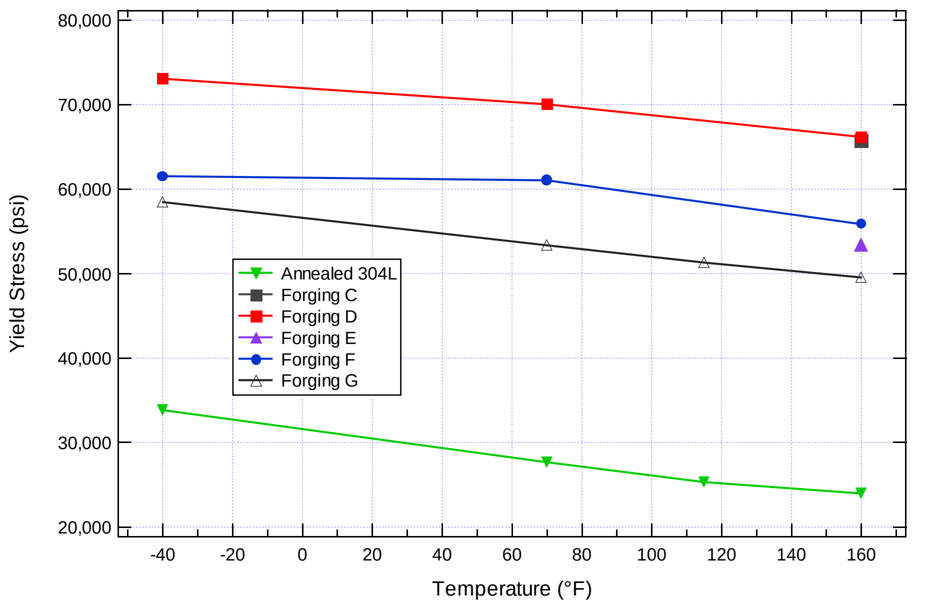

Figure 30. Tensile yield stress as a function of temperature for annealed and HERF material.

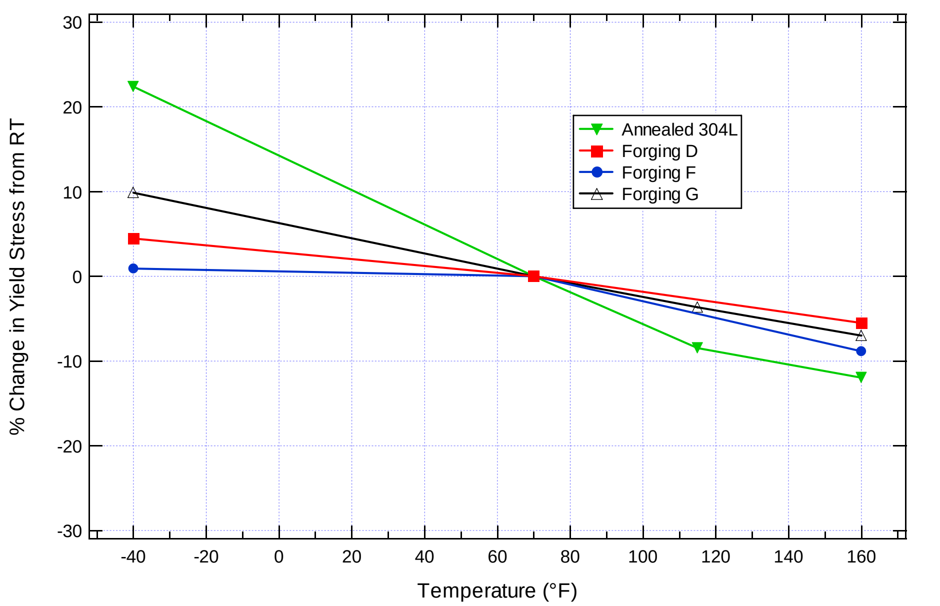

Figure 31. Change in tensile yield stress from 70°F for annealed and HERF material.

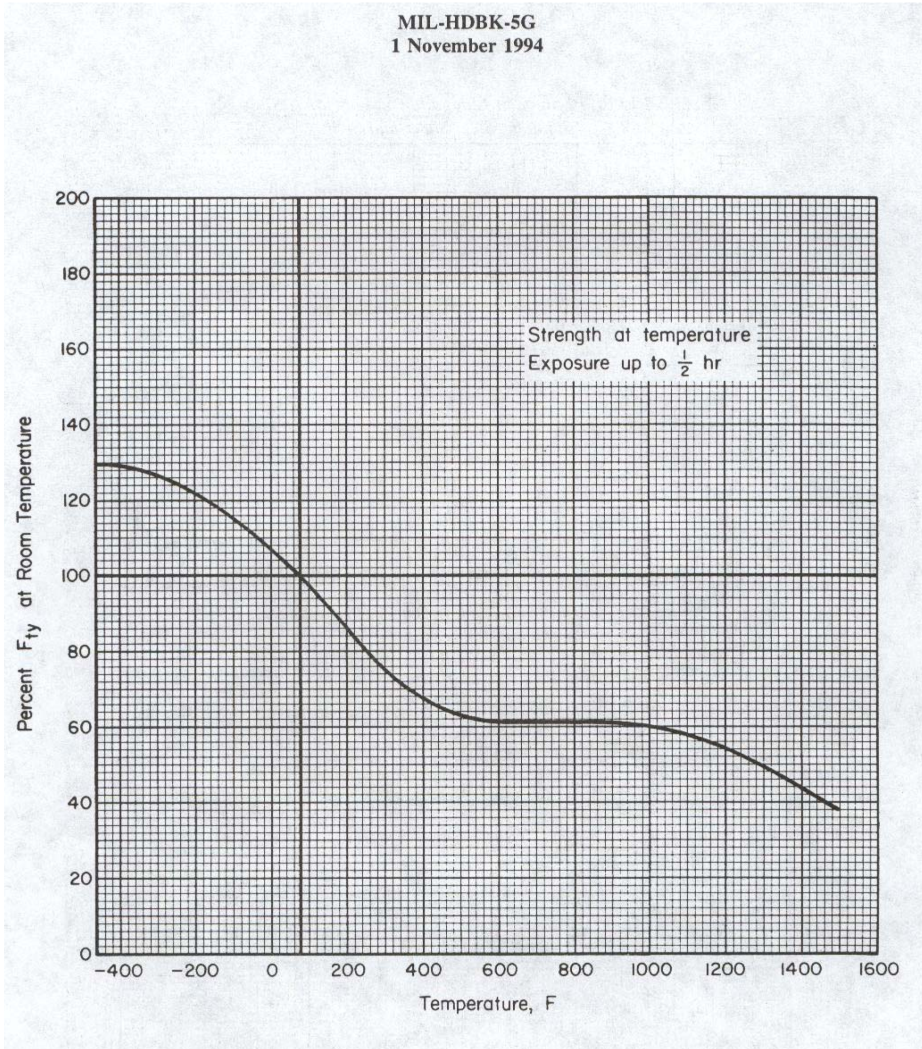

Figure 32. Effect of temperature on the tensile yield strength of AISI 301, 302, 304, 304L, 321 and 347 annealed stainless steel [1].

For comparison of the ultimate yield strength between the materials, the average ultimate strength of the annealed bar stock and four forgings as a function of test temperature is shown in Figure 33. Although the ultimate strength of the HERF material is higher than the annealed 304L, the difference is not as significant as it was for the yield strength. The same data is plotted in Figure 34 as the change in value from the room temperature value. The ultimate strength shows more temperature dependence than the yield strength. However, the HERF forging process does not result in a significant reduction on the temperature dependence of the ultimate strength as it did on the yield strength. A plot of the annealed 304L ultimate strength as a function of temperature from MIL handbook 5 is included in Figure 35 for comparison to this study. This data shows a similar decrease in yield strength at 160°F, about 15%, and a similar increase in yield strength at –40°F, about 25%, as the current study. Finally, the average change in tensile properties with temperature for annealed and HERF materials is tabulated in Table 9.

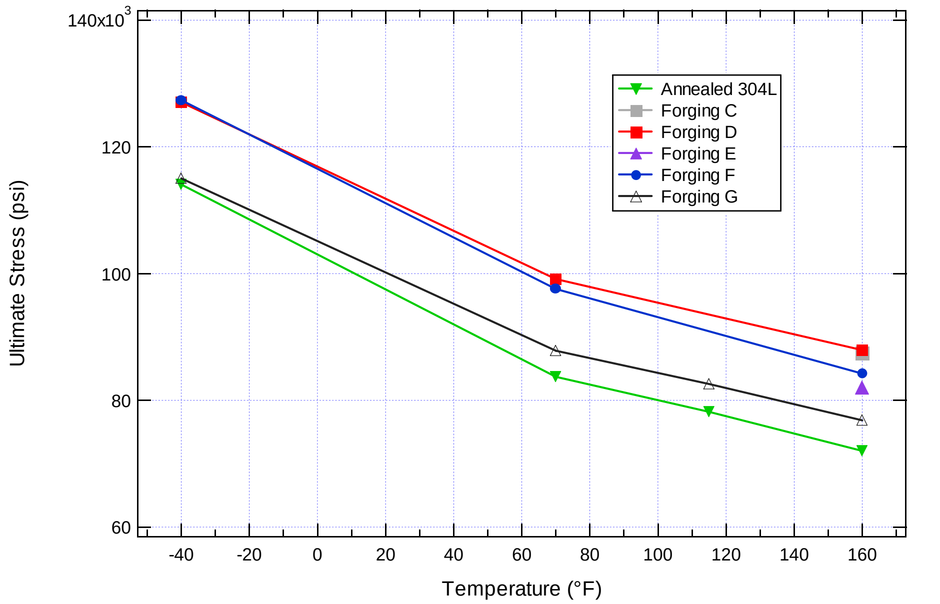

Figure 33. Tensile ultimate strength as a function of temperature for annealed and HERF material.

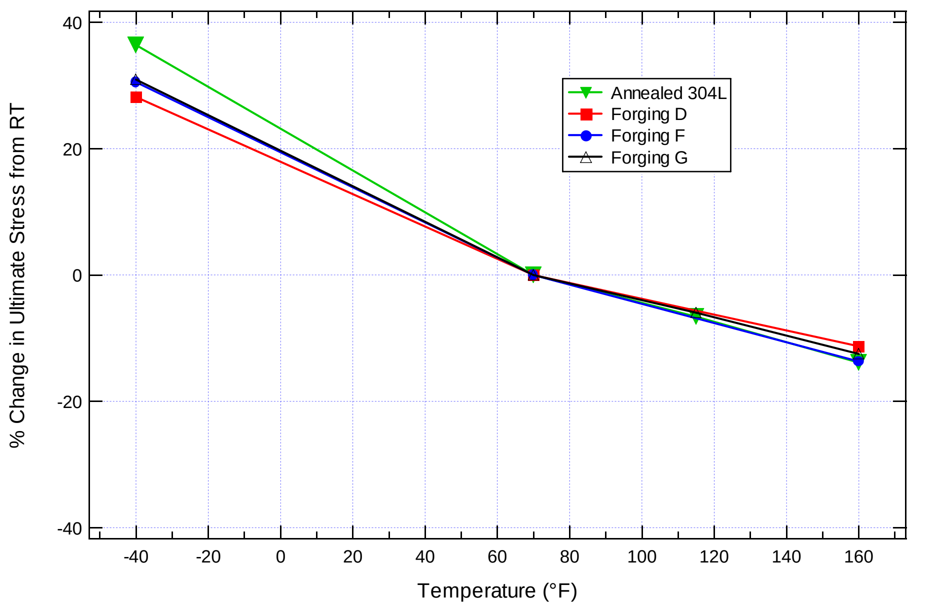

Figure 34. Change in tensile ultimate strength from 70°F for annealed and HERF material.

MIL-HDBK-5G
1 November 1994

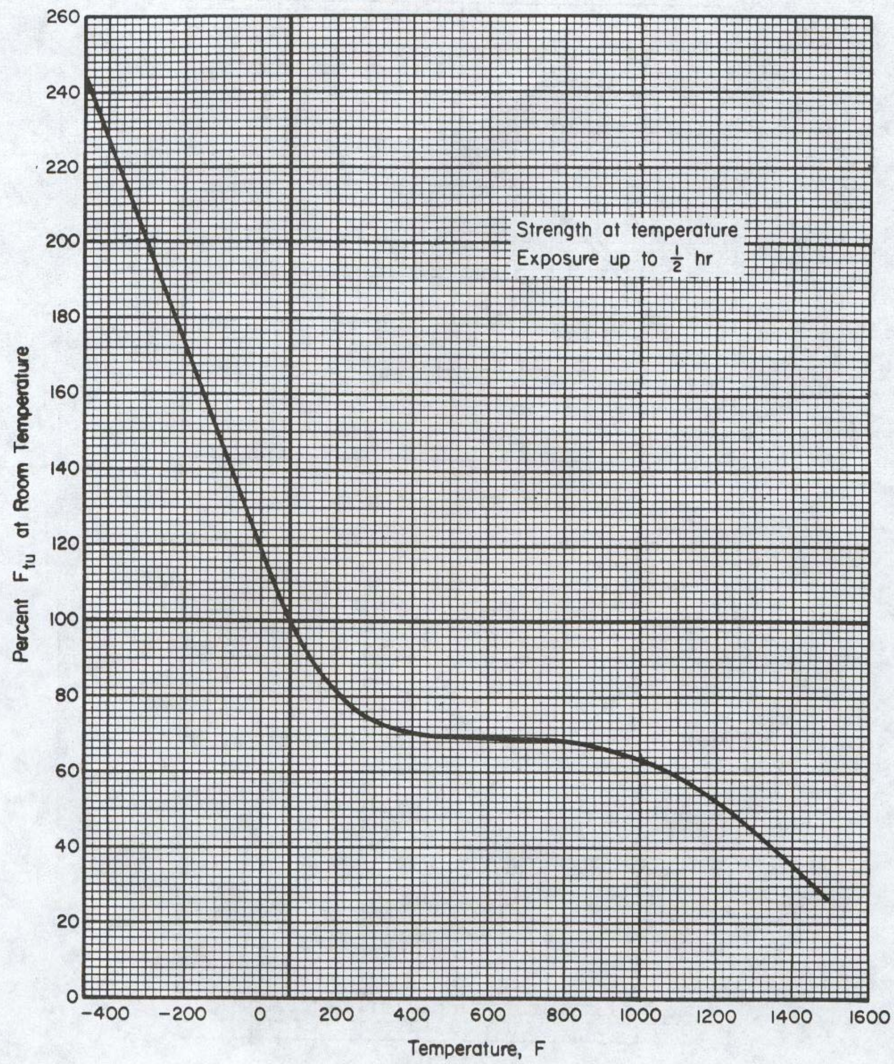

FIGURE 2.7.1.1.1(b). *Effect of temperature on the tensile ultimate strength (F_{tu}) of AISI 301, 302, 304, 304L, 321, and 347 annealed stainless steel.*

Figure 35. Effect of temperature on the tensile ultimate strength of AISA 301, 302, 304, 304L, 321, and 347 annealed stainless steel [2].

Material	Test Temperature (°F)	Average 0.2% Yield Stress (psi)	Average Ultimate Strength (psi)	Change in Yield Stress from 70°F (%)	Change in Ultimate Strength from 70°F (%)
Annealed Bar Stock	-40	33,840	114,040	22.3	36.3
	70	27,660	83,680	0	0
	115	25,320	78,160	-8.5	-6.6
	160	23,970	72,000	-13.3	-14.0
Forging D	-40	73,050	127,050	4.3	28.2
	70	70,033	99,133	0	0
	160	66,167	87,933	-5.5	-11.3
Forging F	-40	61,533	127,367	0.8	30.5
	70	61,033	97,583	0	0
	160	55,850	84,215	-8.5	-13.7
Forging G	-40	58,450	115,050	9.6	31.0
	70	53,350	87,825	0	0
	115	51,300	82,567	-3.8	-6.0
	160	49,533	76,850	-7.2	-12.5

Table 9. Average change in tensile properties with temperature for annealed bar stock, Forging D, Forging F, and Forging G.

Conclusions

This study was successful in providing accurate tensile properties to GTS for 304L stainless steel in the annealed and HERF conditions over the temperature range −40°F to 160°F. This study has shown that relatively small changes in temperature have a measurable and substantial influence on the material properties. These measured properties are now available for future reservoir safety calculations to improve confidence in safety beyond room temperature to extremes that could be endured by the reservoirs. Both the tensile yield strength and the ultimate strength were found to be temperature dependent in the annealed and HERF conditions. The ultimate strength was found to vary more with temperature than the yield strength for the annealed and HERF materials. The HERF process had a noticeable affect in reducing the temperature dependence of the yield strength, but a much smaller affect in reducing the temperature dependence of the ultimate strength. A complete set of stress-strain curves for annealed and HERF 304L stainless steel have been included for a complete documentation of this study.

References

[1] MIL-HDBK-5G, page 2-216.
[2] MIL-HDBK-5G, page 2-217.
[3] Aerospace Structural Metals Handbook, Code 1303, page 16.
[4] Engineering Alloys Digest, Inc., "Alloy Digest Filing Code: SS-5S Stainless Steel" (May 1957).
[5] Aerospace Structural Metals Handbook, Code 1314, page 22.
[6] Muraleedharan, P., Khatak, H.S., Gnanamoorthy, J.B., and Rodriquez, P., "Effect of Cold Work on Stress Corrosion Cracking Behavior of Types 304 and 316 Stainless Steels," *Metallurgical Transactions*, Vol. 16A, No. 2 (February 1985), pp 285-289.
[7] Chiesa, Brown, Antoun, Ostien, Regueiro, Bamman, "Prediction of Final Material State in Multi-Stage Forging Processes," in *Numiform 2004 – The 8th Int. Conf. On Numerical Methods in Industrial Forming Processes*, June 2004.
[8] Chiesa, Antoun, Brown, Regueiro, Jones, Bamman, Yang, "Using Modeling and Simulation to Optimize Forged Material Properties," *Proceedings of the 25th Forging Industry Technical Conference*, April 19-21, 2004, Detroit, MI, pub. Forging Industry Association.
[9] ASTM E4 - Standard Practices for Force Verification of Testing Machines.
[10] ASTM E8 - Standard Test Methods for Tension Testing of Metallic Materials.
[11] Aerospace Structural Metals Handbook, Code 1303, pages 13-14.

Appendix

QUALITY ACCEPTANCE CERTIFICATION REPORT

AlliedSignal Aerospace
P.O. Box 419159
Kansas City, MO 64141-6159

MATERIAL CONTROL NUMBER: 116131 0001 Thru 0015

DATE:

SAMPLE HISTORY:

VENDOR: CARPENTER TECH.			PO NUMBER:	SIZE	HEAT NO.:	ALLOY TYPE:
QUANTITY RECEIVED:	**TESTED: (DESTROYED)**	**RELEASED:**	WR-66887	2 1/2" DIA.	30962-6	304L

APPLICABLE SPECIFICATIONS: P-12044-F

APPLICABLE DRAWINGS:

TEST RESULTS:

I. PHYSICAL AND MECHANICAL PROPERTIES:

ALLOY AND CONDITION:	STRENGTH IN PSI: YIELD .2% OFFSET:	ULTIMATE:	ELONGATION IN ___%	REDUCTION IN AREA ___%	OTHER

TENSILE SPECIMEN TAKEN IN:

II. METALLURGICAL.

GRAIN FLOW: MFN5.0 AVG OF 6

% DELTA FERRITE: (SEVERN FERRITE INDICATOR) <0.5%

INCLUSION RATING: (ASTM-E-45) 1/2 TO 1 D HEAVY

HARDNESS: FERRITE DIST - 1 TO 2 1/2 C THIN

GRAIN SIZE: (ASTM-E-112) 80% 6 / 20% 4 1/2

OTHER STRINGERS-UP TO 1 @ >1.25"

III. CHEMICAL ANALYSIS IN %:

Cr	Ni	Mn	P	Si	Co	Mo	C	S
19.15	10.75	1.695	.0105	.56	.0315	.0115	.0205	.0018

N	O	Al	Fe	B	Cu	V	Ti	Se
.0345	.0018	.003					<0.05	

IV. NONDESTRUCTIVE TESTING:

ULTRASONIC INSPECTION: ACCEPTED

COMMENTS: AMS-2248. CA - <.0005/.0005. CHEMICAL VALUES ARE AVERAGES. MATERIAL RECEIVED "ANNEALED". ADDITIONAL CHEMISTRY FOR INFORMATION ONLY - NOT A SPEC REQUIREMENT. MATERIAL DOES NOT MEET CURRENT REV H AT THIS TIME.

DISPOSITION: CERTIFIED FOR WR USE 10/05/92

APPROVED BY: MILLER

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