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Residual Stresses and Other Properties of Teardrops

M.A. Stroud, D.K. Veirs, J.M. Berg, M.A. Hill, J. Duque and D. Rios

I. INTRODUCTION

The Department of Energy's 3013 Standard for packaging plutonium-bearing materials for storage up to fifty years specifies a minimum of two individually welded, nested containers herein referred to as the 3013 outer and the 3013 inner.¹ Stress corrosion cracking (SCC) is a potential failure mechanism for 3013 inner containers.^{2,3} The bagless transfer container (BTC), a 3013 inner container used by Hanford and Savanna River Site (SRS) made from 304L stainless steel (SS), poses the greatest concern for SCC.^{4,5} The Surveillance and Monitoring Program (SMP) use stressed metal samples known as teardrops as screening tools in SCC studies to evaluate factors that could result in cracks in the 3013 containers.^{6,7} This report provides background information on the teardrops used in the Los Alamos National Laboratory (LANL) SMP studies including method of construction, composition and variability. In addition, the report discusses measurements of residual stresses in teardrops and compares the results with residual stresses in BTCs reported previously.⁴ Factors affecting residual stresses, including teardrop dimensions and surface finish, are also discussed.

II. TEARDROP PROPERTIES

Teardrops used in this study were procured from Metal Samples; a division of Alabama Specialty Products, Inc. Teardrops were procured in multiple batches. The mills associated with the teardrops were Stewart Stainless Supply in Suwanee, GA and Outokumpu in Alpharetta, GA. The 304L stainless steel (SS) used had a 2B mill finish which is a smooth, moderately reflective cold-rolled, annealed to 1040 degree Celsius (°C) and pickled (acid cleaned) finish. Pickling removes scales and improves resistance to corrosion. The procurement information and test reports on the SS prior to formation into a teardrop for Batches 3, 4 and 5 are in Appendix 1. Composition in mass percent for select elements in select teardrops from Batches 1 and 2 obtained at LANL using optical emission spark spectrometer or X-ray fluorescence alloy analyzer, are in Appendix 2. (Use of Batch 2 teardrops in corrosion tests was discontinued due to anomalous behavior. See Appendix 3.) Key composition results are summarized in Tables 1.

Table 1. Chemical composition (average mass percent (%)) of 304L austenitic stainless steel

	Composition of 304L SS in Mass Percent (%)									
Batch	C	Cr	Cu	Mn	Mo	N	Ni	P	S	Si
1		17.8/18.12	0.28	1.32	.22/.29		7.59/8.22			
2		17.8	0.43	1.26	0.27/.34		7.39/8.12			
3	0.024	18.19	0.4	1.68	0.26	0.063	8.07	0.029	0.0030	0.36
4 and 5	0.0202	18.0195	0.4985	1.7370	0.3835	0.0859	8.0125	0.0355	0.0152	0.2230
% variation (Max-Min) ÷ Max	16%	2%	44%	27%	43%	27%	10%	28%	80%	38%

Key mechanical properties of the metal coupons prior to bending are summarized in Table 2. Typical values for annealed 304L SS are also listed for comparison. Ultimate Tensile Strength (UTS) and yield strength increase with increasing cold-working and elongation at fracture decreases.⁸

Table 2. Mechanical properties of 304L austenitic stainless steel measured transverse to rolling direction for Batch 3. Direction of measurement is not known for Batches 2, 4 and 5.

Batch	Ultimate Tensile Strength (UTS) (MPa)	Yield Strength (MPa)	Elongation (at fracture)	Hard RB	Direction of bending relative to the rolling direction
2					Longitudinal
3	636/630	284/274	61.8/63.4%	82/81	unknown
4	686	371	47.5%	89.5	Traverse
5	686	371	47.5%	89.5	Longitudinal
Typical 304L SS	558	269	55%		
% Variation (Batch 4/5 – Batch 3) ÷ Batch 4/5)	8%	30%	25%	9%	

The yield strength of the unbent SS varied approximately 30 percent (%) between the two batches of TDs with available data.

Teardrops were fabricated from rectangular coupons of 304L stainless steel (SS) with dimensions of 1/16 inch thick by 3/4 inch wide by 4 inches long (before bending). An autogenous weld across the width at the apex (center of the bent region) was added to the flat coupon prior to bending. The weld was added to simulate the condition of the metal heat affected zone (HAZ) in 3013 container weld regions. Some coupons were ground to a fine surface finish of 600 grit to remove the weld oxide from the surface prior to bending. All grinding was along the bending (longitudinal) direction. Teardrops were formed by bending the rectangular coupon around a 1/2 inch $\pm$ 1/32 inch radius mandrel and welding the ends together to hold them in place (closure weld). This locked in the high residual stress from the bending. Some teardrops were also cut in half at LANL with a brass wire using Electrical Discharge Machining (EDM) prior to use in experiments to accommodate experimental equipment dimensions but use was discontinued due to indications of altered corrosion behavior (See Appendix 4.) A batch was also manufactured at half width (3/8 inch). Figure 1 shows the four types of teardrops.

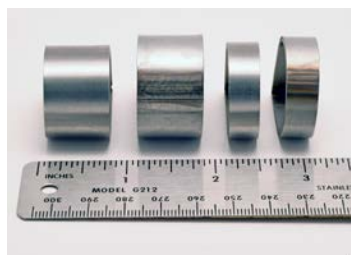


Figure 1. Photograph of a whole ground, whole unground (with slit), half width ground and half width unground teardrops.

Figure 2 is a photograph of ten unground whole teardrops. The weld regions and associated surface oxidation are clearly visible and show lack of uniformity between teardrops.

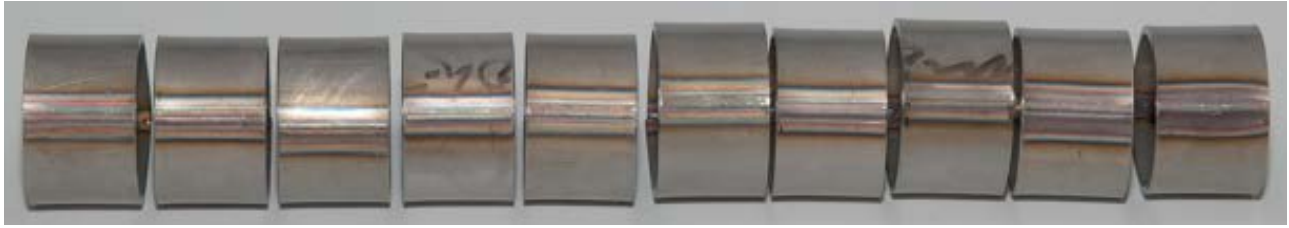


Figure 2. Photograph of Unground Whole Teardrops.

The thickness and the inner radius of curvature of a representative population of the teardrops from Batches 4 and 5 were measured to determine the extent of variability in physical dimensions that might have an impact on residual stress variability. Diameter was measured using calipers. Thickness was measured with micrometers on the flat portion of metal just above the weld that joins the teardrop at the tip (Figure 3.)

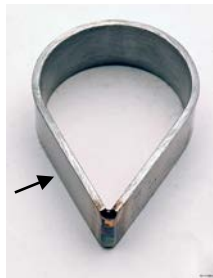


Figure 3. Teardrop showing the location of the thickness measurements

Results are shown in Figure 4. Detailed information on the measurements for each teardrop may be found in Appendix 5.

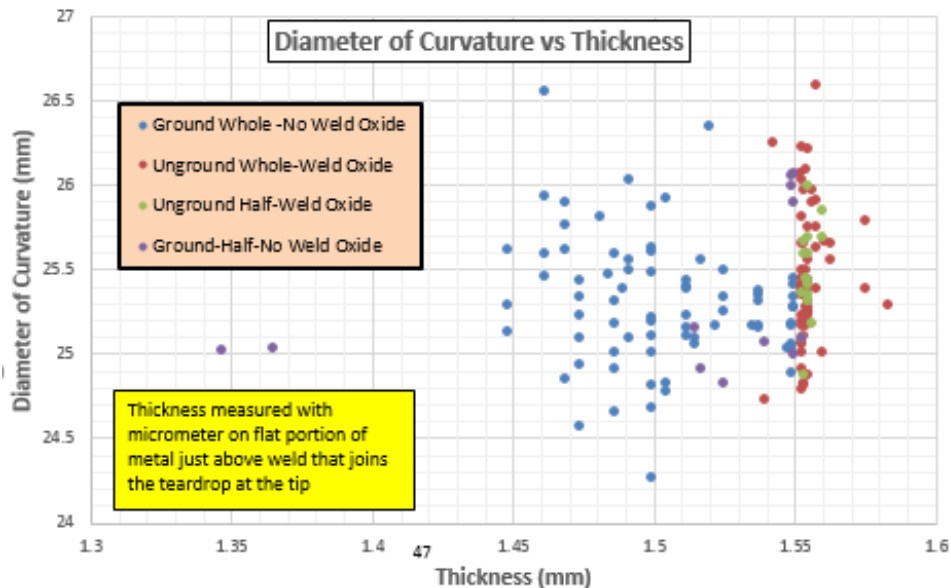


Figure 4. Graph of Diameter of Curvature vs Thickness for Teardrops

Table 3 provides a summary the standard deviation of the thickness (T), diameter (D) and T/D.

Table 3. Summary of the standard deviation in thickness (T), diameter of curvature (D), and the ratio of thickness to diameter of curvature (T/D) between teardrops samples.

	Standard Deviation			
	Ground Whole (mm)	Unground Whole (mm)	Ground Half (mm)	Unground Half (mm)
Thickness (T)	0.029	.006	.073	.002
Diameter of Curvature (D)	0.40	0.41	0.50	.29
T/D	.002	.001	.003	.001

III. Experimental Method

Hill Engineering, LLC used the “split and slit” method to measure residual stresses in a teardrop^{9, 10}. The teardrop was split (closure weld severed) to relax the bending moment prior to the slitting measurement. The “split and slit” approach was used rather than completing the slitting measurement without splitting to minimize plasticity issues. The slitting method uses the deformation of the part during cutting to quantify residual stress. In addition, when the stresses are high, yielding (plastic deformation) at the tip of the cut is more likely during the slitting measurement (which is a potential error). By splitting the teardrop, the magnitude of the remaining residual stress is reduced, which helps minimize non-linear material issues.¹¹

Splitting measurement method

Seven teardrops, TD 60 and TD 48 (Batch 4), TD 5, TD 34, TD 35, TD 47 and TD 49 (Batch 5) were split open at the closure weld (Figure 5) to determine the bending moment stresses.



Figure 5. Split Teardrop.

The strain releases as a result of the splits were measured using strain gages oriented to measure strain in the hoop (longitudinal) direction.

For teardrop TD 60, strain was measured at the five locations, shown in Figure 6. For teardrops TD 34, TD 35, TD 48 and TD 49, strain was measured at locations 1 and 2, and for teardrop, TD47 and TD 5, strain was measured at location 2 only.

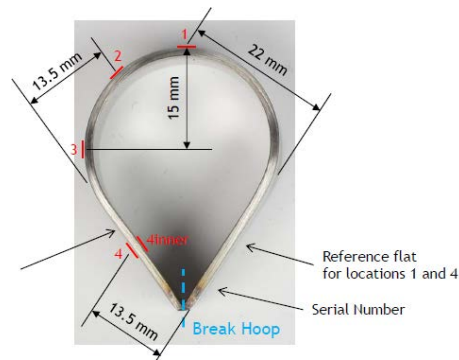


Figure 6. Photograph showing splitting (break hoop) location and strain gage placement for TD 60.

Slitting measurement method

The slitting method was used to measure the hoop residual stress in five of the split teardrops. For additional background information on slitting, consult the references¹⁰.

Each specimen was slit with a wire using EDM, with the slit extending radially inward. For TD 60, the slit was located at **location 2** (Figure 6). For TD 34, TD48, TD35 and TD 49 the slits were located near the weld. (Figure 7).

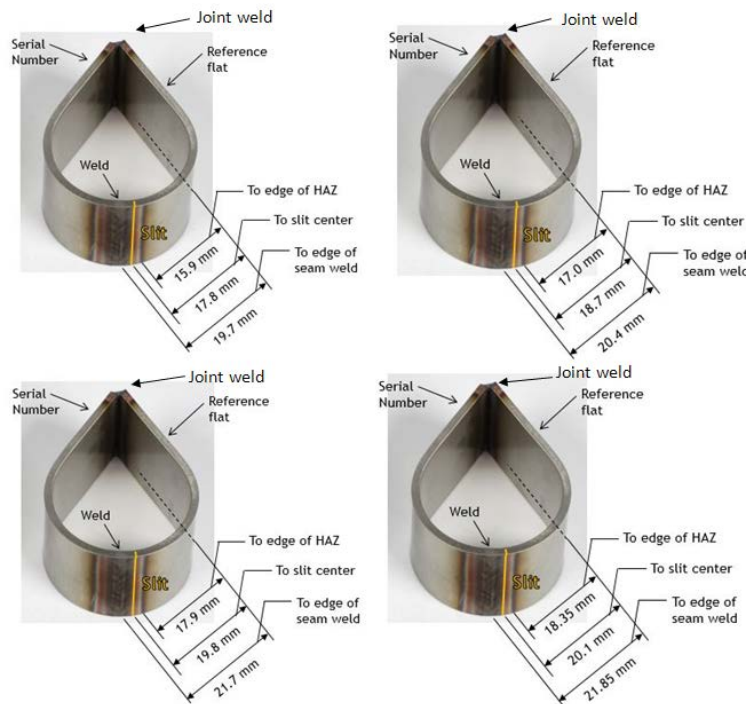


Figure 7. Diagram showing slit location for TD 35 (upper left), TD 34 (upper right), TD 49 (lower left), and TD 48 (lower right).

A single strain gage was applied to the back face of the teardrop, directly behind the slit. For each incremental slit depth, the strain change was monitored using a commercial Wheatstone Bridge instrument and recorded. The measured strain versus slit depth data was used to compute residual

stress. Photographs of the weld region for TD 35 and TD 49 before and after the slitting measurement are shown in Figure 8 and Figure 9.

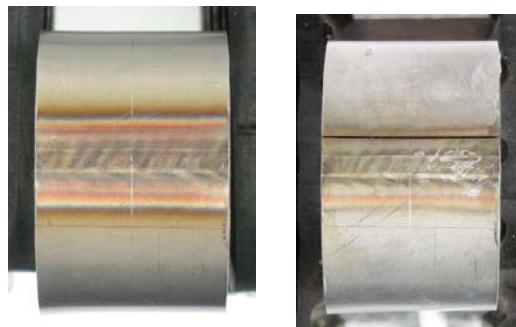


Figure 8. Photograph of the HAZ for TD 35 before the slitting measurement (left) and after the slitting measurement (right).

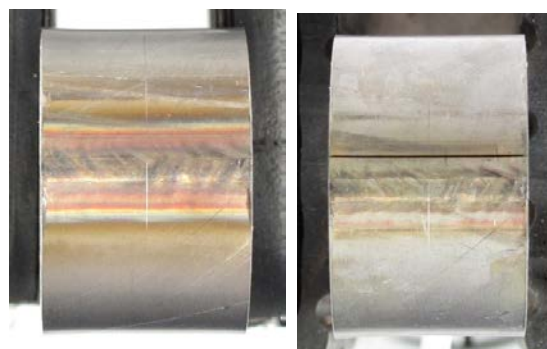


Figure 9. Photograph of HAZ for TD 49 before the slitting measurement (left) and after the slitting measurement (right).

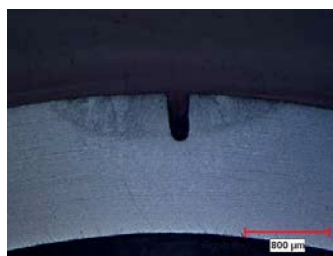


Figure 10. Weld region of a representative teardrop after slitting in the center of the weld.

Stress release correction

The residual stress measured using the slitting method is different from the residual stress that was initially present in the teardrop because splitting (breaking open the hoop) altered the overall residual stress state in the body. The measured strain at the outer diameter (OD) during splitting of the teardrop was used to calculate the stress released at the OD of the teardrop at the slitting plane, assuming a linear-elastic stress-strain relationship. Then, the released stresses in the interior and inner diameter (ID) of the slitting plane were calculated by assuming the teardrop acted like a curved rectangular beam in pure linear-elastic bending.

The total residual stress reported here, are the measured stress released by slitting plus the stress that was inferred from the strain release upon splitting (breaking open) the teardrop.

IV. Results

Split and Slit

Table 3 summarizes teardrop properties, strain gauge locations, the splitting strains and break hoop released stress (bending stress) measured during splitting. See Figures 6 for detailed information on strain gauge location reference. During the splitting (break hoop) operation the stress release was tensile at the OD and compressive at the ID. The table also includes the maximum total residual stress determined from the combined split and slit results. Teardrops are listed in order of increasing thickness.

Table 4. Teardrop properties and strain and released hoop stress at each strain gauge due to splitting and maximum total hoop stress.

TD	Batch	Thickness (mm)	Diameter of Curvature (mm)	Weld Oxide	Surface Finish prior to bending	Gage Location (Outer Wall unless noted)	<i>Splitting Strain</i> (μϵ)	<i>Splitting Released</i> Hoop Stress (MPa)	<i>Split and Slit</i> Max Total Hoop Stress (MPa)
47	5	1.4986	24.28	No	Ground: 600 grit	2	-1656	325	
5	5	1.5189	26.36			2	-2485	487	
60	4	1.5494	25.29			1	-3075	603	
						2	-2897	568	482
						3	-1768	347	
						4	-607	119	
						4 (inner wall)	662	-130 (Compressive)	
34	5	1.5519	25.37	Yes	As delivered 2B Finish (Annealed and Pickled)	2	-2807	550	
						HAZ*	-2778	544	504
35	5	1.5545	25.28			2	-3199	627	
						HAZ*	-3154	618	473
49	5	1.5545	25.32			2	-2123	416	
						HAZ*	-2274	446	352
48	4	1.557	26.6					2	-2636
						HAZ*	-2748	539	480

*The precise location of the slit is shown in Figure 7, 8 and 9.

Detailed results from the “Split and Slit” measurements, including uncertainties in the measurements, are in Appendix 6. The maximum reported uncertainty in the measured values was ± 60 MPa. Calculations of the released stresses assumed the SS in all teardrops had a YM of 196 GPa and Poisson’s ratio of 0.285. Work by Manninen et. al¹² found that the apparent YM of austenitic stainless steels decreased by up to 15% due to cold working. So reported stresses could be up to 15% high if the Young’s Modulus (YM) of the SS changed due to cold working.

Line plots of the measured (slitting), calculated released (splitting), and total residual stress versus depth results are shown in Figures 11-13. (Positive stress values denote tensile stresses and negative compressive stresses). The slit in TD 60 was at location 2 while the slits in the other teardrops were near the weld in the heat-affected zone (HAZ).

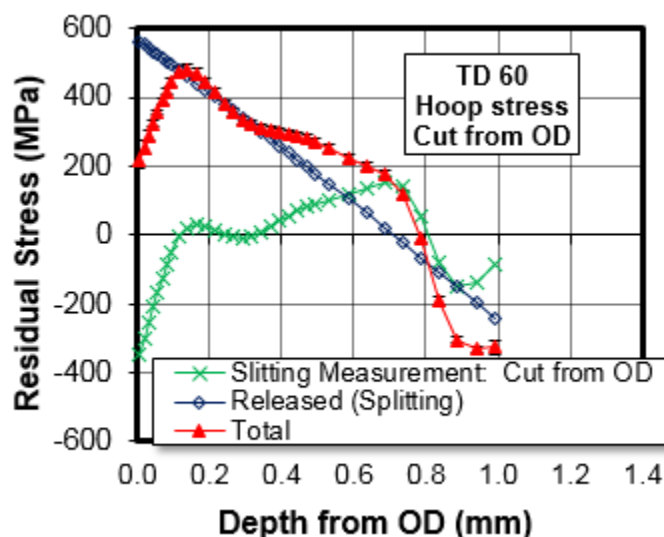
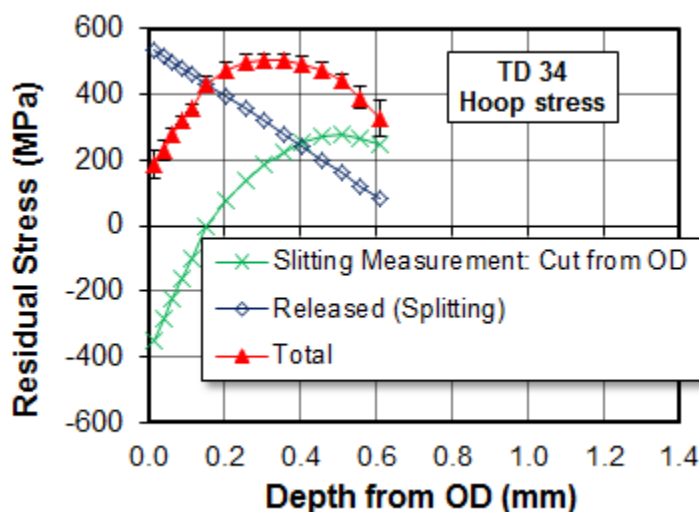


Figure 11. Line plots of the residual stress (slitting measurement, released (splitting), and total) versus depth for teardrop TD 60. Measurements were taken at **location 2**. Error bars are included for the total residual stress. (Positive values denote tensile stresses and negative compressive stresses.)



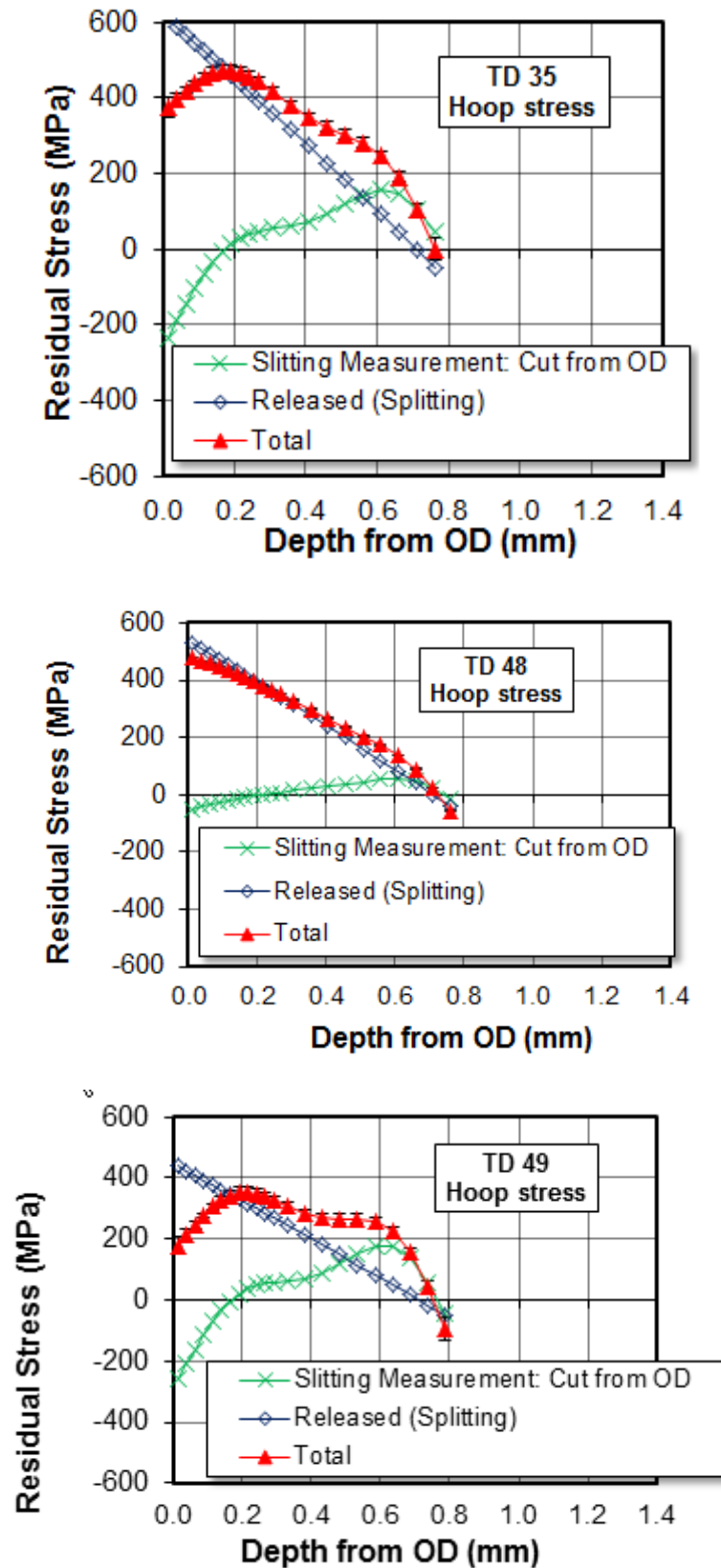


Figure 12. Line plots of the residual stress (slitting measurement, released (splitting), and total) versus depth for teardrop TD 34, TD 35, TD 48 and TD 49. Measurements were taken in the HAZ. Error bars are included for the total residual stress.

Figure 13 shows line plots of the total residual stress versus depth for all teardrops measured.

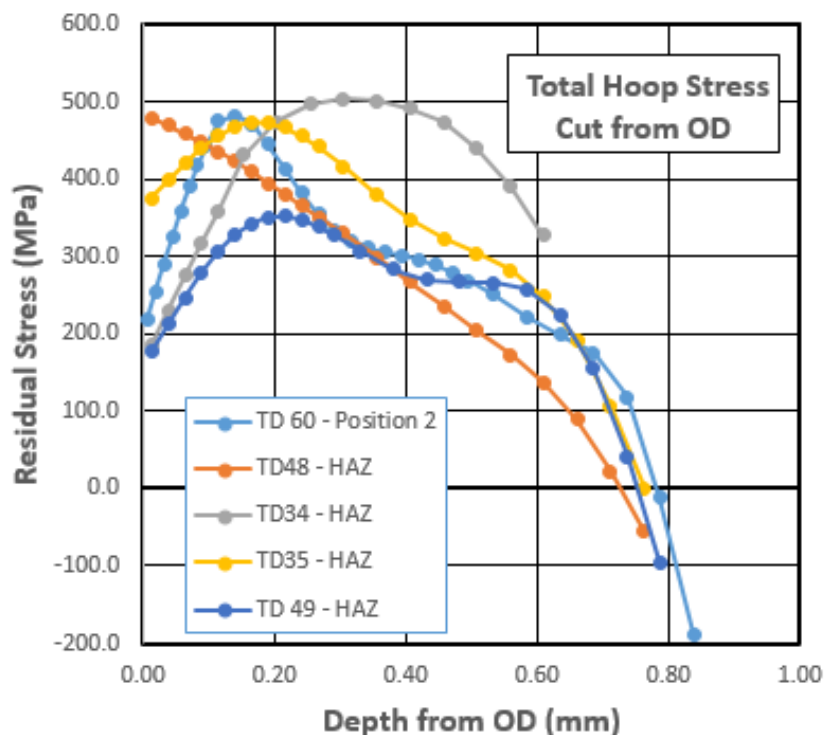


Figure 13. Line plots of the total residual stress versus depth for all measured teardrops

Rolling Direction

The direction of rolling relative to the bending direction was not specified when the teardrops were procured and was unknown. SEM images were used to determine the rolling direction for a teardrop from Batch 2, Batch 4 and Batch 5 (Figure 14). Based solely on inclusion stringer directions, teardrops from Batch 2 and Batch 5 are likely have a rolling direction in the direction of the bend (longitudinal) and the teardrop from Batch 4 across the direction of the bend (transverse).

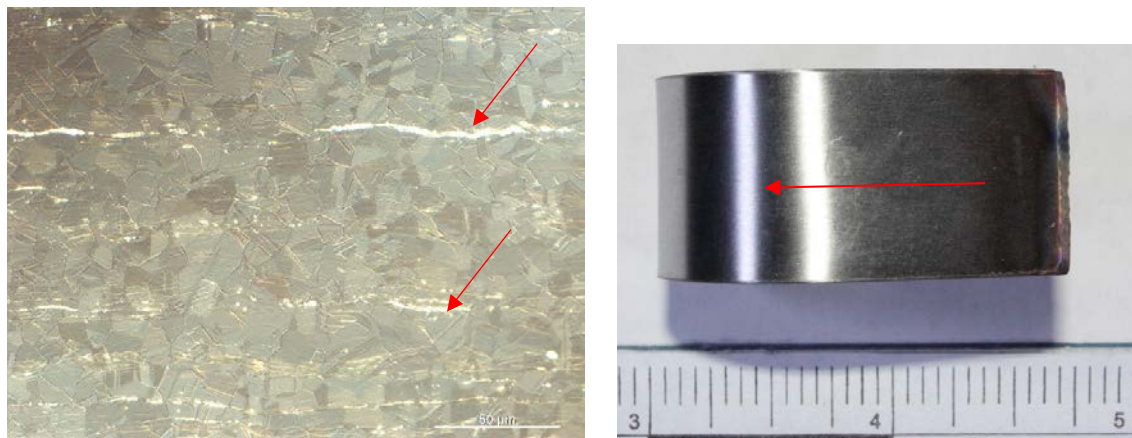


Figure 14. SEM image of teardrop from Batch 5 with arrows indicating the location of the stringers and a photograph of the teardrop indicating the most likely rolling direction was longitudinal.

V. Discussion

The maximum total residual stresses in teardrops measured by the split and slit method ranged from 350 to 500 MPa. TD 49 exhibited significantly lower maximum stress (350 MPa) than the other four teardrops (~470 - 500 MPa). Maximum surface stresses varied from 180 MPa to 480 MPa. The major component of the stress in the teardrop was the bending stress released when the teardrop was split. Calculated released stresses at the outer surface varied from 440 to 610 MPa. Compressive stresses remaining at the outer surface after splitting varied from 50 -360 MPa between teardrops. Maximum total stresses were subsurface for all but TD 48. In all but TD 48, residuals stresses increased in the first 0.1-0.3 mm from the surface then gradually decreased approaching zero midway through the depth of the teardrop at approximately 0.75 mm. While TD 48 had the largest radius of curvature and the greatest thickness, it is not expected that this would account for the different behavior near the surface. TD 48 was the only unground teardrop from Batch 4, which was rolled in the transverse direction, however ground TD 60 was also from Batch 4. Differences in the weld and HAZ between teardrops (Figure 2) could also contribute to the observed differences.

Effects of Teardrop dimensions on residual stress

Table 5 compares the maximum stress and the maximum surface stress measured in the heat affected zone of the weld for four teardrops to the ratio of the thickness of the teardrop to the radius of curvature (T/D).

Table 5. Table of the maximum stress and maximum surface stress and the thickness to radius of curvature ratio (T/D) for select teardrops.

	TD 48	TD 34	TD 49	TD 35
Slit Location	HAZ	HAZ	HAZ	HAZ
Max Stress (MPa) (Surface Stress)	480 (480)	500 (190)	350 (180)	470 (380)
T/D	0.0585	0.0612	0.0614	0.0615

Per ASTM G30-97, T/D is proportional to the strain in u-bend test specimens such as teardrops. There is no apparent correlation between the maximum stresses and the T/D ratio over the range of ratios reported. Results suggest that the variation in the T/D ratio between these four teardrops had minimal effect on residual stresses in the teardrops.

Graphs of thickness (T), diameter of curvature (D) and T/D versus stress released during splitting are in Appendix 7. There is no clear correlation between these teardrop dimensions and the released stress.

Residual stresses at the surface of the teardrop varied from 180 MPa to 480 MPa. Several authors have reported that surface preparation has a significant effect on residual stresses in 304 SS samples.^{13, 14, 15} Zhou reported that residual stresses in 304L austenitic SS flat coupons with 2B finish exhibited near zero residual stresses in the 0.02 mm near the surface.¹³ In contrast, Zhou found that grinding the coupons with a 60# grit abrasive in the longitudinal direction resulted in tensile surfaces stress of approximately 350 MPa. (Figure 15). (The grinding also resulted in increased susceptibility to chloride induced stress corrosion cracking.)

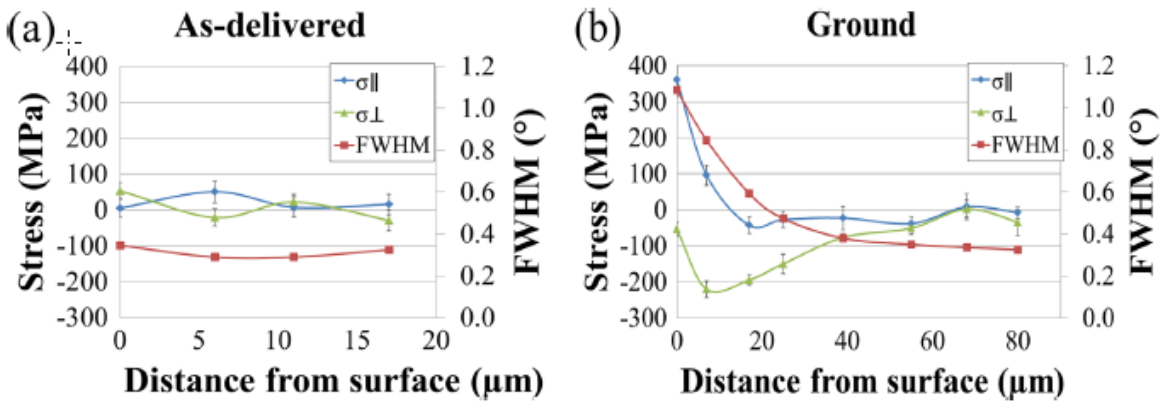


Figure 15. Residual stresses of (a) as-delivered material, (b) ground specimen. Zhou et. al.

Results shown in Figure 13 indicate that ground TD 60 exhibits similar surface residual stresses to teardrops with the original 2B surface finish (TD 34 and TD 35). This suggests the grinding has limited effect on the stresses in the teardrops. Hinds suggested the bending process may relieve surface stresses induced by grinding.¹⁵

Turnbull et al¹⁴ also reported large tensile residual stress in longitudinally ground 304L SS specimens and smaller stresses in transverse dressed (using a 240 grit flapwheel) specimens (Figure 16). The longitudinal residual stress (σ_3) profile for the dressed samples resembled the hoop stress profiles reported in this study for several of the teardrops tested.

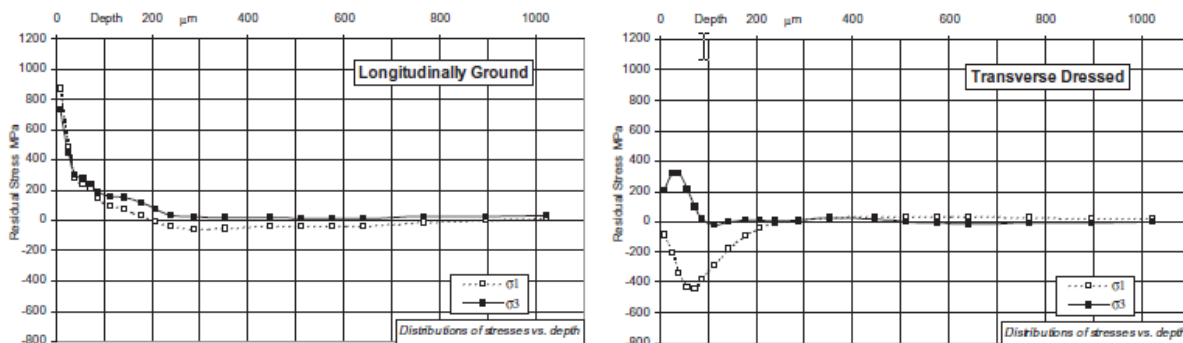


Figure 16. Hole drilling residual stress profile for two specimens (Turnbull et al)

A contributing factor to the large differences in residual stresses between teardrops could be due to variations in the closure weld process. If the bending moment of the teardrop was allowed to relax before or during welding, residual stresses (bending stresses) would be reduced.

Comparison to other Work

Zapp et al used finite-element analysis to estimate the residual stress in a 304L teardrop with no weld in apex.⁶ The analysis was based on simulating the bending of a 10 cm (4") long 304L strip (yield stress: 351 MPa, UTS: 662 MPa) around a 25 mm diameter mandrel. Figure 17 shows the results of that analysis superimposed on a photograph of a teardrop.

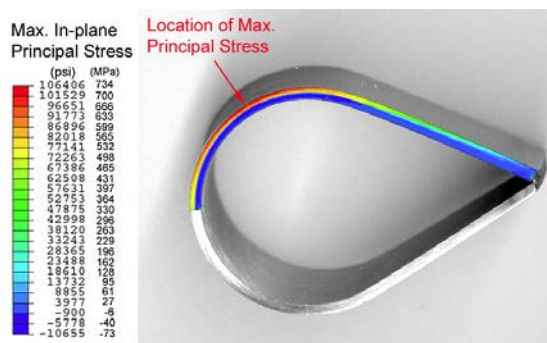
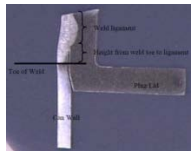
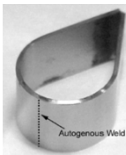
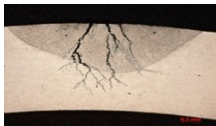


Figure 17. Location of stresses in a teardrop calculated using finite-element analysis (Zapp).

The maximum stress calculated using finite element analysis, 730 MPa, is shown in Figure 17 and was near location 2 (Figure 6). The finite element analysis showed that the apex stress is relieved and continuously redistributed as the 304L strip is bent around the mandrel, and the location of the highest stress is shifted from the apex to the specimen shoulders. This is caused by the increasing contact surface between the 304L strip and the mandrel in the course of forming the specimen, which effectively changes the bending moment of the system. This calculated value of 730 MPa was significantly higher than the total stress (480 MPa) determined from “split and slit” in TD 60 at location 2. The total stress in the apex (weld) region determined from “split and slit” (350 - 500 MPa) brackets the value calculated by finite element analysis (480 MPa) at the apex.

Table 6 shows pictures, identifies the material of construction and surface finish, shows cross sections of the welds of interest, and identifies the welding techniques used for SRS/Hanford BTCs and teardrops.

Table 6. Pictures, material of construction, surface finish weld cross section, and welding technique for the items studied.

Sample Type	Sample Picture	Material of Construction: Stainless Steel	Surface Finish	Sample Weld Region	Welding Technique
SRS/Hanford BTC		304L	Flow Formed		Gas Tungsten Arc Weld (GTAW)
304L Teardrop with weld		304L	2B (cold rolled, annealed and pickled)		GTAW

Results of residual stress measurements in the BTCs, reported elsewhere, and teardrops, reported here are shown in Figure 18. Results for the BTC container are from incremental hole drilling.

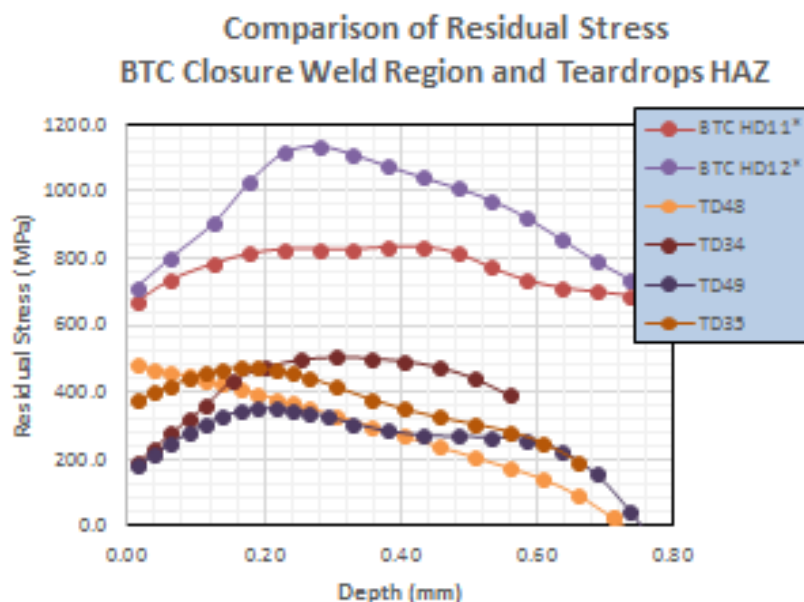


Figure 18. Comparison of residual stresses in BTC and teardrops (TD): BTC measurements were started from the inside wall. *Value does not include correction for stresses released during lid cutting that resulted in a 150 MPa tensile release at the outer wall of the BTCs

Maximum residual hoop stresses in the BTCs near the closure weld were approximately double the stresses measured in the teardrops near the weld. The ultimate tensile strengths were also much higher in the BTC compared to the SS used to form the teardrops. Table 7 compares the material properties of teardrop SS prior to bending and the SS in the BTCs after forming. A significant increase in the ultimate tensile and yield strength of the SS in the teardrop is expected due to the

bending process used to form the teardrops. Properties of annealed 304L SS from the Handbook of Stainless Steel⁸ are also listed for reference.

Table 7. Comparison of material properties of teardrops, BTC and 304L SS.

Sample	Ultimate Tensile Strength (MPa)		Yield Strength (MPa)		Elongation %	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
BTC Flow Formed ¹⁶	1440-1490	1520-1590	1250-1450	1300-1370	4%	4-5%
Annealed SS in teardrops prior to bending (Appendix 1)	630-686		274-371		47.5-63.4	
Typical annealed 304L SS ⁸	558		269		55	
Minimum values for annealed 304L SS ¹⁷	480		170		40	

VI. Conclusions

Teardrops are used as screening tools in corrosion studies to evaluate factors affecting corrosion in BTCs. The maximum residual stresses in teardrops measured by the “split and slit” method varied from 350 to 500 MPa. Residual stresses at the surface varied from 180 MPa to 480 MPa. These stresses are sufficient to result in SCC.¹⁸

Differences in the thickness, diameter and thickness to diameter of curvature (T/D) ratio in the teardrops showed no clear correlation to the released or total stresses in the teardrops. This suggests that variations in thickness and diameter were not a major factor in the stress differences observed between teardrops. There were greater variations in the stress profiles among the unground teardrops than between the unground teardrops and the one ground teardrop, suggesting that surface finish was not the major factor affecting residual stress differences in the teardrops. Differences in the welds could be a contributing factor.

The maximum residual hoop stresses measured in teardrops (350 to 500 MPa) are 50-70% less than the residual hoop stresses measured by incremental hole drilling in the BTC near the weld (1100 MPa). Surface finishes are also very different between the teardrops and containers. These differences, as well as the differences between teardrops, indicate that while teardrops are a valuable screening tool in stress corrosion cracking studies, test specimens with properties closer to BTCs are needed to draw more definitive conclusions.

VII. ACKNOWLEDGEMENTS

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Appendix 1: Teardrop Procurement Information

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Procurement information for 304L teardrops procured from Metal Samples, a division of Alabama Specialty Products, Inc. Teardrops are labeled “304LW” and a #. The TD# cannot be used to determine the batch of origin in most cases since #s were repeated from batch to batch.

Batch	Order Date	Number ordered w/o oxide	Number ordered w/ oxide	Notes
1				
2	12-20-12	40 (#1-#40)	0	Wrapped in VCI paper – suspect defect order showed less corrosion than Batch 1
3	5-16-14	30 (#1-#30)	0	
4	4-24-15	25 (#51-#75)	50 (#1-#50)	
5	11-2-15	50 (#1-#50) <i>(#17-#22 cut into ½ width TDs)</i>	50 (#1-#50) <i>(#12, #15, #17- #22 cut into ½ width TDs)</i>	
6	6-14-16	0	50 (#1-#50)	Half width tear drops

Appendix 1: Teardrop Procurement Information

Page 2 of 3

Certificate of Inspection for Batch 3

		INSPECTION CERTIFICATE CERTIFICADO DE INSPECCION ABNAHMEPROFZEUGNIS according to / de acuerdo con / nach EN 10204-3.1		Document number / N° de certificado / Bescheinigungs-Nr. 0000066712 / Page / Página / Seite: 1 / 1																					
1 ThyssenKrupp Drive, P.O. Box 13000, Calvert, AL 36513-1300 SAMUEL, SON & CO, INC. 1900 GRASSLAND PARKWAY ALPHARETTA GA 30004 USA		Customer's name / Nombre del cliente / Empfänger SAMUEL, SON & CO, INC., ALPHARETTA Customer's order number / N° de Pedido Cliente / Kundenbestell-Nr. 7079071 Manufacturer's work order no. / N° de Pedido Manufactura / Werkauftrag-Nr. 901161347 / 004 Delivery note no. / N° de Entrega / Lieferschein-Nr. B5267624 / 010 Product / Producto / Erzeugnis COIL/BOHRA/BAND Steel grade and quality / Acero / Stahlwerkstoff-Gruppe TYPE 304L/304																							
Terms of delivery / Condiciones de entrega / Lieferbedingungen ASTM A240/A240M, ASME SA-240 Sec. II Part A Ed.2010 ASTM A480/A480M, ASME SA-480 Sec. II Part A Ed.2010																									
Customer's reservation / N° de material adjacente / Kundenmaterial-Nr. 1.42 mm x 1,219.20 mm 0.0560 inch x 48.0000 inch		Product dimensions (Thickness / Width / Length) / (Ansamens / Breite / Länge) / Maße des Erzeugnisses (Dicke / Breite / Länge)		Steelmaking procedure / Proceso de manufactura / Herstellart AOD																					
Rolling No. / N° de Ensayo / Proben-Nr. 6095304		Actual weight / Peso actual / Ist-Gewicht 19,731 lb / 8,950 kg		Coil No. / Bobina No. / Band No. 727360																					
Sample No. / N° de muestra / Proben-Nr. 501300		Sample No. / N° de muestra / Proben-Nr. 1000146793		Sample No. / N° de muestra / Proben-Nr. 1000146794																					
Sum / Suma / Summe 1 19,731 lb / 8,950 kg																									
Heat / Calentado / Schmelze 501300		Chemical composition / Composicion Quimica / Chemische Zusammensetzung <table border="1"> <thead> <tr> <th>% C</th> <th>% Si</th> <th>% Mn</th> <th>% P</th> <th>% S</th> <th>% Cr</th> <th>% Mo</th> <th>% Ni</th> <th>% N</th> <th>% Cu</th> </tr> </thead> <tbody> <tr> <td>0.024</td> <td>0.36</td> <td>1.68</td> <td>0.029</td> <td>0.0030</td> <td>18.19</td> <td>0.26</td> <td>8.07</td> <td>0.063</td> <td>0.40</td> </tr> </tbody> </table>				% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	% N	% Cu	0.024	0.36	1.68	0.029	0.0030	18.19	0.26	8.07	0.063	0.40
% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	% N	% Cu																
0.024	0.36	1.68	0.029	0.0030	18.19	0.26	8.07	0.063	0.40																
Sample Position / Lugar de la muestra / Probenlage TRANSVERSE																									
Inspection lot / Lote de ensayo / Proben 1000146793 1000146794		YS0.2% PSI / MPa 41,189 / 284 39,739 / 274		TS PSI / MPa 92,240 / 636 91,370 / 630																					
		El. A2" % 61.8 63.4		HRB 82 81																					
Dimensions surface / Dimensiones Superficie / Maße Oberfläche Text of identity (spectrometry) / Control de identidad (análisis espectroscópico) / Verweissungsprüfung (Spektralanalyse)		OK OK																							
HEAT - TREATMENT: 1920°F/AIR No weld repairs No intentional additions of Mercury compounds were made or used Free of radioactive contamination EU RoHS Directive 2011/65/EU Compliant Product manufactured in the USA Country of Heat as per ISO 3166-1																									
ALABAMA SPECIALTY PRODUCTS INC (ASPI) ALABAMA LASER TECHNOLOGIES METAL SAMPLES COMPANY ALABAMA RESEARCH AND DEVELOPMENT MTL ID NO. <u>AQ990</u> PO NO. <u>114155</u> ALLOY <u>304L</u> INITIALS <u>JH</u>																									
Baseline of the document / Origen del documento / Aussteller der Bescheinigung Outokumpu Stainless USA, LLC An ISO 9001: 2008 certified company Certificate is generated automatically / Certificado es generado automáticamente / Das Zeugnis wurde elektronisch erstellt		The information provided is a true copy of data on file / Los valores mostrados corresponden a los datos archivados / Angegebene Werte entsprechen den gespeicherten Daten  Andrew Faucett Phone: +1 251 829 3492 Name of expert / Nombre del experto / Name des Sachverständigen		Date of issue and validation / Fecha de emisión y validación / Datum Ausstellung / Bestätigung 12/02/2013																					

Appendix 1: Teardrop Procurement Information

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Certificate of Inspection for Batches 4 and 5



16ga

METALLURGICAL TEST REPORT

Georgia
83 Bonnie Valentine Way
Pendergrass, Georgia 30567
USA

83 Bonnie Valentine Way

Certificate: 6349 5
Customer: 004960 002
Mail To:
STEWART STAINLESS SUPPLY, INC.
3660 SWIFTWATER PARK DRIVE
SUWANEE, GA 30024

Ship To:
STEWART STAINLESS SUPPLY, INC.
3660 SWIFTWATER PARK DRIVE
SUWANEE, GA 30024

Date: 11/17/2014 Page: 1
Steel: 304L
Finish: 2B

Corrosion: ASTM A262/10 A:180Bend-OK

Your Order: M01121716

NAS Order: PN 0046083 03

PRODUCT DESCRIPTION:

STAINLESS STEEL COIL, C.R. ANNEALED & PICKLED. UNS 30403
ASTM A240/13c, A480/13, A666/10; ASME SA240/13, SA480/13, SA666/13
CHEM ONLY ON FOLLOWING ASTM: A276/13, A479/13a, A484/13a, A312/13
CHEM ONLY ON FOLLOWING ASME: SA312/11, SA479/11
AMS 5511N XMRK; MIL-S-5059D AMEND3 (X CROWN MEAS); MIL-S-4043B
NACE MR0175/ISO 15156-3:2003 A, MR0103/07; Q3766D-A X MAG PERM
MIN. SOLUTION ANNEAL TEMP 1900F, WATER QUENCHED

REMARKS:

Mat'l is Free of Mercury Contamination. No weld repairs.
EN 10204:2004 3.1; RoHS 1 & 2 Compliant
Material is Free of Radioactive Contamination
NAS Steel Making Process: EAF, AOD, & Cont. Casting
Product Mfg. by a Quality Mgt. Sys. in Conf. w/ISO 9001
*Melted & Manufactured in the USA; Mat'l is DFARS Compliant

1000°C Anneal?

Product Id	Coil #	Skid #	Thickness	Width	Weight	Length	Mark	Pieces	Commodity Code
07N5R2 A	07N5R2 A		.0602	48.0000	12,560	COIL		1	12773

CHEMICAL ANALYSIS CM(Country of Melt) ES(Spain) US(United States) ZA(South Africa) JP(Japan) Chemical Analysis per ASTM A751/08

HEAT	CM	C %	CR %	CU %	NI %	MO %	N %	NI %	P %	S %
N5R2	US	.0202	18.0195	.4985	1.7370	.3835	.0859	8.0125	.0355	.0152
		SI %								
		.2230								

MECHANICAL PROPERTIES

Product Id#	Coil #	1 d o i c f	UTS KSI	20C .2% YS KSI	ELONG % -2"	% Hard RB	Tail Hard
07N5R2 A	07N5R2 A	F T	99.52	53.80	47.51	89.50	89.50
			686.19 MPa	370.95 MPa	60.50 20.50		

Line #1

ALABAMA SPECIALTY PRODUCTS INC (ASPI)
ALABAMA LASER TECHNOLOGIES METAL SAMPLES COMPANY
ALABAMA RESEARCH AND DEVELOPMENT
MTL ID NO. AS483 PO NO. 118387
ALLOY 304L INITIALS JH

NAS hereby certifies that the analysis on this certification is correct. Based upon the results and the accuracy of the test methods used, the material meets the specifications stated. These results relate only to the items tested and this report cannot be reproduced, except in its entirety, without the written approval of NAS.

Technical
Dept. Mgr.

ABHIJEE BHAVE 11/17/2014

Appendix 2: Teardrop Chemical Composition for Batches 1 and 2

Page 1 of 1

Table A1-1. Chemical Composition (mass %) for select teardrops obtained using a Sigma X-Ray fluorescence alloy analyzer

	MASS Percent (%)			
Element	Batch 1		Batch 2	
Teardrop #	27	28	1	3
Ti	0.53			0.043
V	0.119	0.102	0.112	0.113
Cr	18.12	18.13	18.06	18.11
Mn	1.32	1.32	1.27	1.26
Fe	70.59	70.66	70.63	70.67
Co	0.324	0.319	0.334	0.282
Ni	8.25	8.19	8.09	8.14
Cu	0.276	0.293	0.458	0.409
Nb	0.016	0.015	0.017	0.017
Mo	0.285	0.29	0.341	0.342
Sn	0.018	0.014	0.026	0.017
W	0.067	0.063	0.072	0.058
LEC	0.55	0.55	0.55	0.55

Table A1-2. Chemical Composition (mass %) for select teardrops obtained using an optical emission spark spectrometer

	MASS Percent (%)					
Element	Batch 1			Batch 2		
Teardrop #	24	27	28	1	3	29
Cr	17.8	17.8	17.8	17.7	17.7	18
Mo	0.232	0.231	0.217	0.284	0.267	0.258
Ni	7.82	7.67	7.28	7.79	7.23	7.17

Appendix 3: Variation in Batch 2 Teardrop Corrosion Behavior

Page 1 of 1

Ground 304L SS teardrops from Batches 2 and 3 were placed inside a glass cell for 55 days at 50 °C. Droplets of saturated calcium chloride (CaCl_2) solution with a volume of 20 microliters (μL) were deposited near the HAZ of the weld. The relative humidity in the cell was maintained constant using a saturated solution of potassium acetate (CH_3COOK). Figure A3-1 shows the teardrops from Batch 2 and Batch 3 exposed to the conditions described above.

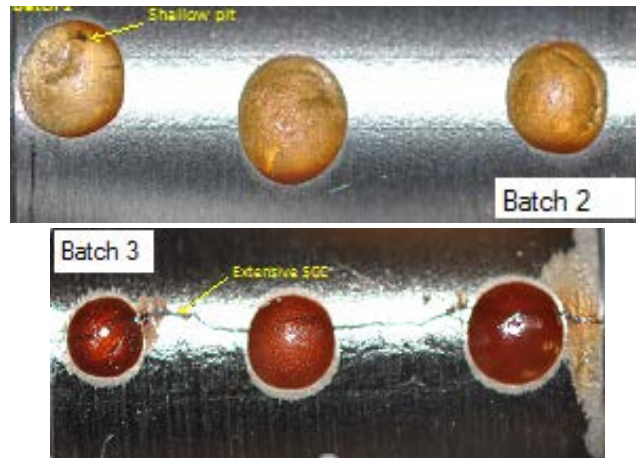


Figure A3-1. Teardrops from Batch 2 and Batch 3 exposed to saturated CaCl_2 for 55 day at 50 °C.

The teardrop from Batch 2 exhibited one shallow corrosion pit. In contrast, the teardrop from Batch 3 showed through wall stress corrosion cracking (SCC) which extended the entire width of the teardrop. Teardrops from other batches exposed to similar conditions showed results consistent with Batch 3 results. Use of teardrops from Batch 2 was discontinued because the corrosion observed varied significantly from corrosion observed on teardrops from other batches. Given available information, it is unclear what caused the difference.

Appendix 4: Teardrops Cut Using EDM Discontinued

Page 1 of 1

Use of teardrops that were cut in half with a brass wire using EDM was also discontinued. The machining process deposits a recast layer on the cutting surface. This edge is more susceptible to corrosion due to galvanic effects between the stainless steel and the copper rich recast layer. Figure A4-1 shows a cut half teardrop that had been exposed to 0.1M hydrochloric acid at 43% relative humidity. Increased corrosion on the cut edge of the teardrop is evident.

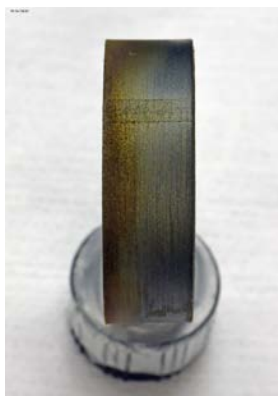


Figure A4-1. Cut half teardrop showing increased corrosion on the cut edge of the teardrop.

Use of ground teardrops as screening tools for corrosion studies was also discontinued. Grinding removed the weld oxide that was representative of weld oxide present in 3013 containers. In addition, studies found that grinding the surface of 304L SS corrosion specimens increased their susceptibility to chloride induced stress corrosion cracking.⁵

Appendix 5: Teardrop Characteristics, Dimensions and Weights

Page 1 of 5

Table A5-1. Teardrop characteristics. Stresses were measured in the highlighted teardrops.

Number	Batch	Half	Weld oxide	Thickness (mm)	Diameter of Curvature (mm)	Weight (grams)
47	5	no	no	1.4986	24.28	
44	5	no	no	1.4732	24.58	
45	5	no	no	1.4859	24.66	
68	4	no	no	1.4986	24.69	22.858
39	5	no	no	1.5037	24.79	
48	5	no	no	1.4986	24.82	
21	5	no	no	1.5037	24.84	
35	5	no	no	1.4681	24.86	
57	4	no	no	1.5486	24.9	23.191
25	5	no	no	1.4859	24.92	
11	5	no	no	1.4732	24.94	
23	5	no	no	1.4859	25.02	
1	5	no	no	1.4986	25.02	
53	4	no	no	1.5469	25.04	22.641
56	4	no	no	1.5481	25.04	23.293
33	5	no	no	1.5138	25.06	
58	4	no	no	1.5481	25.07	22.929
17	5	no	no	1.4732	25.1	
50	5	no	no	1.491	25.1	
75	4	no	no	1.5138	25.1	23.126
13	5	no	no	1.4986	25.12	
63	4	no	no	1.5113	25.12	22.896
43	5	no	no	1.4478	25.14	
62	4	no	no	1.5113	25.16	22.995
71	4	no	no	1.5367	25.16	23.08
66	4	no	no	1.5215	25.18	23.076
74	4	no	no	1.5342	25.18	23.113
72	4	no	no	1.5367	25.18	23.25
52	4	no	no	1.5481	25.18	22.886
40	5	no	no	1.4859	25.19	
55	4	no	no	1.5481	25.19	22.787
15	5	no	no	1.4986	25.2	
7	5	no	no	1.4986	25.22	
31	5	no	no	1.4732	25.23	
61	4	no	no	1.5113	25.24	22.977
9	5	no	no	1.524	25.26	
54	4	no	no	1.5494	25.28	23.082

Appendix 5: Teardrop Characteristics, Dimensions and Weight

Page 2 of 5

Number	Batch	Half	Weld oxide	Thickness (mm)	Diameter of Curvature (mm)	Weight (grams)
60	4	no	no	1.5494	25.29	23.034
30	5	no	no	1.4478	25.3	
46	5	no	no	1.4859	25.32	
73	4	no	no	1.5367	25.32	23.414
36	5	no	no	1.4732	25.34	
70	4	no	no	1.524	25.34	23.133
65	4	no	no	1.5494	25.34	23.024
67	4	no	no	1.5367	25.36	23.126
69	4	no	no	1.5367	25.38	23.209
3	5	no	no	1.4884	25.4	
64	4	no	no	1.5113	25.4	22.864
49	5	no	no	1.5113	25.41	
59	4	no	no	1.5494	25.42	23.001
27	5	no	no	1.4732	25.44	
24	5	no	no	1.5113	25.44	
51	4	no	no	1.5494	25.46	23.293
18	5	no	no	1.4605	25.47	
26	5	no	no	1.4834	25.48	
29	5	no	no	1.4986	25.49	
2	5	no	no	1.491	25.5	
16	5	no	no	1.524	25.51	
19	5	no	no	1.491	25.56	
41	5	no	no	1.5164	25.56	
28	5	no	no	1.4605	25.6	
32	5	no	no	1.4859	25.6	
14	5	no	no	1.4986	25.61	
4	5	no	no	1.4478	25.62	
42	5	no	no	1.4986	25.64	
37	5	no	no	1.4681	25.77	
12	5	no	no	1.4808	25.82	
20	5	no	no	1.4986	25.88	
8	5	no	no	1.4681	25.9	
10	5	no	no	1.5037	25.93	
34	5	no	no	1.4605	25.94	
22	5	no	no	1.491	26.04	
5	5	no	no	1.5189	26.36	
6	5	no	no	1.4605	26.56	
1	5	no	yes	1.5392	24.74	
10	5	no	yes	1.5418	26.26	

Appendix 5: Teardrop Characteristics, Dimensions and Weight

Page 3 of 5

Number	Batch	Half	Weld oxide	Thickness (mm)	Diameter of Curvature (mm)	Weight (grams)
46	5	no	yes	1.5514	26.08	
4	5	no	yes	1.5519	25.08	
6	5	no	yes	1.5519	25.23	
9	5	no	yes	1.5519	25.17	
11	5	no	yes	1.5519	25.42	
12	5	no	yes	1.5519	25.5	
17	5	no	yes	1.5519	26.04	
20	5	no	yes	1.5519	25.2	
21	5	no	yes	1.5519	25.4	
23	5	no	yes	1.5519	25.66	
24	5	no	yes	1.5519	25.46	
25	5	no	yes	1.5519	26.24	
27	5	no	yes	1.5519	25.02	
31	5	no	yes	1.5519	25.36	
32	5	no	yes	1.5519	25.82	
34	5	no	yes	1.5519	25.37	
39	5	no	yes	1.5519	24.92	
44	5	no	yes	1.5519	25.06	
45	5	no	yes	1.5519	24.8	
47	5	no	yes	1.5519	25.39	
8	5	no	yes	1.5524	25.66	
19	5	no	yes	1.5524	25.12	
41	5	no	yes	1.5524	25.98	
40	5	no	yes	1.553	24.84	
48	5	no	yes	1.553	24.82	
7	5	no	yes	1.5532	25.6	
26	5	no	yes	1.5532	26.1	
37	5	no	yes	1.5532	25.5	
38	5	no	yes	1.5532	25.22	
22	5	no	yes	1.5537	25.28	
33	5	no	yes	1.5537	25.18	
42	5	no	yes	1.554	25.26	
50	5	no	yes	1.554	25.56	
5	5	no	yes	1.5542	25.44	
16	5	no	yes	1.5542	26.22	
3	5	no	yes	1.5545	24.88	
15	5	no	yes	1.5545	25.44	
18	5	no	yes	1.5545	25.4	
28	5	no	yes	1.5545	25.26	

Appendix 5: Teardrop Characteristics, Dimensions and Weight

Page 4 of 5

Number	Batch	Half	Weld oxide	Thickness (mm)	Diameter of Curvature (mm)	Weight (grams)
30	5	no	yes	1.5545	25.76	
35	5	no	yes	1.5545	25.28	
43	5	no	yes	1.5545	25.24	
49	5	no	yes	1.5545	25.32	
14	5	no	yes	1.5555	25.9	
36	5	no	yes	1.5558	25.98	
46	4	no	yes	1.557	25.92	23.941
47	4	no	yes	1.557	25.64	23.929
48	4	no	yes	1.557	26.6	23.891
49	4	no	yes	1.557	25.76	24.023
13	5	no	yes	1.557	25.4	
2	5	no	yes	1.5596	25.02	
29	5	no	yes	1.5601	25.68	
42	4	no	yes	1.5621		23.9
44	4	no	yes	1.5621	25.57	23.878
50	4	no	yes	1.5621	25.66	24.033
41	4	no	yes	1.5748	25.4	23.926
43	4	no	yes	1.5748	25.8	23.935
45	4	no	yes	1.5824	25.3	23.552
12-1	5	yes	Yes	1.5519	25.1	
12-2	5	yes	Yes	1.5545	25.32	
15-1	5	yes	Yes	1.5527	25.68	
15-2	5	yes	Yes	1.554	25.7	
17-1	5	yes	Yes	1.554	25.36	
17-2	5	yes	Yes	1.5535	25.46	
18-1	5	yes	Yes	1.5519	25.37	
18-2	5	yes	Yes	1.554	25.6	
19-1	5	yes	Yes	1.554	25.42	
19-2	5	yes	Yes	1.553	25.6	
20-1	5	yes	Yes	1.5545	25.44	
20-1	5	yes	Yes	1.5596	25.7	
21-1	5	yes	Yes	1.5596	25.86	
21-2	5	yes	Yes	1.5545	26	
22-1	5	yes	Yes	1.553	24.88	
22-2	5	yes	Yes	1.5558	25.19	

Appendix 5: Teardrop Characteristics, Dimensions and Weight

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Number	Batch	Half	Weld oxide	Thickness (mm)	Diameter of Curvature (mm)	Weight (grams)
17-1	5	yes	No	1.3462	25.03	
17-2	5	yes	No	1.364	25.04	
18-1	5	yes	No	1.5164	24.92	
18-2	5	yes	No	1.5138	25.16	
19-1	5	yes	No	1.5481	26	
19-2	5	yes	No	1.5481	26.06	
20-1	5	yes	No	1.5519	25.1	
20-2	5	yes	No	1.5494	25	
21-1	5	yes	No	1.5392	25.08	
21-2	5	yes	No	1.524	24.84	
22-1	5	yes	No	1.5489	26.08	
22-2	5	yes	No	1.5494	25.9	

Appendix 6. Split and Slit data for Teardrops

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Table A6-1. Hoop residual stresses measured by “Split and Slit” techniques for TD 60 (Batch 4). Slit was located at location 2. (See Figure 6) Maximum total stress is highlighted.

TD 60				
Depth from OD	Measured	Released	Total	Uncertainty
(mm)	(MPa)	(MPa)	(MPa)	(MPa)
0.01	-344.6	563.0	218.4	24.8
0.02	-299.0	553.3	254.3	19.3
0.03	-253.7	543.7	290.0	14.0
0.04	-209.0	534.0	325.0	9.6
0.06	-165.7	524.3	358.6	6.9
0.07	-124.7	514.6	389.9	7.3
0.08	-86.8	504.8	418.0	9.5
0.10	-52.9	495.1	442.2	12.0
0.11	-5.5	480.4	474.9	14.3
0.14	21.2	460.8	481.9	14.3
0.17	29.2	441.1	470.3	13.1
0.19	24.0	421.3	445.3	11.8
0.22	12.4	401.5	413.9	11.3
0.24	0.8	381.5	382.3	11.5
0.27	-6.5	361.6	355.1	11.6
0.29	-7.1	341.5	334.4	11.6
0.32	-1.1	321.4	320.3	11.3
0.34	10.2	301.2	311.3	11.1
0.37	24.7	280.9	305.6	11.1
0.39	40.4	260.5	300.9	11.1
0.42	55.5	240.1	295.6	11.2
0.44	69.1	219.6	288.7	11.4
0.47	80.8	199.0	279.8	12.0
0.50	90.7	178.3	269.0	12.7
0.53	103.8	147.2	251.0	12.0
0.58	116.2	105.4	221.6	12.0
0.64	134.9	63.3	198.2	11.9
0.69	154.2	20.9	175.0	11.6
0.74	140.4	-21.9	118.5	11.4
0.79	53.4	-65.0	-11.6	11.2
0.84	-80.5	-108.4	-188.9	11.0
0.89	-151.5	-152.1	-303.6	11.3
0.94	-136.3	-196.2	-332.5	10.8
0.99	-84.8	-240.6	-325.4	19.3

Appendix 6. Split and Slit data for Teardrops

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Table A6-2. Hoop residual stresses measured by “Split and Slit” techniques for TD 34 and TD 35. Slit was located near the weld. (See Figure 7) Maximum total stress in each TD is highlighted.

TD 34					TD 35				
Depth from OD (mm)	Measured (MPa)	Released (MPa)	Total (MPa)	Uncertainty (MPa)	Depth from OD (mm)	Measured (MPa)	Released (MPa)	Total (MPa)	Uncertainty (MPa)
0.01	-350.2	535.2	185.1	42.2	0.01	-232.4	607.7	375.3	24.2
0.04	-286.4	516.7	230.3	30.3	0.04	-188.4	586.6	398.2	16.3
0.06	-223.2	498.1	274.9	19.5	0.06	-145.2	565.5	420.3	9.5
0.09	-161.5	479.4	317.9	12.0	0.09	-104.2	544.3	440.1	6.2
0.11	-102.6	460.6	358.0	12.4	0.11	-66.8	523.0	456.2	8.7
0.15	-1.4	432.4	431.0	21.3	0.14	-34.2	501.6	467.4	12.3
0.20	79.3	394.5	473.8	25.5	0.17	-7.3	480.2	472.9	14.8
0.25	140.0	356.3	496.3	24.0	0.19	13.8	458.7	472.4	15.9
0.30	185.8	317.8	503.6	21.0	0.22	29.5	437.1	466.5	15.9
0.36	222.2	279.1	501.2	20.5	0.24	40.7	415.4	456.1	15.2
0.41	251.8	240.0	491.8	21.6	0.27	48.6	393.6	442.2	14.2
0.46	272.4	200.7	473.1	21.6	0.30	54.8	360.8	415.7	12.3
0.51	278.8	161.1	439.9	23.6	0.36	61.9	316.8	378.7	13.0
0.56	268.7	121.1	389.8	35.4	0.41	75.2	272.5	347.7	13.7
0.61	246.9	80.9	327.9	56.2	0.46	95.8	227.9	323.6	13.4
					0.51	120.8	182.9	303.7	13.0
					0.56	144.0	137.5	281.5	13.3

Appendix 6. Split and Slit data for Teardrops

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Table A6-3. Hoop residual stresses measured by “Split and Slit” techniques for TD 48 (Batch 4) and TD 49 (Batch 5). Slit was located near the weld. (See Figure 7) Maximum total stress in each TD is highlighted.

TD 48					TD 49				
Depth from OD (mm)	Measured (MPa)	Released (MPa)	Total (MPa)	Uncertainty (MPa)	Depth from OD (mm)	Measured (MPa)	Released (MPa)	Total (MPa)	Uncertainty (MPa)
0.01	-50.4	529.5	479.1	3.0	0.01	-260.9	438.1	177.3	28.6
0.04	-42.4	511.1	468.7	1.6	0.04	-210.4	423.0	212.5	19.3
0.06	-34.6	492.7	458.1	0.8	0.06	-160.8	407.7	246.9	11.1
0.09	-27.1	474.2	447.1	1.2	0.09	-113.7	392.4	278.7	7.1
0.11	-20.3	455.7	435.3	1.7	0.11	-70.8	377.1	306.3	10.1
0.14	-14.4	437.1	422.7	1.9	0.14	-33.6	361.7	328.0	14.4
0.17	-9.3	418.4	409.1	1.9	0.17	-3.3	346.2	342.9	17.3
0.19	-4.8	399.6	394.8	1.7	0.19	19.9	330.7	350.6	18.6
0.22	-0.5	380.8	380.3	1.6	0.22	36.5	315.1	351.7	18.5
0.24	3.6	361.9	365.5	1.6	0.24	47.5	299.5	347.0	17.4
0.27	7.7	343.0	350.6	1.8	0.27	54.4	283.8	338.2	16.2
0.30	15.2	314.4	329.6	1.7	0.29	58.6	268.1	326.6	15.4
0.36	22.0	276.1	298.1	1.7	0.33	61.8	244.3	306.1	14.6
0.41	29.1	237.4	266.6	1.7	0.38	70.7	212.5	283.1	15.7
0.46	36.5	198.5	235.0	1.6	0.43	89.9	180.4	270.3	15.9
0.51	44.5	159.3	203.9	1.6	0.48	118.4	148.1	266.5	15.3
0.56	52.7	119.8	172.5	1.6	0.53	150.1	115.5	265.6	14.9
0.61	57.5	80.0	137.6	1.6	0.58	174.1	82.7	256.8	15.2
0.66	49.5	40.0	89.4	1.7	0.64	175.3	49.7	224.9	15.4
0.71	22.1	-0.4	21.7	1.6	0.69	138.3	16.4	154.7	14.7
0.76	-14.7	-41.1	-55.9	2.9	0.74	59.1	-17.2	42.0	19.9
					0.79	-44.4	-51.0	-95.4	35.9

Appendix 7. Graphs of Stress versus Teardrop Dimensions

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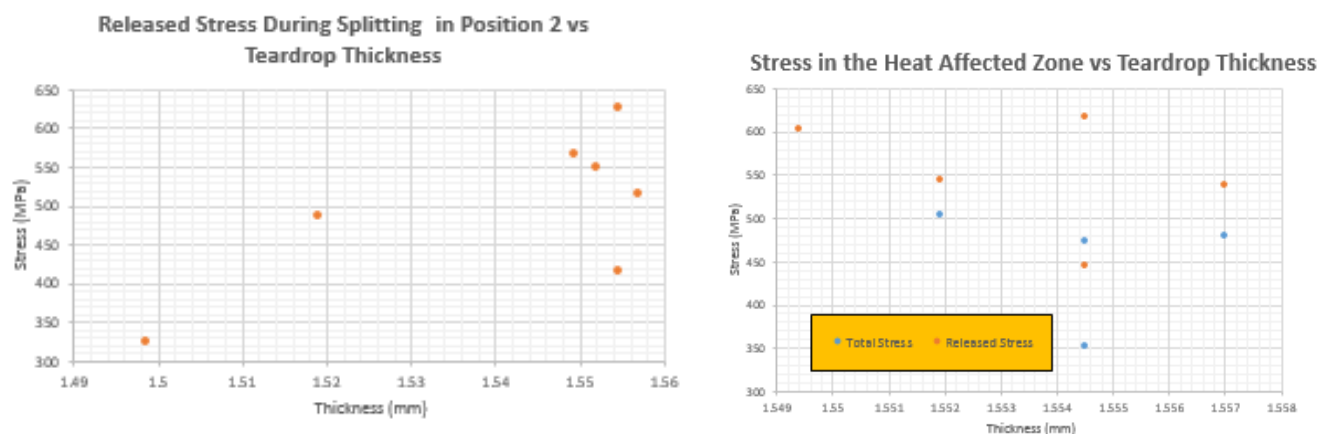


Figure A7-1. Graphs of stress vs teardrop thickness (T)

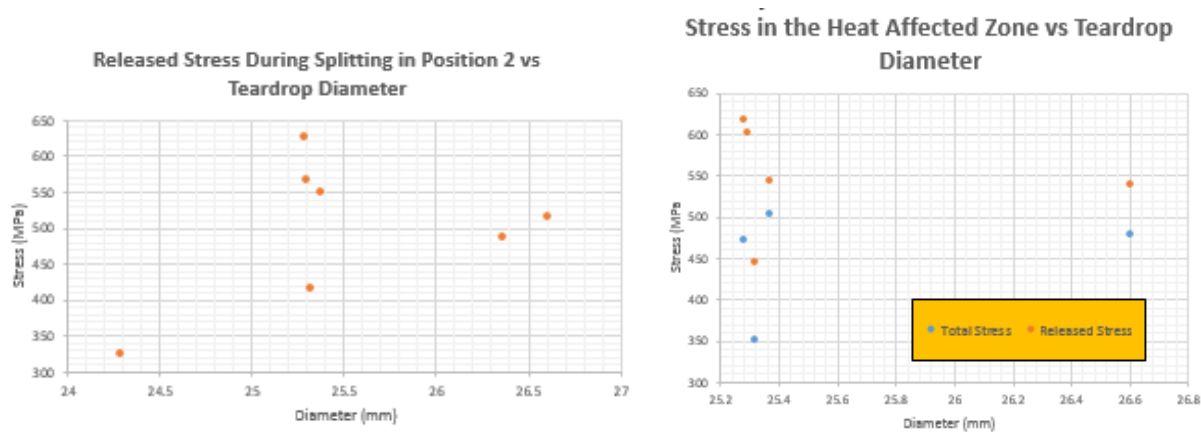


Figure A7-2. Graphs of stress vs teardrop diameter of curvature (D)

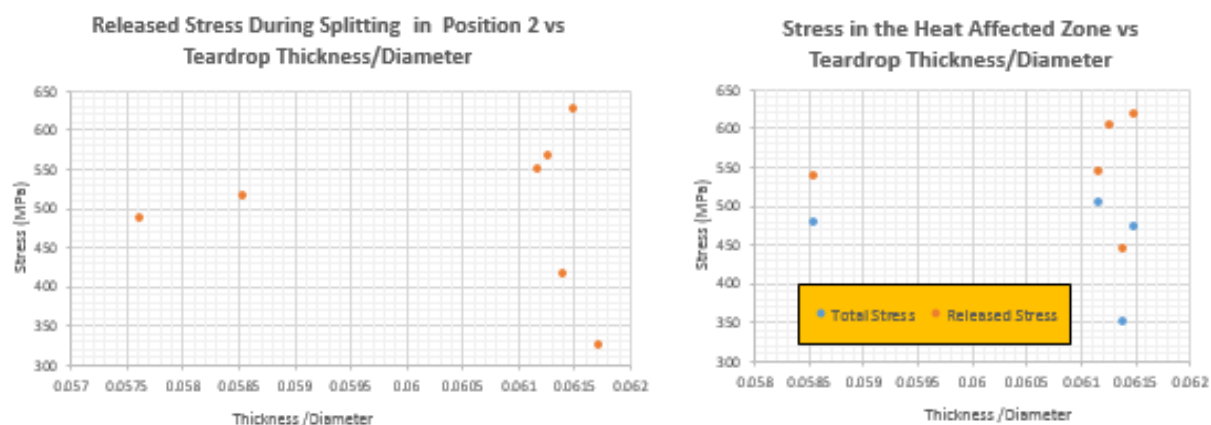


Figure A7-3. Graphs of stress vs teardrop T/D

There is no clear correlation between teardrop thickness (T), diameter (D) or T/D and released stress during splitting at Position 2 or released or total stress in the HAZ.