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IMPACT TESTING OF STAINLESS STEEL MATERIALS[1]

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ABSTRACT

Stainless steels are used for the construction of numerous spent nuclear fuel or radioactive material containers that may be subjected to high strains and moderate strain rates (10 to 200 per second) during accidental drop events. Mechanical characteristics of these materials under dynamic (impact) loads in the strain rate range of concern are not well documented. The goal of the work presented in this paper was to improve understanding of moderate strain rate phenomena on these materials. Utilizing a drop-weight impact test machine and relatively large test specimens (1/2-inch thick), initial test efforts focused on the tensile behavior of specific stainless steel materials during impact loading.

Impact tests of 304L and 316L stainless steel test specimens at two different strain rates, 25 per second (304L and 316L material) and 50 per second (304L material) were performed for comparison to their quasi-static tensile test properties. Elevated strain rate stress-strain curves for the two materials were determined using the impact test machine and a “total impact energy” approach. This approach considered the deformation energy required to strain the specimens at a given strain rate. The material data developed was then utilized in analytical simulations to validate the final elevated stress-strain curves. The procedures used during testing and the results obtained are described in this paper.

INTRODUCTION

The Department of Energy’s (DOE) National Spent Nuclear Fuel Program (NSNFP), working with the Office of Civilian Radioactive Waste Management (OCRWM), the Idaho National Engineering and Environmental Laboratory (INEEL) and other DOE sites, has supported the development of canisters for loading and interim storage, transportation, and disposal of DOE spent nuclear fuel (SNF). These canisters must be capable of performing a variety of functions during all three of these designated uses. A reduction of the structural integrity of these canisters at any stage of use could affect radionuclide containment or criticality control, key factors in the safe handling of the DOE SNF. Handling and transport operations require that the canister design has a high degree of confidence against failure of the containment boundary if the canister is subjected to loads (e.g., accidental drop events) resulting in large plastic deformations, high strains, or a range of moderate strain rates.

To assess the containment integrity of these SNF canisters under dynamic, impact loading, the preferred approach is to use nonlinear analytical methods with limited confirmatory testing. Improved software and methodologies for performing inelastic, large deformation analyses are becoming of age and offer numerous advantages relative to full-scale component testing; relatively low cost analytical simulations, ease of evaluating material and design options, elimination of costs associated with actual fabrication, testing, and post-test disposal, etc. In order to rely on a purely analytical approach, accurate results from methodologies and software must be demonstrated which in turn mandate a precise definition of inelastic, dynamic material properties (e.g. true stress-strain curves at elevated strain rates). Other variables such as temperature, welded and aged material properties, and project unique conditions must also be considered.

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The INEEL developed a drop-weight impact test machine (ITM) to begin the consideration of these variables and determine elevated strain rate stress-strain curves for stainless steel materials. During 2003, the ITM was fabricated at the INEEL as part of a Laboratory Directed Research and Development (LDRD) project. The fabricated ITM is pictured in Fig. 1. A previous paper [1] presented at the 2004 ASME PVP Conference described the ITM and discussed the results of standard tensile tests performed in the formulation of the ITM test process and initial test system checkout efforts. This present paper provides the results from the first series of tests after system checkout.

The purpose of the work performed was to utilize the ITM to improve understanding of strain rate phenomenon by experimentally studying the mechanical properties of candidate materials subjected to impact loading. The objective of the work during 2004 was to determine strain rate effects for 304L and 316L stainless steel materials under tensile, dynamic impact loading at room temperature. The stainless steel materials, 304L and 316L, are those actually used or proposed for use in the design of the DOE SNF canisters. Dynamic impact tests of 304L and 316L stainless steel tensile test specimens at two moderate strain rates, 25/second (304L and 316L material, NSNFP funded) and 50/second (304L material, LDRD funded) were performed for comparison to static tensile properties.

The ultimate goal is to develop true stress-strain curves at various strain rates and temperatures for these steels and provide justification of the adjusted material true stress-strain curves. The data developed can be used to establish an analysis methodology that can then be applied in analytical simulations to more accurately predict the deformation and resulting material straining in spent nuclear fuel containers, canisters, and casks under accidental drop events. The long-term goal is to develop sufficient data to provide clear and distinct guidance regarding impact analyses (e.g. accidental drop events) and how personnel can perform these analyses and obtain viable results without the need to perform expensive drop tests. Findings from this work can also help determine a basis for establishing allowable strain limits for these large deformation, inelastic events.

TEST DESCRIPTION

The goal behind the design of the ITM was to create a test device that could be used to investigate structural impact responses of multiple materials, including steels, concrete, plastics, etc. A hydraulic-based test system could have been developed to evaluate constant strain rate effects (with certain limits on strain rates and test specimen sizes) but the full representation of an actual drop event would not be present. The ITM was considered the most appropriate technique for producing material responses similar to those generated by

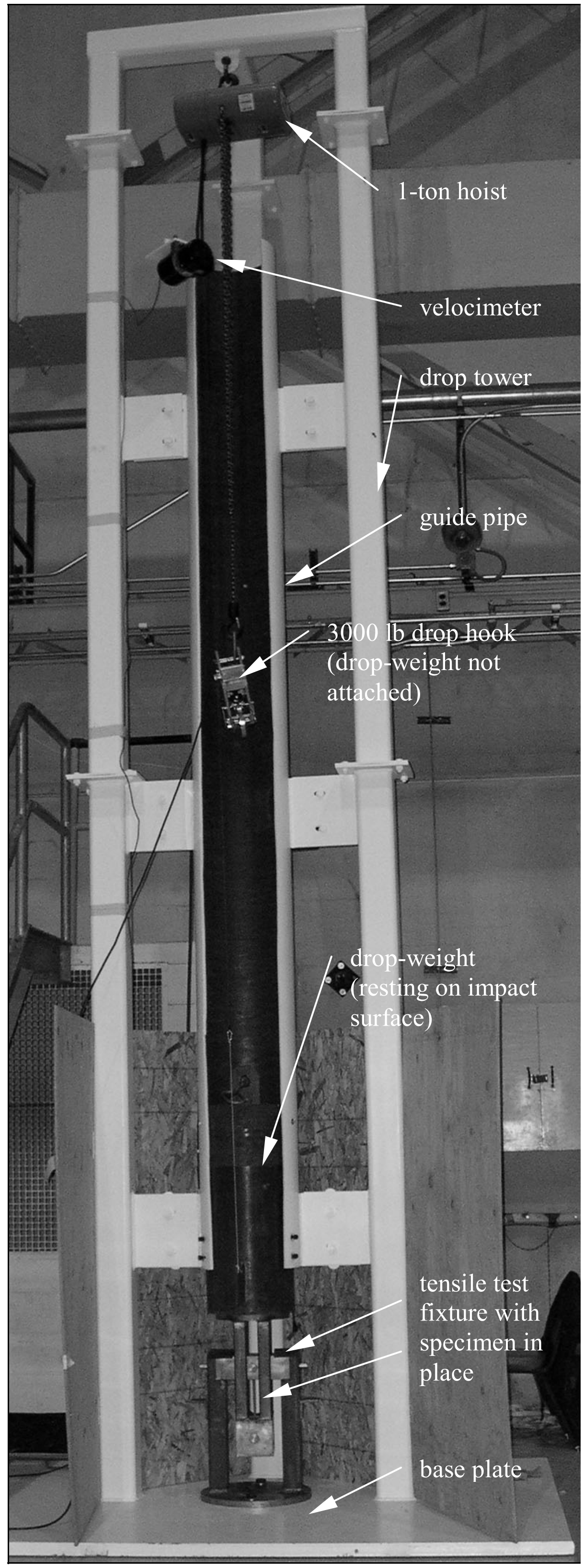

Figure 1. Impact Test Machine With Tensile Test Fixture and Test Specimen in Place

actual impulsive forces that occur during drop events, realizing that strain rate will vary with time during the test. The strain rate for such events typically starts high and decreases as the drop energy is dissipated. The ITM drop-weight machine was also chosen for this testing effort because it appeared to be a quick and inexpensive alternative for conducting dynamic impact tests of relatively large test specimens, up to ½-inch thickness. The elevated strain rate range for canister design impact events is typically characterized by moderate strain rates, 10 sec-1 ≤ $\dot{\varepsilon}$ ≤ 200 sec-1. Use of the drop-weight machine in this range was not expected to produce significant wave propagation effects [2].

The basic concept behind the ITM design was that of a falling weight impacting a test specimen resulting in elevated rate plastic deformation. The falling weight was controlled within a vertical tower, while the loading on the test specimen was controlled by way of a specimen holder. The ITM consisted of a drop tower (including base plate, structural tube framing and vertically slotted pipe with an attached hoist and velocimeter), a drop-weight referred to as a 'pig', a drop hook (electro-magnetic quick release mechanism), and test fixture. The ITM was approximately 23-feet tall. A 14-inch diameter steel bar (pig) was dropped within the confines of the 16-inch Schedule 40 slotted pipe rigidly supported by the structural steel tube frame members. The ITM was capable of dropping from 100 pounds up to 2000 pounds of impact weight, with a maximum drop height of about 13 feet. By using a combination of different weights, drop heights, and test specimen geometry, varying strain levels and strain rates were achieved in the test specimens.

To carry out a tensile test under a moderate strain rate, the ITM incorporated a special tensile holding fixture. The tensile test fixture is shown in Fig. 2. The tensile test specimen fixture consisted of a support stand and an impact driver. The support stand was made up of a bottom plate that bolts to the ITM base plate, two vertical legs, and an upper cross-member. The impact driver consisted of a top (impact) plate, four vertical legs, and a lower cross-member. All structural members of the impact driver and support stand were fabricated from rigid, solid bar and plate. The impact driver was connected to the support stand through the pinned ends of the dogbone tensile test specimen. During a test, the dropped impact weight contacted the impact driver, transferring its kinetic energy to the test specimen by way of the lower cross-member. The impact force was applied to the lower end of the dogbone specimen and was reacted through the upper end of the specimen into the upper cross-member of the fixture support stand. The pinned ends on the dogbone specimen provided for pure tension loading of the specimen.

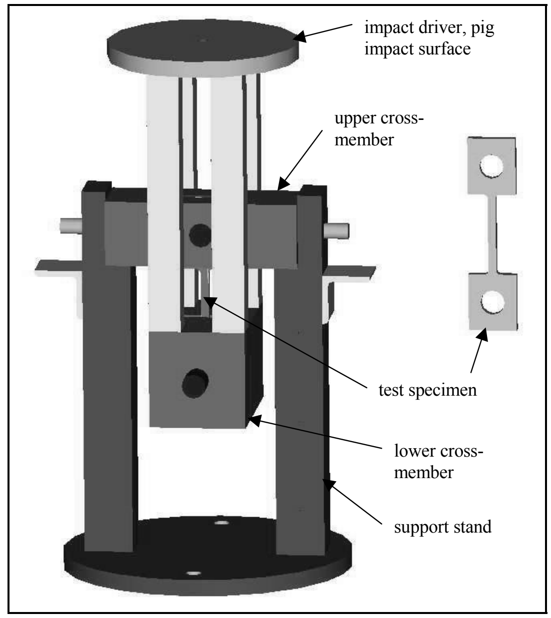

Figure 2. Tensile Test Specimen Fixture

Two similar tensile test specimen geometries were used with the ITM to generate the results reported herein for strain rates of 25/second and 50/second. The tensile test specimens were 12-inches in length, 3-inches in width, and were fabricated from ½-inch thick ASME SA-240 plate, oriented in the plate longitudinal direction. The length of the reduced section (test length minus the transition radii) was 4-1/2-inches for Geometry 1 and 1-1/4-inches for Geometry 2. Geometry 1 was used to generate a strain rate of 25/second in both the 304L and 316L materials. Geometry 2 was used to generate a strain rate of 50/second in the 304L material. Figure 3. shows the Geometry 1 test specimen dimensions.

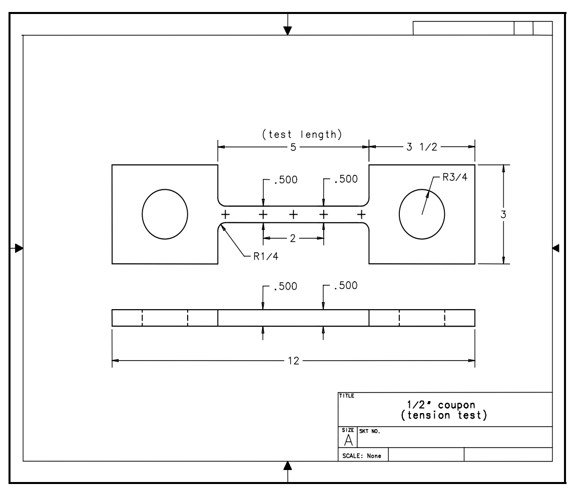

Figure 3. Tensile Test Specimen Geometry 1

TEST PROCEDURE AND DATA ACQUISITION

In order to define the effects of elevated strain rate for the 304L and 316L materials, the quasi-static, tensile true stress/true strain curve was chosen as the basis for comparison. Quasi-static tensile testing of ½-inch thick coupons was conducted following the methodology of ASTM A370 [3]. All quasi-static tests were conducted at room temperature. Force-displacement results from these tests were converted to engineering and true stress/strain plots using standard methods. The engineering stress-strain curves are shown in Fig. 4., Fig. 5. and Fig. 6. for the various materials and heats involved in this research.

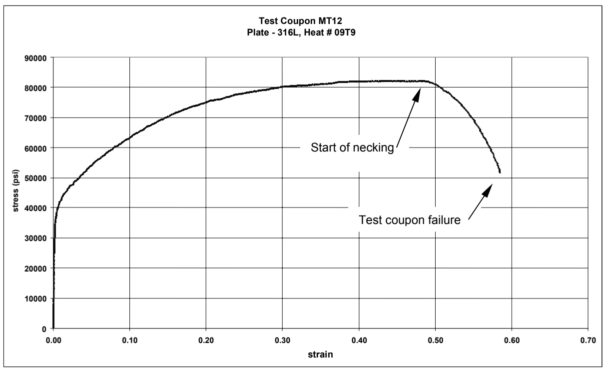

Figure 4. Quasi-Static Engineering Stress-Strain Curve for 316L Material, Heat 09T9

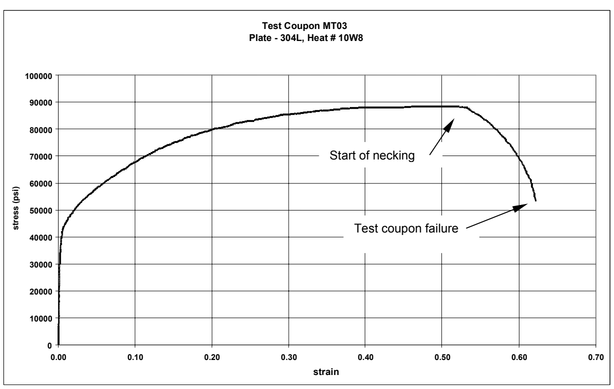

Figure 5. Quasi-Static Engineering Stress-Strain Curve for 304L Material, Heat 10W8

Impact test specimens were measured and marked prior to testing to assure tolerances were satisfied, pre-test gage lengths were defined, and tracking identification was clear. The testing process began with the insertion of a test specimen into the tensile test fixture. The drop-weight was positioned at the predetermined height to achieve the desired strain rate. When test preparations were complete, the electromagnetic drop hook was tripped allowing the pig to fall under the influence of gravity.

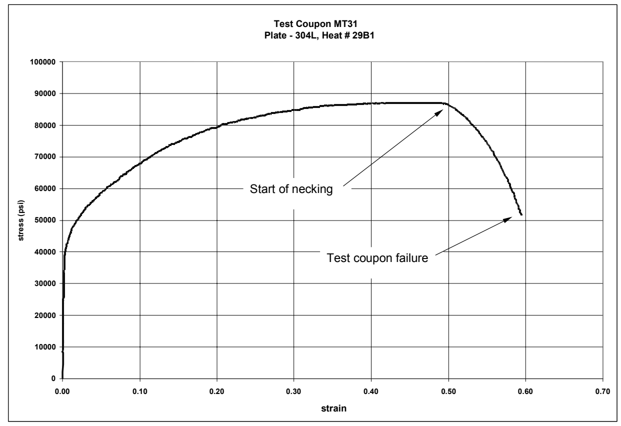

Figure 6. Quasi-Static Engineering Stress-Strain Curve for 304L Material, Heat 29B1

During an impact test, impact velocity and specimen acceleration history were measured directly. Specimen final strain measurements were taken directly from the specimen after the test was completed. Impact velocity was measured by attachment of a velocimeter to the lower end of the drop-weight (pig). Acceleration histories were recorded using 500 g and 5000 g accelerometers mounted on one end of the impact driver lower cross-member. Velocity and acceleration histories were recorded on a Data Acquisition System (DAQ) 2000A at a rate of 5000 samples per second for 20 seconds. Accelerations were recorded with the goal of determining the resulting impact force history and the impact time interval. Specimen temperatures were also measured before and following the test. However, it was assumed that the material properties did not change significantly during the drop event due to any change in temperature.

A high-speed digital camera was used to record image data of the impact event. The camera was positioned to look directly at the specimen front surface and displacement histories at defined specimen locations on the test length were recorded during the drop event. All imaging data was recorded at a frame rate of 3000 frames per second resulting in a .000333 second time interval per image. Motion analysis of the image data was used to determine displacement histories of the defined specimen locations and the corresponding specimen engineering and true strain histories and strain rates.

METHODOLOGY

ITM response, data acquisition, and data evaluation techniques were not fully established at the beginning of the test effort and had to be developed as limitations were exposed. In the early stages of planning and ITM testing, the intent was to determine the three parameters necessary to plot a modified stress-strain curve at a specified strain rate. These three parameters included the force imposed on the tension test specimen, the amount of strain achieved in the test specimen, and the time interval over which the impact force caused the total strain. These direct measurements were the preferred approach for determining the actual strain rate and stress-strain curve of the material under dynamic impact loading conditions. The standard way of analyzing the output of a drop-weight machine assumes the weight behaves as a rigid body and that one can simply apply Newton's laws of motion. Multiplication of the acceleration output by the appropriate mass leads to the force (varying with time) in the specimen and the engineering stress. This approach was planned because a dynamic force transducer capable of direct measurement of specimen forces at the g levels being produced in the specimen by the ITM during the impact testing could not be found.

In practice, the acceleration output proved to be masked with considerable noise and appeared to contain extraneous oscillations comparable in size to the signal produced by the mechanical resistance of the specimen. Different filtering approaches were applied, but the resulting changes to either the timing of the event or the acceleration responses did not yield results that were considered acceptable. Force histories appeared unreasonably high.

As an alternative solution to the direct measurement of the specimen force and strain during the impact event, a total impact energy approach was used that considers the specimen deformation energy. Deformation energy is the energy required to deform (strain) a material a specified amount. It is the area under the stress-strain diagram up to a specified strain level. For this approach, the quasi-static true stress/true strain material curve was determined and the area under the curve at the strain level of interest was evaluated for comparison to the energy dissipated by the ITM test specimen during the impact test. The 'strain level of interest' was the maximum uniform strain achieved in an actual test at a given, elevated strain rate. Knowing the energy input to the specimen during the impact test and assuming a shape for the elevated strain rate curve being generated, the corresponding true stress value was established by bounding the input energy to the value of true strain achieved in the test. Several strain values were evaluated for each curve at a given elevated strain rate. A brief literature search [4, 5] indicated that the shape of elevated strain rate curves for stainless steels relative to the quasi-static shape was similar (the addition of a constant to each stress point-'shifted') or expanding (multiplication of each stress point by a constant-'factored'). Variations in curve shape were addressed by applying both a shifted and a factored technique to determine the elevated strain rate curve. Both techniques were based on the established shape of the quasi-static curve as determined from a standard tensile coupon test. The assumption that the modulus of elasticity does not have any dependency on strain rate was made in the curve development. The energy input to the specimen was determined by applying momentum theory to the total impact energy assuming an inelastic impact of the pig and impact driver. This assumption was substantiated by agreement between the theoretical combined velocity of the pig and impact driver and the combined velocity as determined from integration of the test acceleration data.

This total impact energy approach limited testing to maximum strains in the uniform strain region (less than the necking strain or strain corresponding to ultimate stress) of the stress-strain curve because if test specimen failure occurred, the amount of energy expended in breaking the specimen could not be determined (total energy input was known, but the amount of energy remaining in the combined pig and impact driver mass following specimen failure was not).

For a given impact test, the strain rate achieved was determined using high-speed photography. The time interval of the impact event and beginning and end of the event were also determined directly using this technique. At an applicable frame rate, displacements in time of known points on the specimen were measured directly from the frame exposures and converted to strains. Specimen strain measurements taken directly from the specimen following the test, confirmed the adequacy of the final imaging strain values. A typical true strain history as determined from the camera imaging is shown in Fig. 7. for Specimen 304L-40. For this type of drop-weight testing and in actual drop events where the impact force and input energy are not constant with time throughout the deformation event, the strain rate varies as the input energy is dissipated. For this evaluation effort, the 'test' strain rate was defined as that strain rate occurring early in the specimen response stage where the occurring strain was nearly constant with time. A typical strain rate determination is shown by the slope of the dashed line in Fig. 7. where the strain rate for Specimen 304L-40 was established at: 0.1558/0.0060 ≈26/second. ITM test results with strain rates equal to the

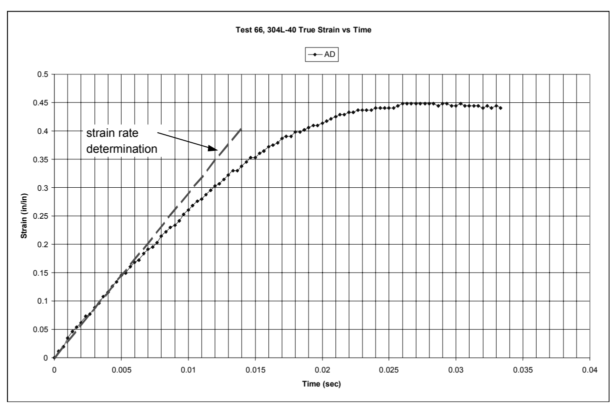

Figure 7. Camera Determined True Strain History and Strain Rate for Specimen 304L-40

target strain rate ± 2/second were considered acceptable for establishing the final target strain rate curve.

A total of four tests at the target strain rates with different achieved maximum strains for each material and heat number were used to determine the final target strain rate curves. Test conditions and resulting true strains and strain rates for the final tests are given in Table 1. The four tests for each material and heat number resulted in four factor and shift values that were averaged to determine the final elevated strain rate curve. The factor and shift values are those values which, when applied to the quasi-static curve up to the strain level of interest, produce an elevated strain rate curve with the same deformation energy dissipated by the test specimen in achieving the target strain rate and strain level of interest.

Table 1. Final ITM Impact Tests

Test ID	Heat No.	Impact Weight (lbs)	Impact Height (in)	Uniform Strain (%)	Strain Rate (sec^{-1})
304L-32	10W8	790	43	21.9	24.4
304L-39	10W8	1097	43	30.5	24.9
304L-43	10W8	1513	31	32.4	25.2
304L-40	10W8	1347	38	34.4	26.0
304L-55	29B1	1513	14	41.2	49.8
304L-56	29B1	1347	15.75	41.5	48.8
304L-73	29B1	1097	20	39.5	51.7
304L-75	29B1	790	25.375	34.1	49.3
316L-8	09T9	1513	36	38.8	25.9
316L-9	09T9	1347	40	37.9	24.4
316L-12	09T9	1097	45	34.9	25.2
316L-23	09T9	790	50	26.6	24.4

The effects of elevated strain rate on the true stress-strain curve were determined by comparison of the elevated curve to the quasi-static curve. With the modified stress-strain curve reflecting a specified elevated strain rate established, analytical evaluations (using ABAQUS/Explicit [6]) were then made to determine how close the plastic analysis evaluations match the actual deformations of the test specimens, further evaluate the appropriate shape of the elevated strain rate curve, and establish an appropriate analysis methodology consistent with the developed data.

RESULTS

Moderate strain rates of 25/second and 50/second were achieved at strain levels in the uniform strain region, i.e., below the point of specimen necking. Quasi-static material true stress/true strain curves and elevated strain rate true stress/true strain curves were developed, evaluated, and compared. The test results and factor and shift values determined for the 304L and 316L materials and heat numbers from the ITM impact tests are summarized in Table 2. Figure 8., Fig. 9., and Fig.10. depict the resulting true stress-strain curves determined for the 304L and 316L materials at the target strain rates of 25/second and 50/second. Data shown in these figures beyond the maximum strain values identified in Table 2 were extrapolated to the fracture strain determined from the quasi-static coupon tests. Testing to date has not determined the actual elevated strain rate fracture strain, which may be different than the values shown in the figures.

Table 2. Factor and Shift Values for 304L and 316L Material

Test ID	Heat No.	Max. Strain (in/in)	Strain Rate (sec.$^{-1}$)	Factor Value	Shift Value
304L-32	10W8	0.2189	24.4	1.42	31816
304L-39	10W8	0.3054	24.9	1.33	28172
304L-43	10W8	0.3242	25.2	1.30	26185
304L-40	10W8	0.3438	26.0	1.28	25144
Avg.	**10W8**	–	**25.1**	**1.33**	**27829**
304L-55	29B1	0.4116	49.8	1.37	35684
304L-56	29B1	0.4146	48.8	1.36	34564
304L-73	29B1	0.3949	51.7	1.43	40719
304L-75	29B1	0.3406	49.3	1.50	44147
Avg.	**29B1**	-	**49.9**	**1.41**	**38779**
316L-8	09T9	0.3878	25.9	1.27	23663
316L-9	09T9	0.3788	24.4	1.28	24232
316L-12	09T9	0.3493	25.2	1.30	25186
316L-23	09T9	0.2661	24.4	1.36	27300
Avg.	**09T9**	–	**25.0**	**1.30**	**25095**

With the modified stress-strain curves reflecting elevated strain rates of 25/second and 50/second established, ABAQUS/Explicit was used to evaluate an analytical model of the ITM test using pig impact weights and drop heights corresponding to the 12 impact tests shown in Table 1. The corresponding quasi-static stress-strain properties were also analytically evaluated for comparison purposes using the test impact weight and drop height. Three simulations for each test used the three different stress-strain curves established for the two materials and strain rates: the quasi-static base curve and the factored and shifted curves. For comparison purposes, the final specimen change in length (Δ L) achieved in the actual test and simulation was reported. This measurement represented the maximum axial inelastic deformation obtained in the test specimen. A summary of the average % difference in the change in gage length (Δ L) between the actual test and ABAQUS/Explicit simulation results for the two materials and strain rates is shown in Table 3.

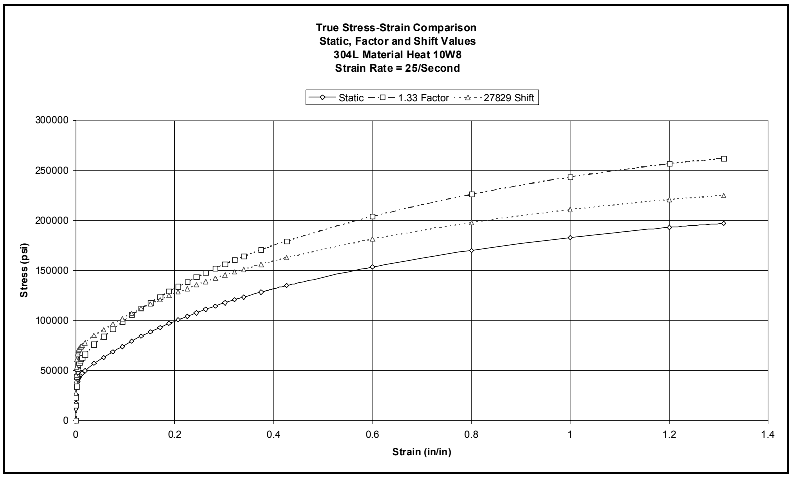

Figure 8. True Stress-Strain Comparison 304L Heat 10W8, SR = 25/Second

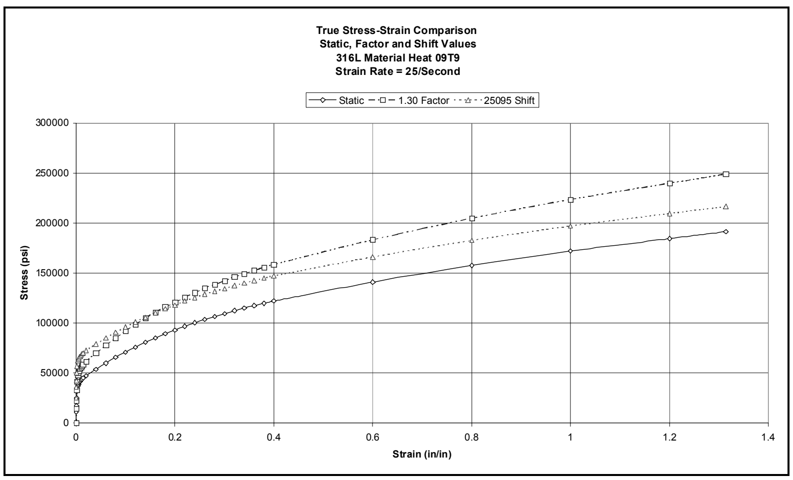

Figure 9. True Stress-Strain Comparison 316L Heat 09T9, SR = 25/Second

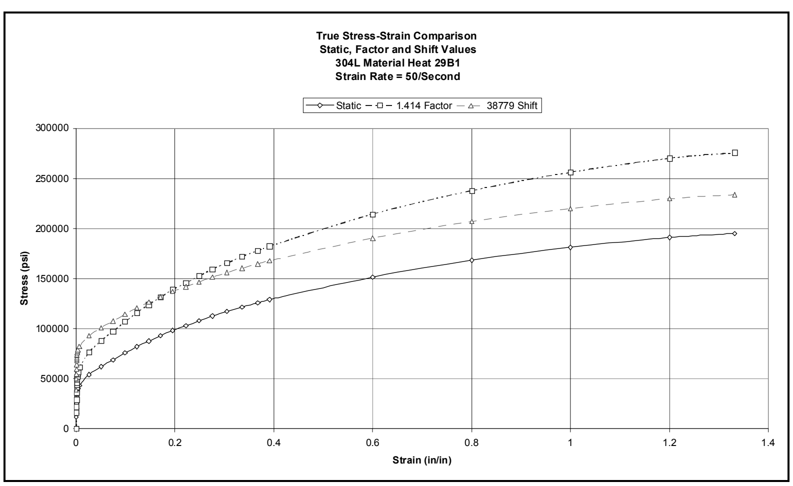

Figure 10. True Stress-Strain Comparison 304L Heat 29B1, SR = 50/Second

Average % Difference in Gage Length Δ L		
304L Heat 10W8, SR 25/Second		
Quasi-Static	1.33F	27829S
31	3	1
316L Heat 09T9, SR 25/Second		
Quasi-Static	1.30F	25095S
28	3	4
304L Heat 29B1, SR 50/Second		
Quasi-Static	1.41F	38779S
35	3	7

Table 3. Summary of Average % Difference in Gage Length Δ L From Actual Test Value

The test results showed that yield strength, flow stress, and ultimate stress are dependent upon strain rate and increase with an increase in strain rate for both the 316L and 304L materials. At a given strain level, the 304L material exhibited slightly higher flow stress magnitudes relative to the 316L material as expected from the static results. The 304L material appeared to have a slightly better energy absorption capacity at the strain rates investigated. These differences, as shown in Fig. 11., were not large and might have resulted somewhat from variation in mill processes as well as material properties.

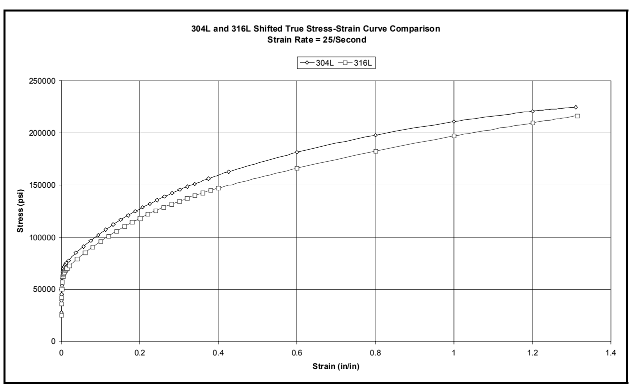

Figure 11. Shifted True Stress-Strain Comparison for 304L and 316L Materials

Because impact testing was limited to strain in the uniform strain region, conclusions concerning strain rate effects on failure stress, failure strain, and total elongation could not be drawn at this time. However, based on a very limited number of necked test specimens, it appeared that the necking strain remains relatively constant with strain rate. The quasi-static stress-strain curve results indicated necking at the same strain level as the higher, elevated strain rate curves. This preliminary observation requires further study at higher strain levels and strain rates. At an elevated strain rate of approximately 25/second, the necking true strain for 304L was approximately 0.401 inch/inch while that for 316L was 0.405 inch/inch. Figure 4. and Fig. 5. indicate quasi-static true necking strains of approximately 0.418 inch/inch for the 304L material and 0.398 inch/inch for the 316L material.

As shown in Table 3, reasonable agreement was obtained between actual test results and predicted analytical results using an ABAQUS/Explicit model incorporating the newly developed elevated material curves. Considerable error (28% - 35%) resulted when the quasi-static stress-strain curve was incorporated, indicating that strain rate effects are real and significant even in the moderate range. The selected factored and shifted curves improved the correlation, reducing the error on average to less than 7%.

As indicated by Table 3, both the factored and shifted curves showed good agreement and validated the energy method used to determine the curves. Table 3 focuses results only on the final displacement value and not the multiple intermediate displacement values the test specimen experiences as the impact event progresses. Comparing the values in Table 3 may be misleading if final displacement was simply a function of energy input since both the factored and shifted curves contain the same energy (area under the stress-strain curve) at the maximum strain level. Figure 12. shows the actual test and ABAQUS/Explicit results for the displacement history of a location near the bottom of the gage length on test specimen 316L-12. This test was one of the better elevated strain rate tests, but is typical of the correlated results and its specific factor and shift values are within 0.5% of the average factor and shift values used to determine the final elevated strain rate curves (see Table 2). During the actual test, this specimen achieved a total true strain of 0.3493 in/in in the gage length. The figure shows good agreement with actual test results of the specimen displacement history for both the factored and shifted methods and supports the results indicated in Table 3. Although the differences are small, the plot

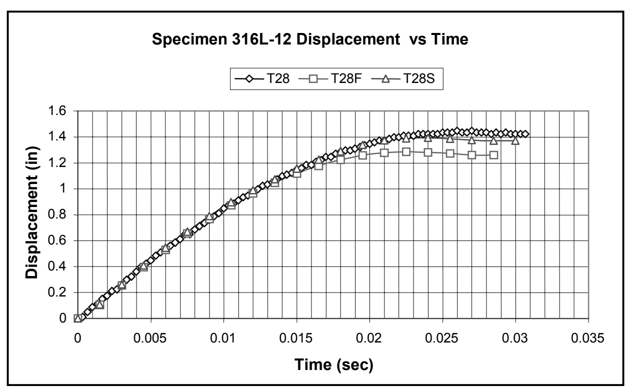

Figure 12. 316L-12, Displacement vs Time Comparison

indicates that the shifted curve approach yields slightly better final displacements up to strain levels near necking.

CONCLUSIONS

An improved understanding of the strain rate phenomenon for 304L and 316L material was determined by experimentally studying their mechanical properties subjected to impact loading. Tension only testing of SA-240 304L and 316L longitudinal plate material was performed with maximum strains being limited to the material uniform strain region. Elevated true stress-strain curves were developed from the drop-weight impact test data for the two materials at the two specified strain rates using a total impact energy approach. This approach required an assumption on the actual shape of the elevated strain rate curve. To account for variations in the curve shape, two curves at each strain rate for each material and heat were developed using both a factored and shifted adjustment of the quasi-static true stress-strain curve. With the modified stress-strain curves reflecting the specified elevated strain rates established, analytical evaluations (using ABAQUS/Explicit) were made to determine how close the plastic analysis evaluations matched the actual deformations of the test specimens. Correlation with analytical simulations was considered a validation of the material impact testing performed and justification of the modified stress-strain curve.

In the near term, test results to date indicate that the total impact energy shifted curve approach yields the best correlation with analytical results in the uniform strain region for moderate strain rates of 25/second and 50/second for both the 304L and 316L materials. However, more work is needed to better define the actual shape of the elevated strain rate true stress-strain curve. At a true strain of 0.400 in/in near the end of the uniform strain region, an increase in material strength of approximately 25% is predicted relative to the static case for a strain rate of 25/second. An approximate increase of 30% was observed for the 304L material at a strain rate of 50/second.

The elevated strain rate data developed from this test effort can be used to improve drop event analytical evaluation methodologies. The elevated strain rate curves developed can be used in analytical simulations to more accurately predict the deformation and resulting material straining in spent nuclear fuel containers, canisters, and casks under accidental drop events.

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