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2014 Accomplishments – Tritium Aging Studies on Stainless Steel:

Fracture Toughness Properties of Forged Stainless Steels - Effect of Hydrogen, Forging Strain Rate, and Forging Temperature

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Materials Science and Technology

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CONTENTS **PAGE**

List of Figures **Page**

List of Figures (con't) **Page**

List of Tables	**Page**

FRACTURE TOUGHNESS PROPERTIES OF FORGED STAINLESS STEELS: EFFECT OF HYDROGEN, FORGING STRAIN RATE, AND FORGING TEMPERATURE

I. SUMMARY

Forged stainless steels are used as the materials of construction for tritium reservoirs. During service, tritium diffuses into the reservoir walls and radioactively decays to helium-3. Tritium and decay helium cause a higher propensity for cracking which could lead to a tritium leak or delayed failure of a tritium reservoir. The factors that affect the tendency for crack formation and propagation include: Environment; steel type and microstructure; and, vessel configuration (geometry, pressure, residual stress). Fracture toughness properties are needed for evaluating the long-term effects of tritium on their structural properties. Until now, these effects have been characterized by measuring the effects of tritium on the tensile and fracture toughness properties of specimens fabricated from experimental forgings in the form of forward-extruded cylinders. A key result of those studies is that the long-term cracking resistance of stainless steels in tritium service depends greatly on the interaction between decay helium and the steels' forged microstructure.

New experimental research programs are underway and are designed to measure tritium and decay helium effects on the cracking properties of stainless steels using actual tritium reservoir forgings instead of the experimental forgings of past programs. The properties measured should be more representative of actual reservoir properties because the microstructure of the specimens tested will be more like that of the tritium reservoirs. The programs are designed to measure the effects of key forging variables on tritium compatibility and include three stainless steels, multiple yield strengths, and four different forging processes. The effects on fracture toughness of hydrogen and crack orientation were measured for type 316L forgings. In addition, hydrogen effects on toughness were measured for Type 304L block forgings having two different yield strengths. Finally, fracture toughness properties of type 304L stainless steel were measured for four different forging strain rates which and two forging temperatures. Tritium exposures have been and are being conducted on companion specimens for property measurements in the upcoming years.

A number of conclusions can be drawn from the results in this report. First, Type 316L stainless steel cup forgings have very high fracture toughness with values exceeding 6800 lbs/in on average. The fracture toughness varies with specimen orientation and location within the forging. Fracture toughness from the cup section of the forging is about 20% lower than that measured for specimens taken from the stem section. This is due to the forging strain variations within the part. Hydrogen pre-charging reduced the fracture toughness of Type 316L stainless steel stem and cup forgings by about 30%. Secondly, the fracture toughness of Type 304L stainless steel block forgings is extremely high and exceeds 12000 lbs/in for a low yield strength heat and 8500 lbs/in for a high yield strength heat. Hydrogen pre-charging reduced the fracture toughness of the block forgings to values that were between 33% and 50% of their non-charged values. This effect of hydrogen on toughness was greater in the Type

304L forgings than the Type 316L forgings but was not strongly dependent on yield strength for the values tested. Finally, the fracture toughness properties of Type 304L stainless steel forgings depend on forging strain rate and forging temperature. Values are improved by forging at 871°C versus 816°C and toughness values exceeded 10000 lbs/in for forgings conducted at 871°C. Hydraulic-Press forgings conducted at 871°C had the highest toughness values (>14,000 lbs/in); Screw-Press forgings conducted at 816°C had the lowest fracture toughness values (<8000 lbs/in).

This report fulfills the requirements for a portion of the Enhanced Surveillance Campaign (ESC) FY14 Level 2 milestone 5309 to "provide input to the Laboratories in the form of technical reports on significant ESC results for informing the stockpile decisions." It also fulfills a Savannah River Site Work Authorization Execution Plan (WAEP) for Stockpile Support, 402, to provide an "Annual Stockpile Aging Assessment Report".

II. INTRODUCTION

Tritium reservoirs are constructed from forged stainless steels and filled and stored at the Savannah River Site. The vessels are constructed from forged stainless steels because of their good compatibility with tritium. These steels are highly resistant to, but not immune from, the embrittling effects of hydrogen isotopes and helium from tritium decay. Cracking in storage vessels has been observed after extended service times and material properties like ductility, elongation-to-failure, and fracture toughness are reduced with time as tritium and its radioactive decay product, He^3, slowly accumulate within the vessel walls during service (1-8). Because of these tritium aging effects, one of the primary interests of the Savannah River Site's Enhanced Surveillance Campaign is to measure tritium effects on steel behavior and fracture toughness values for use by the Design Agencies for fracture modeling, reservoir life prediction, and safety margin calculations (9 - 21).

New experimental research and development programs are underway and were described in a recent report (22). These programs are first-of-a-kind because they set out to measure tritium and decay helium effects on the cracking properties of stainless steels using actual tritium reservoir forgings instead of the experimental forgings of past programs. In this way, the properties measured will be more representative of actual reservoir properties because the microstructure of the specimens will be more like that of the forged reservoirs. The test matrices for the various programs are designed to measure the effects of specific forging variables on tritium compatibility and were described earlier (22). The programs include three heats of stainless steel, multiple yield strengths, four different forging processes, and four different reservoir forgings.

The fracture toughness properties of one heat of Type 316L and two heats of Type 304L stainless steels were measured. For type 316L forgings, the properties were measured for specimens cut in two different orientations from the stem and cup portions of the forging. Fracture toughness properties were also measured for Type 304L block forgings having two different yield strengths. For both forgings, hydrogen effects on toughness were measured by thermally pre-charging specimens with hydrogen prior to testing. Finally the effect of forging strain rate and temperature on fracture toughness was investigated in Type 304L stainless steel. Forging remnants from an earlier forging study were supplied by the Kansas City Plant (KCP). They had conducted a study to characterize microstructure and mechanical properties of stainless steel forged with four different processes at different temperatures: (1) Screw Press (SP); (2) Mechanical Press (MP); (3) Hydraulic Press (HP); and, (4) High-energy-rate forging (HERF) (23). For this study, specimens were cut from the KCP forging remnants and fracture toughness measured. This program will help to answer the question “Which manufacturing process produces the forging microstructure most resistant to tritium embrittlement effects?”

III. EXPERIMENTAL PROCEDURE

Table I lists the compositions of the stainless steels used in this study. The Type 316L stainless steel was in the form of a cylindrical-cup forging. The Type 304L stainless steels were in the form of two cylindrical block forgings and multiple rectangular remnants cut from forgings used in a study conducted at the Kansas City Plant (23). Figure 1 shows a drawing of the Type 316L stainless steel cup. Arc-shaped fracture toughness specimens were cut from the cup in the CR-orientation and from the stem in the CL-orientation (Figure 2). Also shown in Figure 2 is the specimen numbering scheme that was used to track the original location and orientation of each specimen from the forging. The specimen geometry is shown in Figure 3. Figure 4 is a photograph of the as-cut forging and specimens. Similarly shaped specimens were cut from two Type 304L stainless steel cylindrical block forgings shown in the drawing in Figure 5. The forgings were produced to have two different yield strengths: nominally, 60 ksi and 70 ksi. The orientation and location of the fracture toughness specimens cut from the block forgings are shown in Figure 6. Figure 7 shows a photograph of the as-cut forgings and specimens. Finally, round tensile specimens were machined from the stem, cup, and block forgings for verifying the as-forged mechanical properties (Table II) and are shown in Figures 8 and 9. Additional details of the test matrices for the stem, cup, and block forging studies including tritium pre-charging schedules and experimental plans are given in the technology development plan (22).

Table I - Compositions of Types 316L and 304L Stainless Steel Forgings (Weight %)

Material	MCN	Forging	Cr	Ni	Mn	P	Si	Co	Mo	C	S	N	O	Al
304L Block LY	200952	11459	18.6	9.5	1.7	-	.57	.061	.098	.022	.001	-	-	-
304L Block HY	200952	11460	18.6	9.5	1.7	-	.57	.061	.098	.022	.001	-	-	-
316L Cup	200948	7K0010	16.6	12.9	.71	.011	.51	.029	2.3	.009	.004	.036	.001	.003
304L Ref.22	Ref. 23	Remnant	19.5	10.7	1.6	.028	..52	-	-	.029	.006	.030	-	-

Table II Room Temperature Mechanical Properties of Stem, Cup, and Block Forgings

Material	MCN	Forging / Direction	Yield Strength ksi	Ultimate Strength ksi	Elongation %
316L Stem	200948	7K0010 – Longitudinal	52.8	83.3	52.0
316L Stem	200948	7K0010 - Cylindrical	57.7	88.5	60.7
316L Cup	200948	7K0010 - Longitudinal	71.9	98.3	50.8
304L Block LY	200952	11459 - Longitudinal	59.9	89.4	67.6
304L Block LY	200952	11459 - Cylindrical	60.4	95.3	58.1
304L Block HY	200952	11460 - Longitudinal	67.5	93.9	56.8
304L Block HY	200952	11460 - Cylindrical	71.7	101.9	53.5
304L Remnant	Ref 23	Process	(see Table V)		

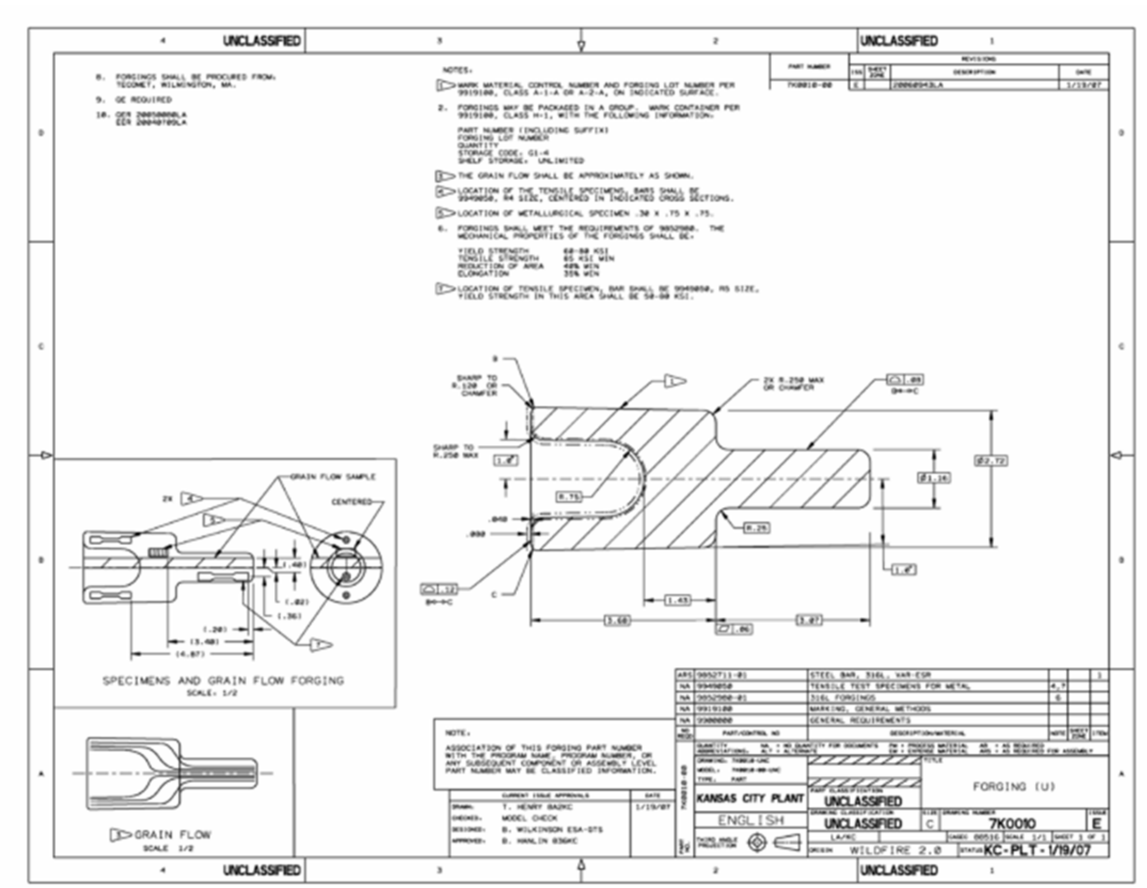


Figure 1. Type 316L Stainless Steel Cup 7K0010 Forging.

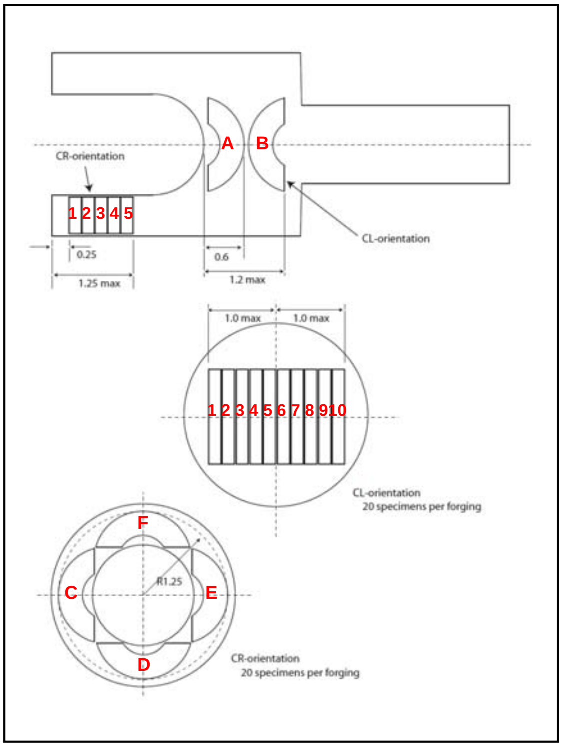


Figure 2. Fracture Toughness Specimen Location and Orientation - Type 316L Forging: Specimens Labeled "A" or "B" were Cut from the Stem Portion of the Forging and Specimens Labeled "C", "D", "E", or "F" from the Cup Portion of the Forging.

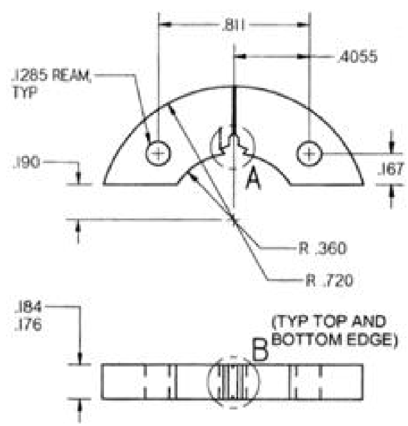


Figure 3. Shape and Dimensions of Fracture-Toughness Specimen in Inches.

Figure 4. Photograph of Type 316L Stainless Steel Cup Forging Showing As-Cut Specimens.

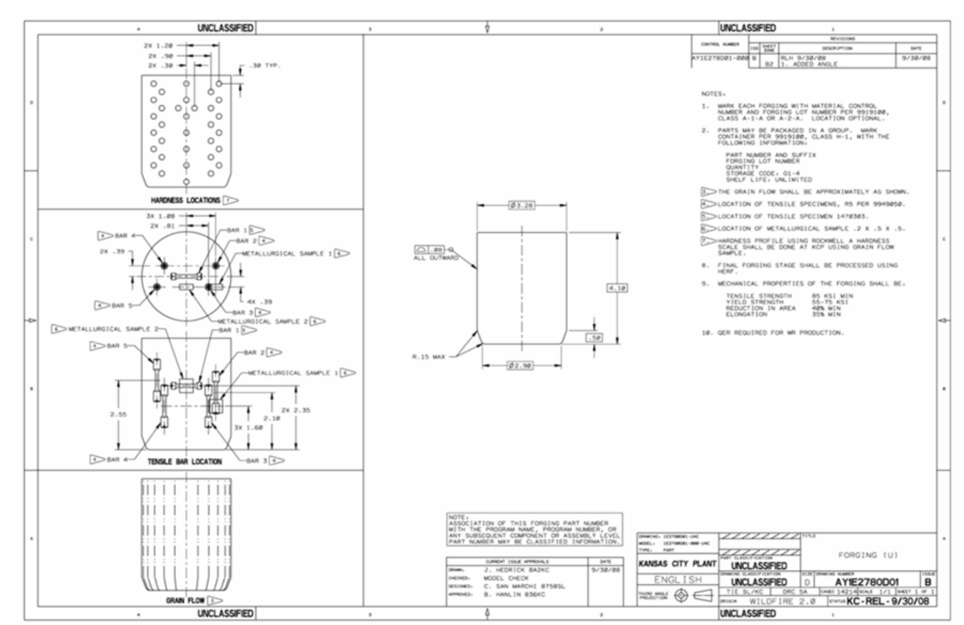


Figure 5. Type 304L Stainless Steel Cylindrical Block 1E2780 Forging.

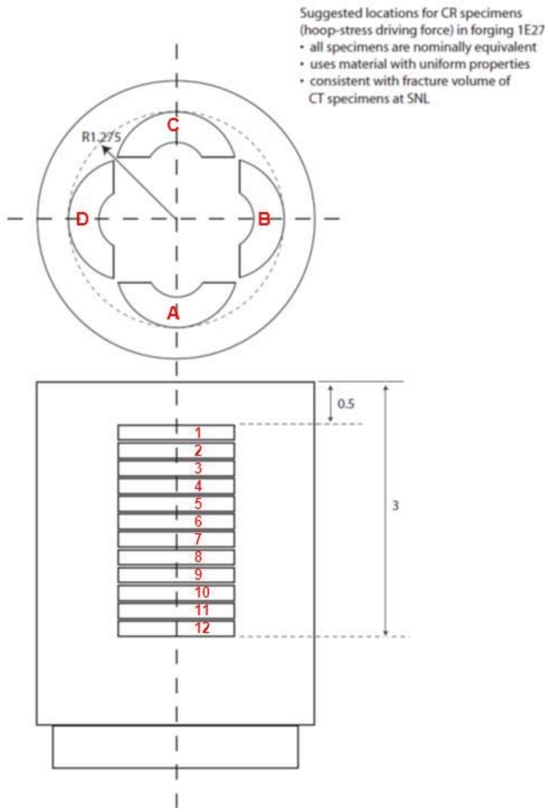


Figure 6. Fracture Toughness Specimen Location and Orientation For Type 304L Cylindrical Block Forging.

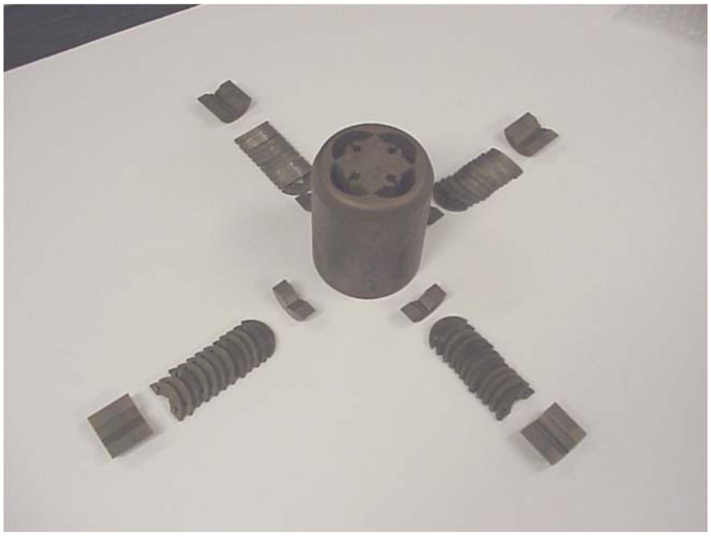


Figure 7. Type 304L Cylindrical Block Forging and As-Cut Fracture Toughness Specimens.

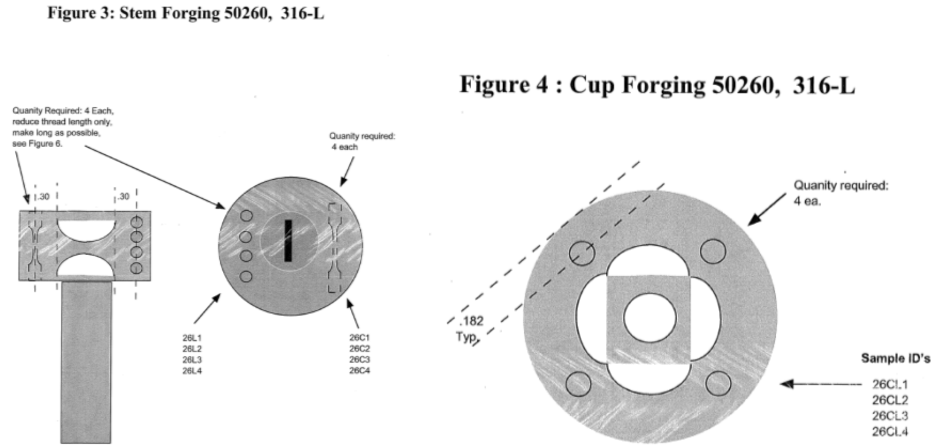


Figure 8. Orientation of Tensile Specimens Cut From Type 316L Stem and Cup Forgings.

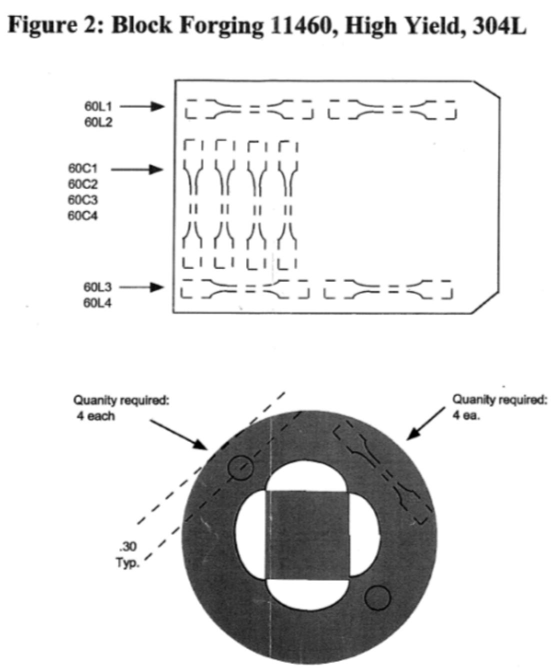


Figure 9. Orientation of Tensile Specimens Cut From Type 304L Block Forgings.

In order to investigate the effect of forging strain rate and temperature on fracture toughness, remnants from experimental forgings were obtained from the Kansas City Plant (KCP). KCP had produced forgings to study the effect of forging strain rate and temperature on microstructure and mechanical properties (23). The forgings were produced using multiple forging processes: Screw Press, Mechanical (Pneumatic) Press, Hydraulic Press, and High-Energy-Rate Forging (HERF). The forging process flow diagram used by Switzner, et al. (23) is shown in Figure 10. Note that the Kansas City study investigated the effect on microstructure and mechanical properties of four different final forging processes as well as three different forging temperatures. Also, an annealing step prior to the final forging operation was used as part of the process for some of the forgings.

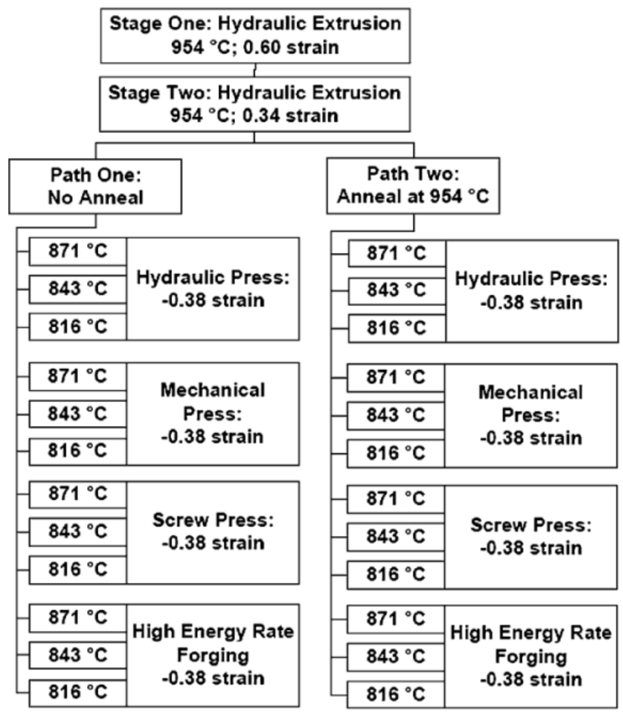


Fig. 1. Flowchart matrix for 304L stainless steel processing experiments.

Figure 10. Forging Process Flow Diagram Showing Four Forging Processes and Three Forging Temperatures: Hydraulic-Press, Mechanical-Press, Screw-Press, and High-Energy-Rate Forging (23).

For this study, arc-shaped fracture mechanics specimens from the center section of the billets used in the work by Switzner (23). The shape of the billet after each stage of the forging process is shown in Figure 11. Figure 12 shows that the fracture toughness specimens were machined from the final stage billet using sections that were previously used for hardness and grain flow characterization. The available remnants were from billets forged at 816°C and 871°C as well as the billets that were annealed at 954°C prior to the final forging blow.

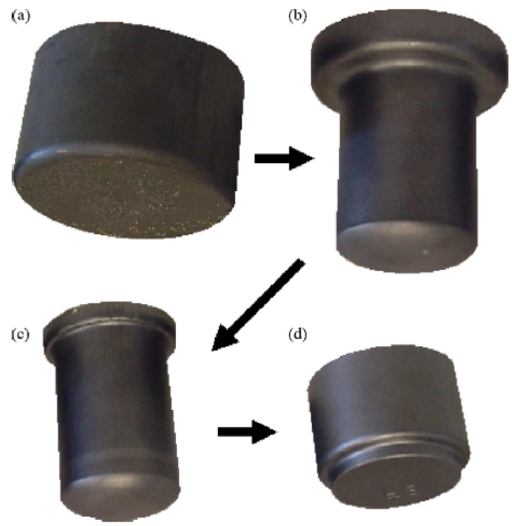
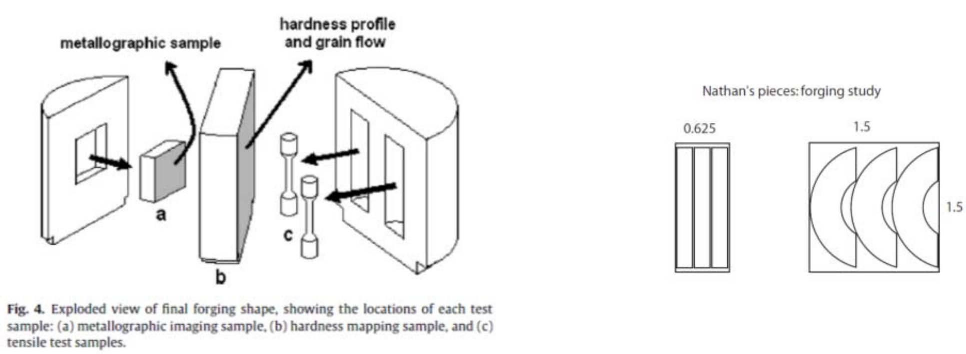


Figure 11. Product of each step for 304L Stainless Steel: (a) Billet Prepared for First Extrusion; (b) After First Extrusion; (c) After Second Extrusion; and (d) After Final Forging (23).

The compositions of the steels are given in Table I. The nominal strain rates for the various forging processes are listed in Table III: Engineering strain rates range from 1 s^{-1} to 125 s^{-1} (23). The size of the remnant section(s) limited the number of specimens that could be fabricated. The test matrix includes fracture toughness measurements on as-forged specimens and two sets of tritium aging conditions. Further details are given in the program plan described in Reference 22.



(a) (b)

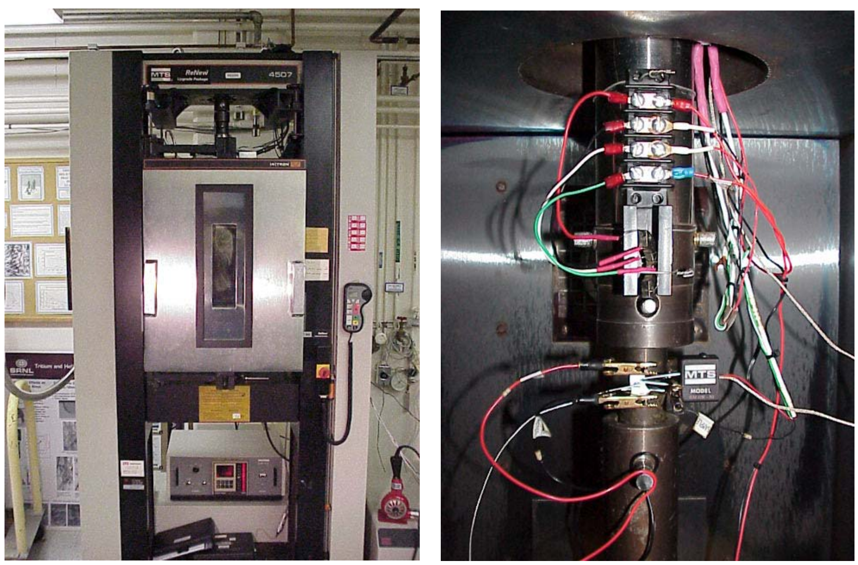
Figure 12. Center Section of Final Forged Billet Used For: (a) Hardness Profile and Grain Flow (22) and (b) Arc-Shaped Fracture Toughness Specimens.

Table III - Nominal Strain Rates for Forging Processes (23)

Forging Process	Approximate Forging Die Contact Velocity (mm/s)	Deformation Time (s)	Engineering Strain Rate (s^{-1})
Hydraulic Press	60	0.4	1
Mechanical Press	300	0.08	5
Screw Press	500-575	0.04-0.05	8-10
HERF	5600-7500	0.003-0.005	80-125

Some of the specimens cut from the Type 316L stainless steel forgings and the Type 304L block forgings were pre-charged with hydrogen or tritium gas at 623 K and an over-pressure of 34.5 MPa and then stored in air at 223 K. The storage temperature was chosen so as to minimize tritium off-gassing loss and to allow for the build-in of helium from tritium decay until testing is performed (this process sometimes takes years to accomplish). Tritium-exposed specimens will be tested at a later date. The hydrogen isotope content of the pre-charged specimens is estimated by using established hydrogen solubility values to be 3700 atomic parts per million (appm) for Types 304L and 316L stainless steels (24).

J-integral tests were conducted at room temperature in air using a screw-driven testing machine and a crosshead speed of 0.002 mm/s while recording load, load-line displacement with a gage clipped to the crack mouth, and crack length (Figure 13). Crack length was monitored using a DC potential drop system and guidelines described in ASTM E647-95 (25). The J-Integral versus crack length increase (J-R) curves were constructed from the data using ASTM E1820-99 (26). Fracture toughness values are determined by using the intercept of an offset line with the J-R curve as shown in Figure 14 which shows data on the effect of tritium from an earlier study (12). The offset line has a slope that is proportional to the flow strength of the material. As the material yields before cracking the crack tip blunts and changes shape. In effect, the ASTM procedure is determining the point at which the crack begins to grow after blunting has occurred. The slope of the blunting line in the standard is generally taken to between 4/3 and 2 times the material’s flow strength based on best fits to numerous alloys. The flow strength is defined as the average between yield and ultimate strengths. This study included materials having a range of flow strengths with an overall average of 80 ksi. For the Stem, Cup, and Block forgings, the best-fit slope for the blunting line was (2.5 x Flow Strength). For the Forging Effects study, the best-fit slope was (2.2 x Flow Strength). These best-fit values were used to determine fracture-toughness values to avoid later complications in the analysis because hydrogen, tritium, and decay helium all affect flow strength, and tensile specimens would not be available for each condition. The blunting lines are shown for the J-R Curve results to show the goodness of fit to the data. No attempt was made at this time to quantify the fracture toughness differences as a function of blunting-line slope. In general, fracture toughness values determined with steeper sloped blunting lines are lower and therefore, more conservative. In these high work-hardenable stainless steels, the J-R curve clearly deviates away from the lower sloped blunting lines as the material in front of the crack work hardens prior to crack extension. Because of this, the fracture toughness properties reported here should be conservative.



(a) (b)

Figure 13. (a) Mechanical Testing Machine with Environmental Chamber For Non-Charged and Hydrogen-Charged Specimens. (b) Fracture-Toughness Specimen with Crack Length DC Potential Drop Leads and Thermocouple.

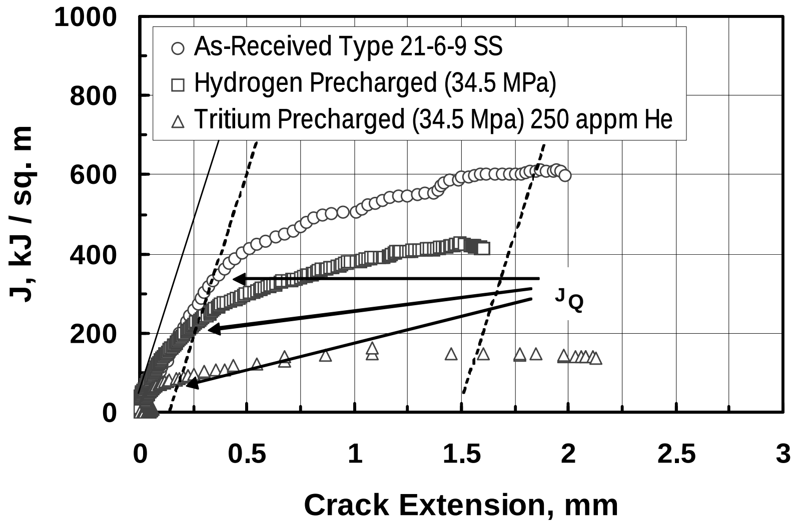


Figure 14. Typical J-R curves for As-received (Not Charged), Hydrogen Pre-charged, and Tritium Pre-charged Type 21-6-9 Stainless Steels. J_Q Values Shown Were Determined from the Intercept of the J-R Curve with the 0.2 mm Offset Line (12).

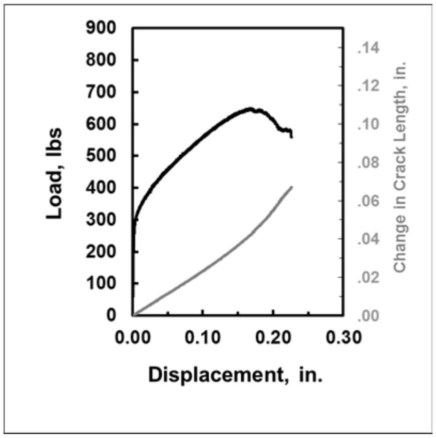
IV. EXPERIMENTAL RESULTS

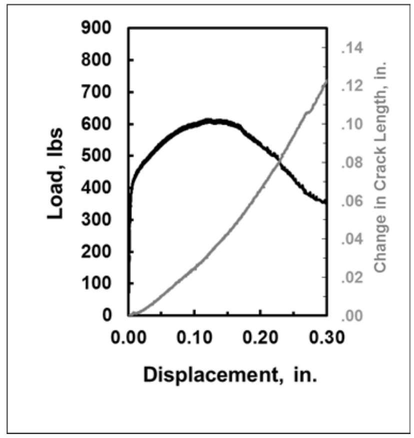
Type 316L Stem and Cup Forgings

Figure 15(a) shows the typical load-displacement and crack length records obtained during a fracture toughness test for a specimen taken from the stem portion of the Type 316L forging. The shape of the load-displacement curve is a general indication of toughness as the area under the curve (force x distance) is used to calculate the energy of fracture (J-Integral). Note however, the raw values of load and load-line displacement depend on the initial crack length and cannot be used to draw hard conclusions. Figure 15 (b) shows the load-displacement record for a hydrogen-charged specimen taken from the same forging. Note the long rise on the load-displacement record prior to maximum load in the non-charged specimen of Fig 15(a). This is an indicator of very high toughness material. On the other hand, the hydrogen pre-charged specimen in Fig. 15(b) shows less of a rise to maximum load and generally will show faster drop offs in load after the peak. These differences were typical for the specimens tested throughout this study. Figure 16 shows the J-R curves calculated from the load-displacement-crack length records. The non-charged specimen had an extremely high fracture toughness value 10,262 lbs/in. This value represents the J-integral value at the first point of significant (non-blunting) crack extension and is indicated in Figure 16 by the intercept of the J-R curve with the offset line. Hydrogen pre-charging caused a reduction in fracture toughness to 7497 lbs/in. This effect of hydrogen on toughness was typical for other specimens tested. Note also, that, in general, the J-R Curve tends to flatten from hydrogen pre-charging, which indicates that less energy is needed for crack propagation (i.e., lower tearing modulus). The fracture toughness values for each of the specimens tested are listed in Table IV at the end of this section.

Multiple tests indicate that the stem forging has an average fracture toughness value of 8681 ± 2304 lbs/in. The high standard deviation is in part because the average value includes specimens from two different locations within the forging: Specimens with an “A” label in Table IV were closer to the cup than “B” specimens (Fig. 2). Secondly, the high variation is commonly seen in materials with extremely high toughness especially when determined using sub-sized specimens (26). At the point of crack initiation, the load displacement curve goes through a broad maximum. Small differences in crack-initiation loads can result in very large differences in area under the load-displacement curve which is used to calculate J-integral fracture toughness values. The size and thickness of the specimens was limited by the shape and size of the forging and the time required to diffuse hydrogen and tritium into companion specimens at temperatures that do not significantly change the forging microstructure. Hydrogen pre-charging reduced the fracture toughness values of the stem to an average value of 6380 ± 968 lbs/in. Thus the hydrogen-precharged specimens have fracture toughness values that average about 73% of the value of the as-forged specimens. The large standard deviation on the average toughness values may call into question this conclusion. However, the conclusion is supported by examining the fracture toughness values of specimens from similar locations. In Table IV, hydrogen pre-charging reduced the toughness of “A” specimens from 10310 lbs/in to 7497 lbs/in or 5788 lbs/in and “B” specimens from 7051 lbs/in to 5854 lbs/in.

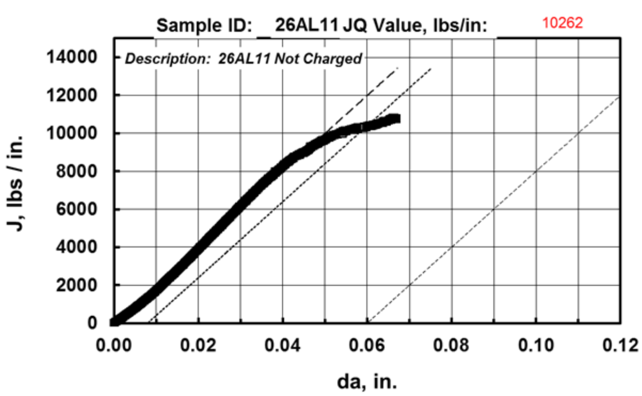
Figures 17 and 18 show the load-displacement records and J-R curves for specimens cut from cup portion of the forging. The as-forged specimen in this case had a fracture toughness value of 7729 lbs/in. Note that this value is not as high as the fracture toughness values for specimens taken from the stem section of the same forging (Figure 16). The most likely reason for the difference is that the stem portion is strained less than the cup during the forging operation. For the hydrogen precharged specimen taken from the cup forging, Figure 18 indicates a fracture toughness value of 4548 lbs/in. which is less than 60% of the non-charged specimen. Table IV shows that the average value of toughness for the cup forging is 6886 ± 939 lbs/in for non-charged specimens and 4690 ± 135 lbs/in for hydrogen precharged specimens. So for the Type 316L cup forging, hydrogen precharging reduces fracture toughness to a value that is just 68% of the non-charged value.



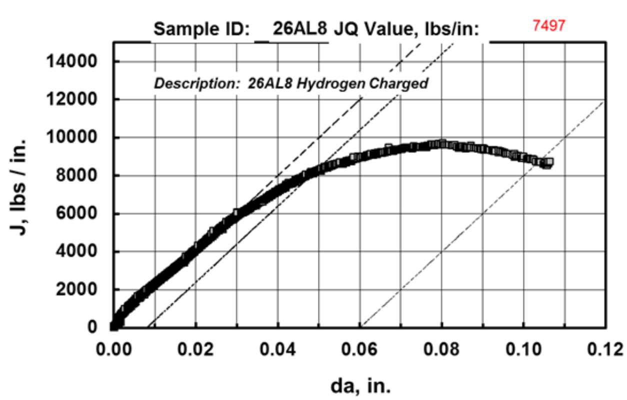


(a) **(b)**

Figure 15. Load-Displacement Diagrams – Type 316L Stem Forging: (a) Not Charged (b) Hydrogen Pre-Charged.

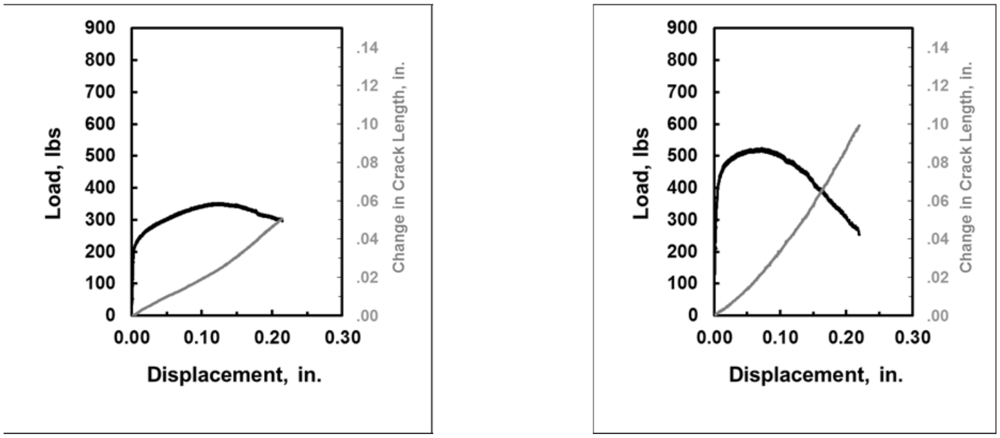


(a)



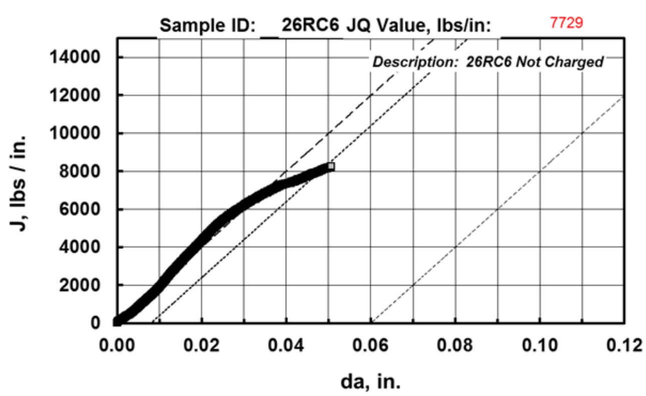
(b)

Figure 16. J-R Curves for Type 316L Stem Forging: (a) Not Charged and (b) Hydrogen Pre-Charged.

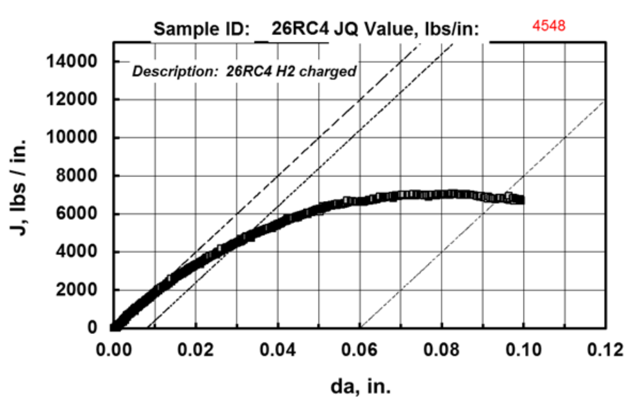


(a) **(b)**

Figure 17. Load-Displacement Diagrams – Type 316L Cup Forging: (a) Not Charged and (b) Hydrogen Pre-Charged.



(a)



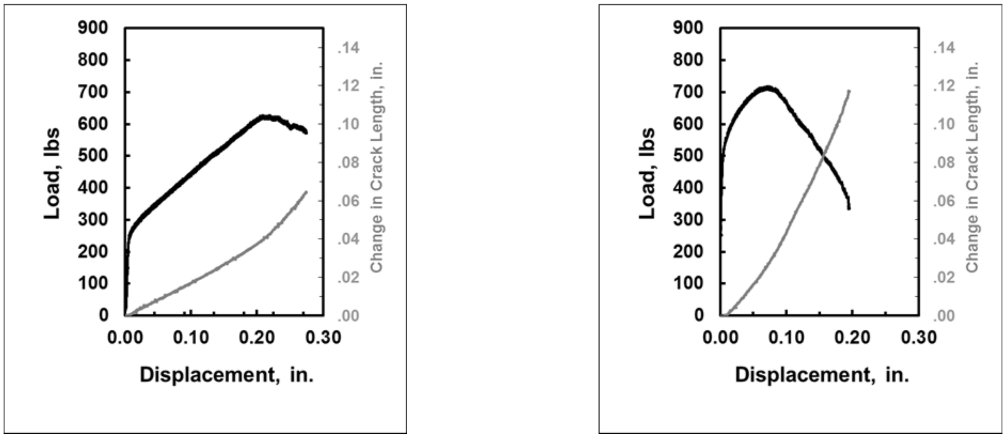
(b)

Figure 18. J-R Curves for Type 316L Cup Forging: (a) Not Charged and (b) Hydrogen Pre-Charged.

Type 304L Block Forgings

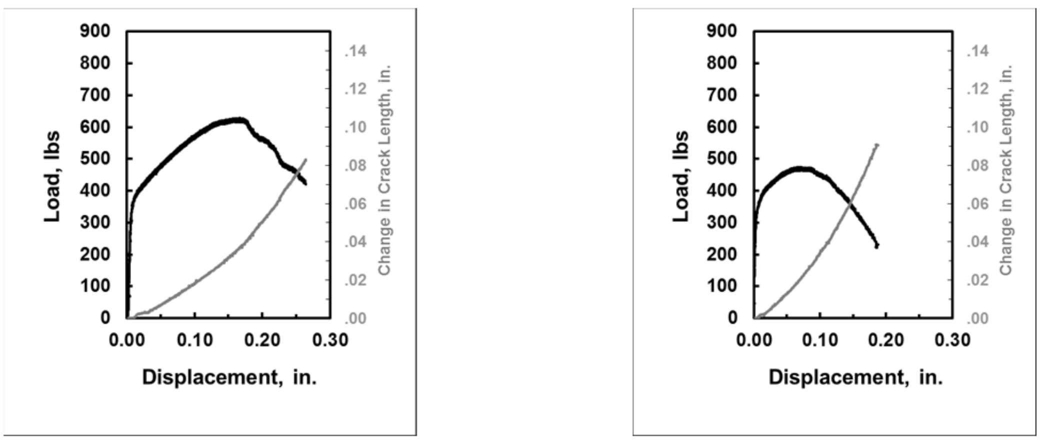
Figures 19 and 20 show typical load-displacement records obtained during fracture toughness tests for specimens taken from the two Type 304L stainless steel block forgings. Notice the large difference in the shape of the load-displacement curves for the non-charged and hydrogen charged specimens. Specimens not charged show a steep rise to peak load while the specimens pre-charged with hydrogen show a sharp turnover at peak and a more rapid reduction in load with displacement after peak. The difference between not-charged and hydrogen pre-charged specimens was even more pronounced for the J-R curves shown in Figures 21 and 22. For both the low and high yield strength forgings, the hydrogen pre-charged specimens had lower fracture toughness values and flatter J-R curves than non-charged specimens. For the low strength forging, the fracture toughness values averaged 12517±623 and the high strength forging averaged 8562±2813 (Table IV). Hydrogen pre-charging reduced the fracture toughness value of the low-strength block forging to 4210±241 lbs/in and to essentially the same level, 4344±208 lbs/in, for the high-strength block forging. This result indicates that Type 304L stainless steel affected more by hydrogen than Type 316L stainless steel. The hydrogen pre-charged specimens had fracture toughness values between 33% and 50% of the non-charged values; whereas, for the Type 316L forging, the hydrogen pre-charged values were between 68% and 73% of the non-charged values. These fracture toughness reductions are large, but both materials still retain a very high value of fracture toughness. The differences between the low and high yield strength toughness values are somewhat obscured by the fact that only two specimens were available for the high-yield strength heat in the non-charged condition and one of these specimens had a particularly low value of toughness. Further work is needed to investigate the reason for this low value and will be conducted during the upcoming year.

Figure 23 shows a graphical comparison of the fracture toughness values of the stem, cup, and block forgings before and after hydrogen pre-charging. Again, notice that the fracture toughness values of the cup forging tend to be lower than the stem forging, and that the Type 304L stainless steel block forgings were affected more by hydrogen charging than the Type 316L stainless steel forging.



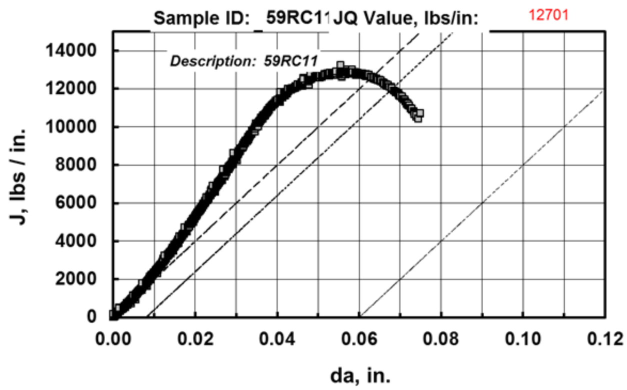
(a) **(b)**

Figure 19. Load-Displacement Diagrams – Type 304L Block Forging (Low Yield Strength): (a) Not Charged and (b) Hydrogen Charged.

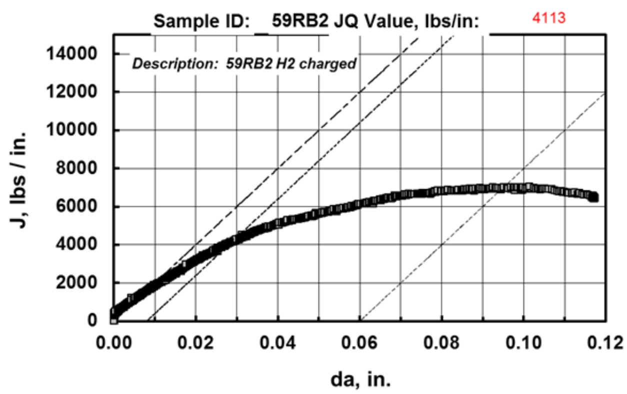


(a) **(b)**

Figure 20. Load-Displacement Diagrams – Type 304L Block Forging (High Yield Strength): (a) Not Charged and (b) Hydrogen Charged.

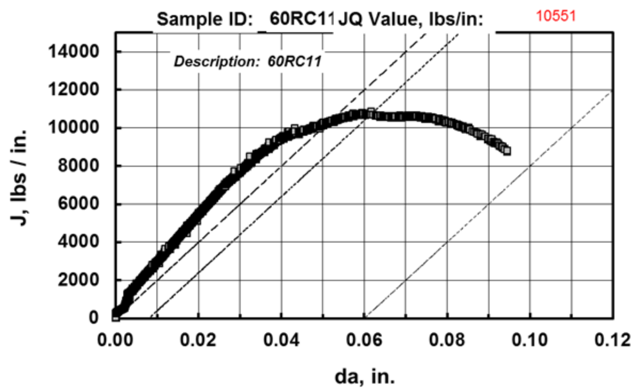


(a)

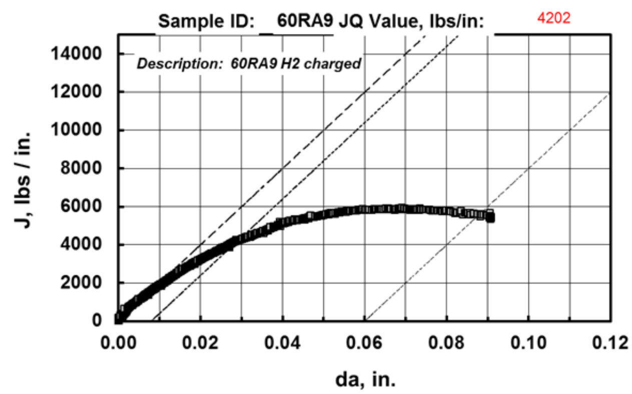


(b)

Figure 21. J-R Curves for Type 304L Block Forging (Low Yield Strength): (a) Not Charged and (b) Hydrogen Charged.



(a)



(b)

Figure 22. J-R Curves for Type 304L Block Forging (High Yield Strength): (a) Not Charged and (b) Hydrogen Charged.

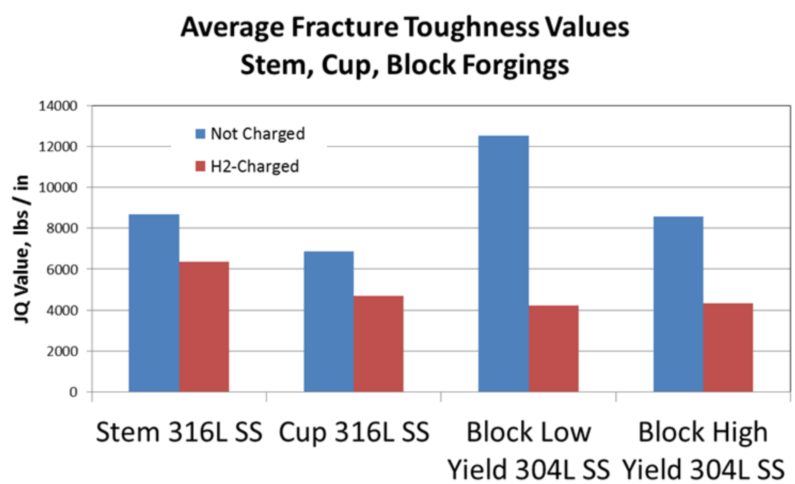


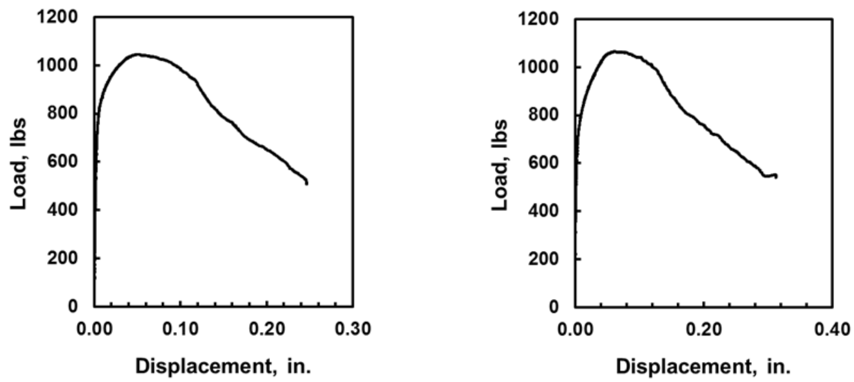
Figure 23. Average Fracture Toughness Values for Stem, Cup, and Block Forgings

Table IV – Fracture Toughness Values of Stem, Cup, and Block Forgings

Specimens Not Charged				
Specimen	**Source**	**J_Q**	**AVG**	**StDev**
		lbs/in	**lbs/in**	**lbs/in**
26AL11	Stem	10310	8681	2304
26BL13	Stem	7051		
26RC6	Cup	7729	6886	939
26RD8	Cup	5573		
26RE10	Cup	7347		
26RF4	Cup	6895		
59RC1	Block LY	12701	12517	623
59RA1	Block LY	11823		
59RB6	Block LY	13028		
60RC11	Block HY	10551	8562	2813
60RB6	Block HY	6573		
Specimens Pre-Charged with Hydrogen Gas				
Specimen	**Source**	**J_Q**	**AVG**	**StDev**
		lbs/in	**lbs/in**	**lbs/in**
26AL2	Stem	5788	6380	968
26AL8	Stem	7497		
26BL4	Stem	5854		
26RC4	Cup	4548	4690	135
26RD1	Cup	4704		
26RF2	Cup	4817		
59RA9	Block LY	4032	4210	241
59RB2	Block LY	4113		
59RD4	Block LY	4484		
60RA9	Block HY	4202	4344	208
60RB2	Block HY	4246		
60RD4	Block HY	4583		

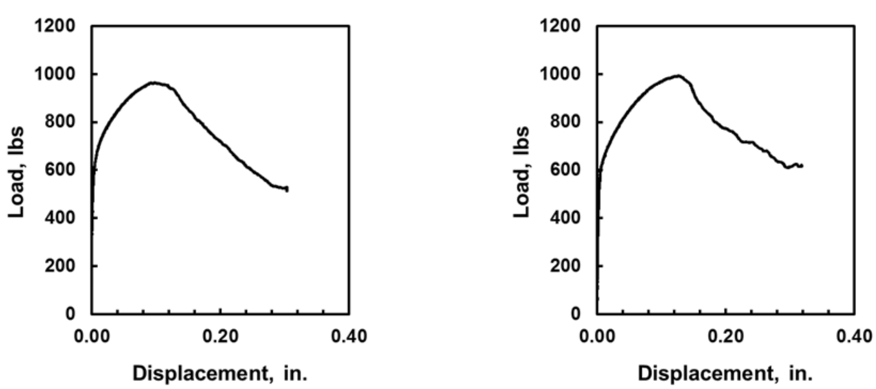
Effect of Forging Strain Rate and Temperature

Figures 24-27 show the load-displacement records for the fracture toughness tests for specimens taken from the SP, MP, HP, and HERF forgings conducted at two different forging temperatures, 816°C and 871°C. In general, for the forging processes conducted at 871°C, the load-displacement records were broader, indicating a microstructure with higher toughness.



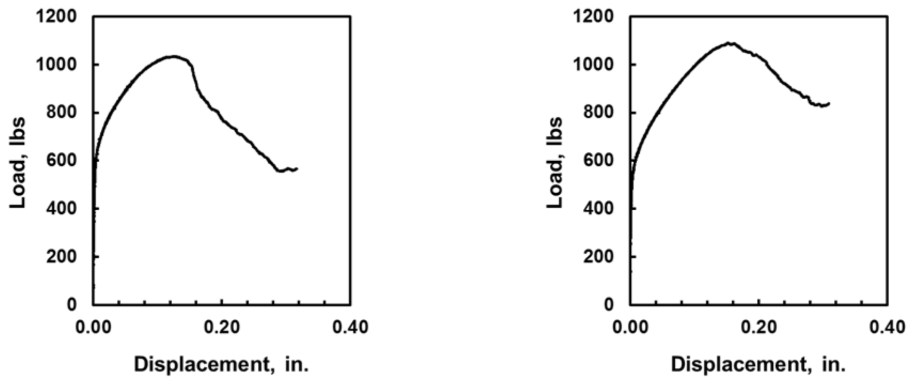
(a) **(b)**

Figure 24. Load-Displacement Diagrams – Screw-Press Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871 °C.



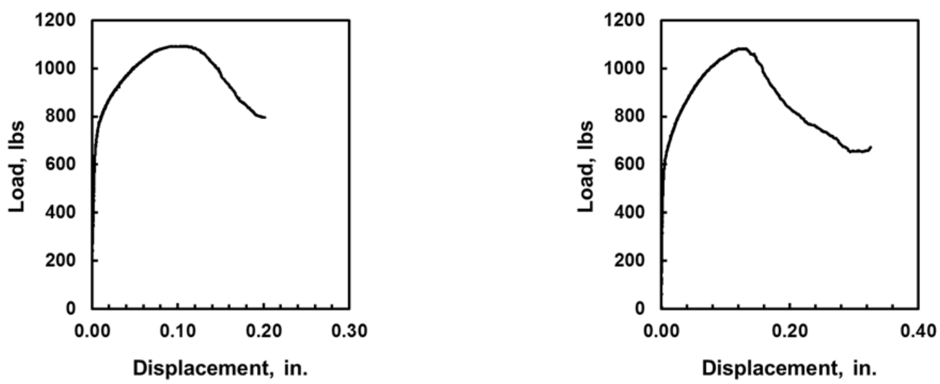
(a) **(b)**

Figure 25. Load-Displacement Diagrams – Mechanical-Press Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.



(a) **(b)**

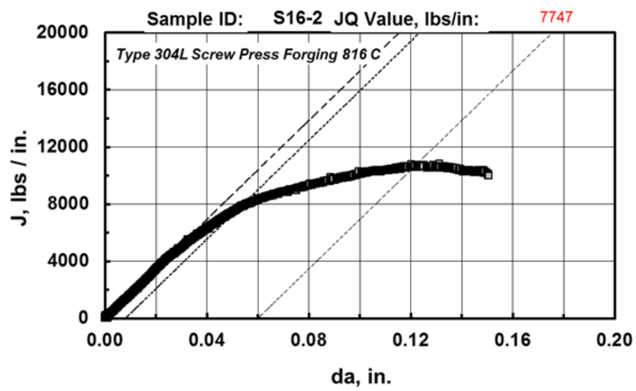
Figure 26. Load-Displacement Diagrams – Hydraulic-Press Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.



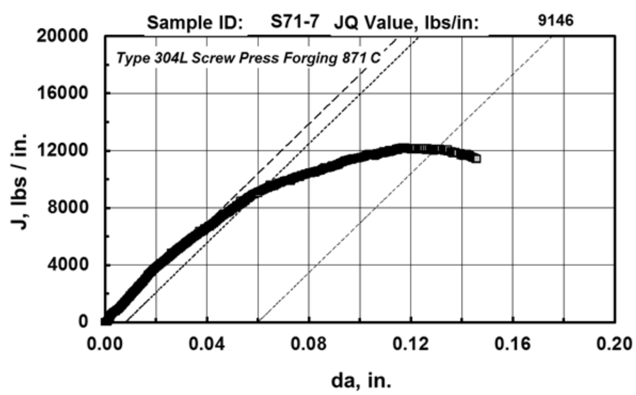
(a) **(b)**

Figure 27. Load-Displacement Diagrams – High-Energy-Rate Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.

The J-R curves for each of the forging processes and temperatures are shown in Figures 28-31. Table V lists the individual fracture toughness values and Figure 32 represents a summary of the results on the effect of forging process and temperature on fracture toughness. First, the data indicate that each process produces a material with a very high fracture toughness (with the exception of the Screw-Press Forgings conducted at 816°C) having fracture toughness values in excess of 9000 lbs/in. Secondly, fracture toughness of higher temperature forgings was improved for all but the Mechanical-Press process. Finally, the Screw-Press Forging process conducted at 816°C resulted in the lowest average fracture toughness value, less than 8000 lbs/in.

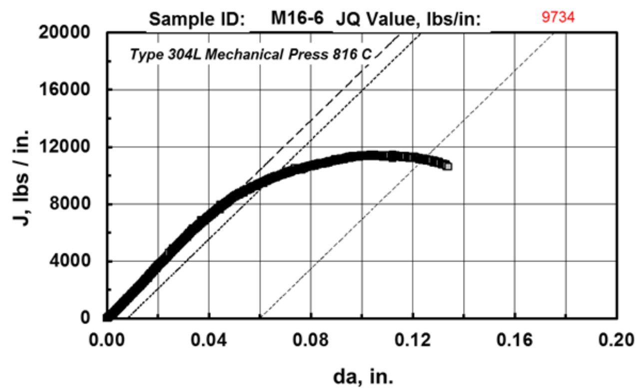


(a)

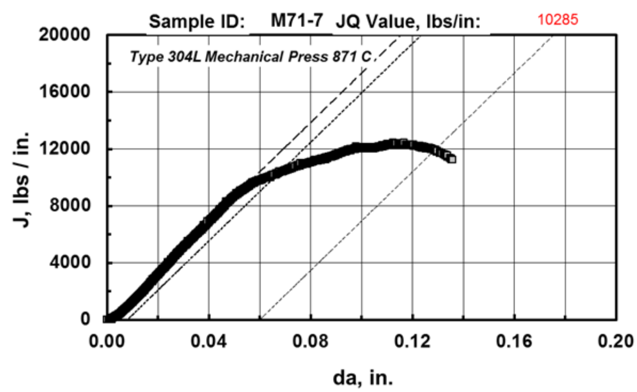


(b)

Figure 28. J-R Curves – Screw-Press Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.

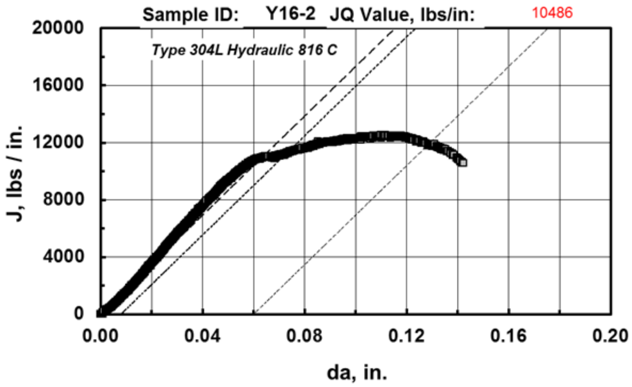


(a)

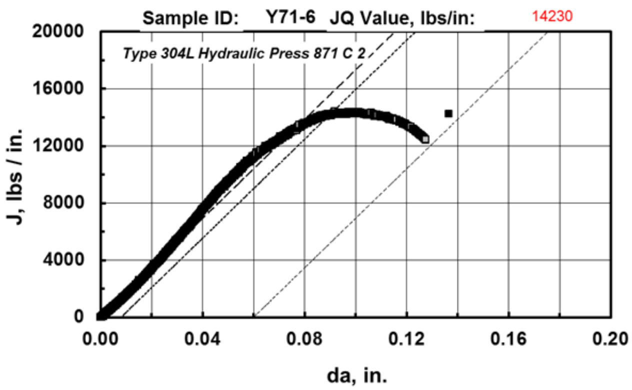


(b)

Figure 29. J-R Curves – Mechanical-Press Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.

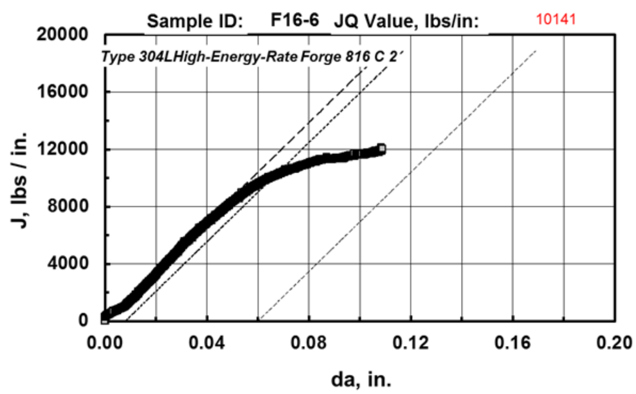


(a)

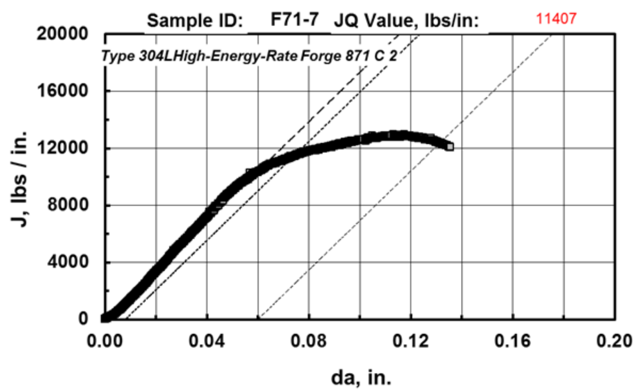


(b)

Figure 30. J-R Curves – Hydraulic-Press Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.



(a)



(b)

Figure 31. J-R Curves – High-Energy-Rate Forgings Type 304L Stainless Steel: (a) 816°C and (b) 871°C.

Table V Average Fracture Toughness Values for Forging Processes and Temperatures

ID	Yield Strength	Ultimate Strength	Process	Forging Temp.	J_Q
	psi	psi		°C	lbs/in
S16-2	71791	95141	Screw Press	816	7747
S16-6	71791	95141	Screw Press	816	7569*
S71-7	66860	91516	Screw Press	871	9146
M16-2	69036	94126	Mech. Press	816	12458
M16-6	69036	94126	Mech. Press	816	9734
M71-2	63234	91080	Mech. Press	871	10887
M71-7	63234	91080	Mech. Press	871	10285
Y16-2	66425	92966	Hydraulic Press	816	10486
Y16-6	66425	92966	Hydraulic Press	816	11385
Y71-6	59753	89485	Hydraulic Press	871	14230
F16-2	68165	94416	HERF	816	11667
F16-6	68165	94416	HERF	816	10141
F71-2	64394	92386	HERF	871	12528
F71-7	64394	92386	HERF	871	11407
AF16-4	66425	92676	Annealed + HERF	816	10067
AF71-4	66425	92676	Annealed + HERF	871	11608
S2A-6	66280	92241	Stage 2	954	9573*

*****_Specimen had low flow strength as indicated by the slope of the blunting line._

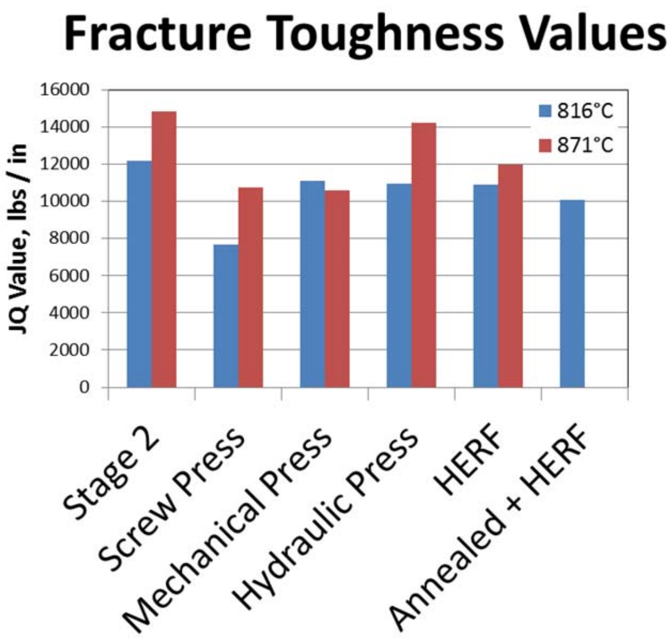


Figure 32. Average Fracture Toughness Values After Various Forging Processes for Type 304L Stainless Steel

V. Summary and Conclusions

The effects of hydrogen on the fracture toughness properties of Type 316L and Type 304L stainless steel forgings were measured. First, fracture toughness properties were measured in Type 316L forgings in the stem and cup sections of the forging. Second, for the Type 304L block forgings, hydrogen effects and fracture toughness properties were measured for forgings having two different yield strengths. Finally, fracture toughness properties of type 304L stainless steel were measured for four different processes: Screw-Press Forging, Mechanical-Press Forging, Hydraulic-Press Forging, and High-Energy-Rate Forging. The following are the main conclusions that were drawn from the work to date:

1. The fracture toughness of Type 316L stainless steel forgings were very high and exceeded 6800 lbs/in. on average. The fracture toughness of specimens cut from the cup section of the forging is about 20% lower than that measured for specimens cut from the stem section.

2. Hydrogen pre-charging reduced the fracture toughness of Type 316L stainless steel stem and cup forgings by about 30%.

3. The fracture toughness of Type 304L stainless steel block forgings is extremely high and exceeds 12000 lbs/in for a low yield strength heat and 8500 lbs/in for a high yield strength heat.

4. Hydrogen pre-charging reduced the fracture toughness of Type 304L stainless steel block forgings to values that were between 33% and 50% of their non-charged values. This effect of hydrogen on toughness was greater in the Type 304L forgings than the Type 316L forgings.

5. The fracture toughness properties of Type 304L stainless steel forgings were improved by forging at 871°C versus 816°C. Fracture toughness values exceeded 10000 lbs/in for forgings conducted at 871°C.

6. Screw press forgings conducted at 816°C had the lowest fracture toughness values but still exceeded 7000 lbs/in.

VI. FUTURE WORK

Companion specimens for all of the conditions described in this report have been prepared and are being exposed to tritium gas and will be aged for future testing. The fracture toughness properties of the stem, cup, and block forgings will be measured after tritium exposures as a function of three different decay helium contents. The combined effects on toughness of forging strain rate, forging temperature, tritium, and decay helium will be explored for two different decay helium contents.

VII. ACKNOWLEDGEMENTS

The author wishes to acknowledge Glenn Chapman and Jim Wilderman for their assistance in conducting the mechanical and fracture toughness tests.

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