Contract No:

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Determination of Static and Dynamic Crush Strengths of Stainless Steel Honeycomb Material

Final Report

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8/2/2018

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Introduction

Honeycomb structures are ideal energy absorbers due to the high axial strength compared to the low density of the material and consistent mechanical properties. Lighter density materials used in honeycomb structures, like aluminum, have been studied intensively because of their use in aerospace applications. However, relatively denser materials like stainless steel have been less studied. The purpose of this project is to determine if 304 Stainless Steel hexagonal honeycomb can be used in applications related to the field of radioactive material packaging by determining the crush strength of the structure. The material properties of 304 Stainless Steel can be found in Appendix A and Figure 1 shows the dimensioning convention used.

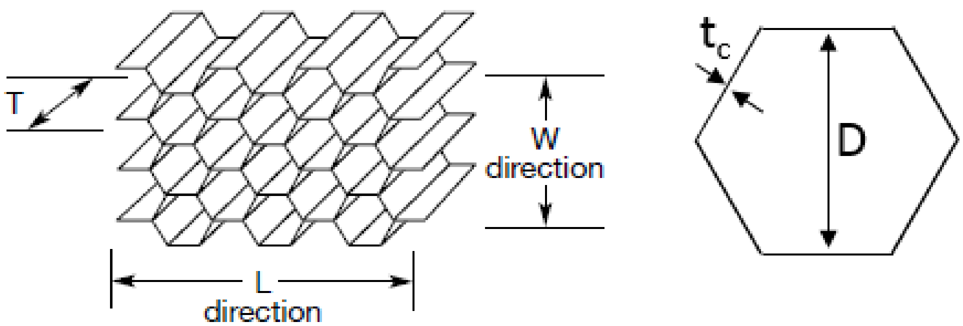

Figure 1: Honeycomb Dimensions

Both the static and dynamic crush strengths of the 304 Stainless Steel hexagonal honeycomb will be evaluated to determine the differences between the two strengths. The difference in strain rate on the material during the static and dynamic tests is the cause of the differing crush strengths.

Testing Information

Static Crush Strength

The compression testing to determine the static crush strength will use an Instron compression test machine. This Instron machine uses a 20 ksi capacity load cell and can record data at differing low strain rates. From the data collected a stress strain curve will be developed which should have a similar shape to that shown in Figure 2. The peak compressive strength shown in Figure 2 occurs before the initial buckling of the honeycomb material, while the plateau after that peak strength represents the crush strength of the honeycomb material as buckling occurs.

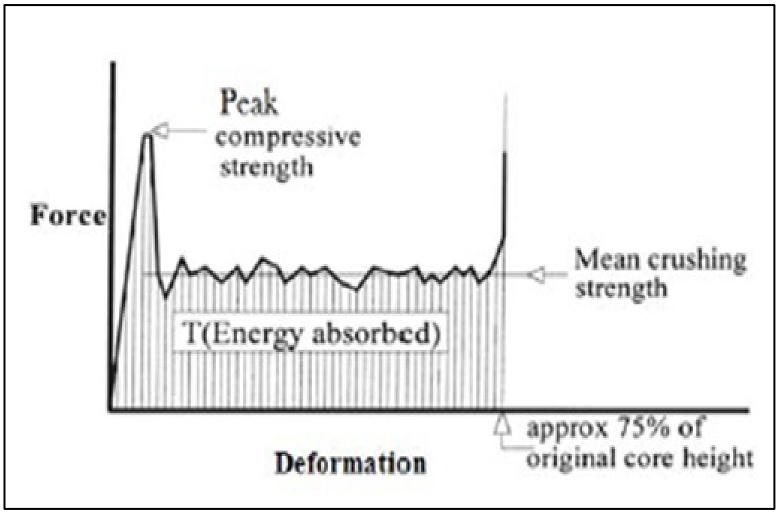

Figure 2: Example Stress Strain Curve for Static Crush Testing

Additionally, the static crush strength determined from testing can be compared to an analytical model for hexagonal honeycomb structures developed by Tomaz Wiezbicki [1]. Wiezbicki's model is based on the rolling deformation of the hexagonal cell walls of the honeycomb structure. The following equation will give an approximate static crush strength based on the analytical model.

$$\sigma_{Crush} = (16.56)(S_y)\left(\frac{t_c}{D}\right)^{\frac{5}{3}}$$

Dynamic Crush Strength

The testing to determine the dynamic crush strength of the 304 Stainless Steel honeycomb structure involves dropping a 43.8 lb stainless steel impactor from a height around 5 feet onto the honeycomb structure. The honeycomb structure will be placed on a rigid surface so that all of the energy transferred from the impactor will be absorbed by the stainless steel honeycomb. The impactor will be dropped using a quick release hook and an acrylic guide pipe. The test setup can be seen in Figure 3 and the full testing procedure can be seen in Appendix B.

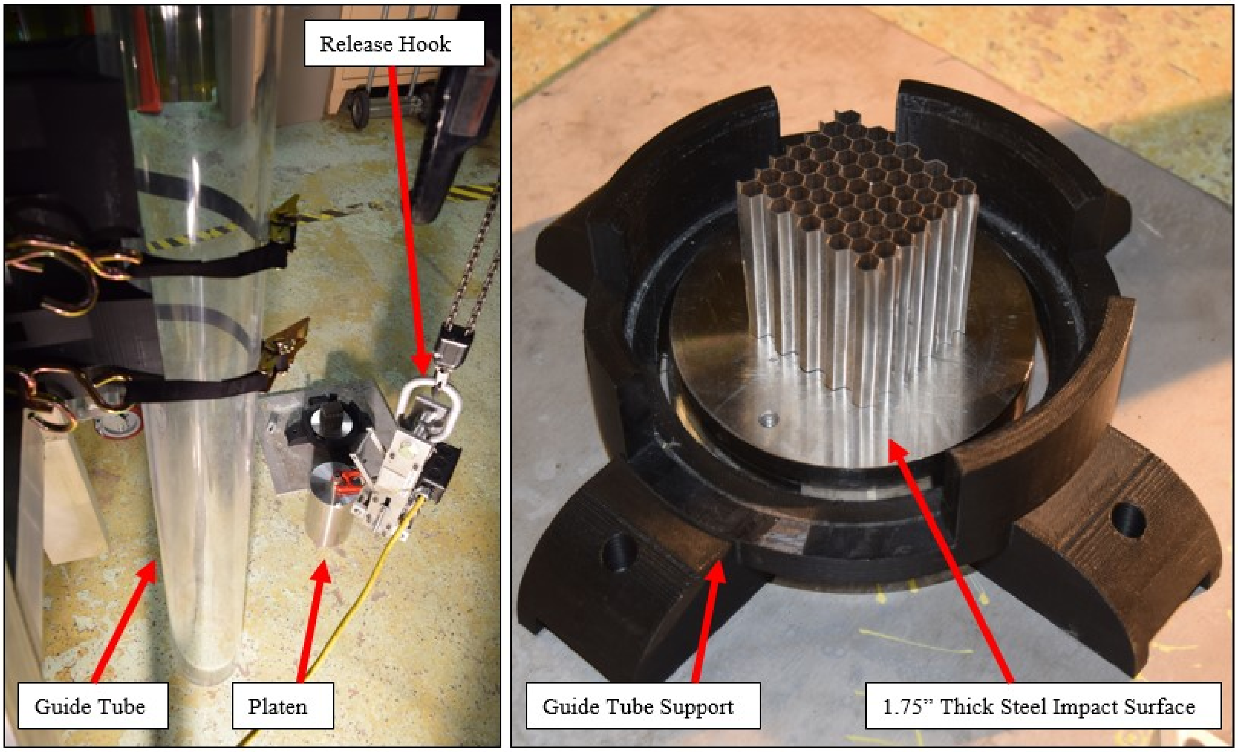

Figure 3: Dynamic Crush Strength Test Setup

In order to determine the dynamic crush strength of the honeycomb structure from this test the change in thickness of the honeycomb structure must be measured. The change in thickness combined with the height of the drop, weight of the impactor, and area of the honeycomb face being impacted can give the dynamic crush strength of the stainless steel honeycomb.

$$\sigma_{crush} = \frac{W_{impactor} H_{drop}}{(T_i - T_f) * A}$$

Results and Discussion

Five test samples from Honeycomb Products Inc were tested to determine the crush strengths of the 304 Stainless Steel honeycomb structure. These samples have a 0.003 inch ribbon thickness and a 0.25 inch cell diameter. The majority of the samples were tested under the dynamic condition because dynamic crushing is the most likely failure mode for an impact absorber being used radioactive packaging. Samples 1-3 were tested dynamically while Sample 5 was tested on the Instron compression machine. Sample 4 was first tested under the dynamic condition and then under the static condition to determine if pre-crushing could affect the crush strength of the material. The test samples were measured and weighed before testing with the information being recorded in Table 1.

Table 1: Dimensions of Honeycomb Samples

Test Sample	Length	Width	Initial Height	Weight	Density
S1	2.280 in	1.980 in	2.518 in	0.1289 lb	19.59 pcf
S2	2.332 in	1.946 in	2.518 in	0.1289 lb	19.57 pcf
S3	2.267 in	1.977 in	2.517 in	0.1304 lb	19.97 pcf
S4	2.313 in	1.927 in	2.519 in	0.1276 lb	19.64 pcf
S5	2.365 in	1.895 in	2.518 in	0.1115 lb	17.20 pcf

Dynamic Crush Strength Results

The dynamic crush tests of samples 1-4 occurred in accordance with the procedure found in Appendix B. The same stainless steel impactor, at a weight of 43.8 lb, was dropped from varying heights between 50-55 inches for each test. The test parameters and calculated dynamic crush strengths of each sample are shown in Table 2. The average dynamic crush strength of the four samples is 1520 psi with all individual crush strengths being within 20% of the average. Aluminum honeycomb has a crush strength variation of 15% [2] therefore the 20% variation of the stainless steel honeycomb is a reasonable range.

Table 2: Dynamic Crush Strength of Honeycomb Samples

Test Sample	Post Test Height	Impactor Drop Height	Dynamic Crush Strength
S1	2.119 in	53.48 in	1300.5 psi
S2	2.220 in	54.73 in	1780.3 psi
S3	2.136 in	54.86 in	1407.1 psi
S4	2.209 in	50.60 in	1604.2 psi

In order to determine if the peak compressive strength shown in Figure 2 significantly changes the dynamic crush strength, due to the relatively large amount of energy absorbed at the initial stages of impact, Samples 1 and 2 were tested again. By testing Samples 1 and 2 again the effect of the peak compressive strength is removed because the honeycomb material has already begun buckling. The test of the pre-crushed samples occurred in the same manner as the previous tests with the same 43.8 lb impactor. As seen in Table 3 the dynamic crush strengths were changed by about 10% for each sample but the crush strength sample 1 decreased while the crush strength of sample 2 increased. The small differences in crush strengths between tests and inconsistent trend of changes indicates that the peak compressive strength was inconsequential.

Table 3: Pre-Crushed Dynamic Crush Strength of Honeycomb Samples

Test Sample	Post Test Height	Impactor Drop Height	Dynamic Crush Strength	Percent Difference
S1	1.662 in	53.88 in	1189.1 psi	8.94%
S2	1.906 in	53.92 in	1952.3 psi	9.21%

Static Crush Strength Results

Static testing was performed using the Instron compression machine for samples 4 and 5. Sample 4 was statically tested after being involved in the dynamic impact testing to investigate the effects of pre-crushing when under static loading. Figures 4 and 5 indicate the crush strengths of test samples 4 and 5 respectively. Sample 4 has a static crush strength of about 1300 psi which is a 21% decrease compared to the dynamic crush strength of the sample. Sample 5 has a crush strength of only 650 psi. Sample 5 is likely so much lower because of the quality of the brazing material on the sample.

Brazing is used on honeycomb structures that are produced through the corrugated method. In the corrugated method, corrugated sheets of stainless steel material are joined using a brazing material and welds. Sample 5 had a lower overall density (Table 1) to the other test samples because not as much brazing material was used. Figure 6 compares the brazing quality of Sample 5 to one of the higher density samples. The differences in density between the two samples in conjunction with the large differences in crush strength indicate that density and brazing play a major role in determining the crush strength of the honeycomb structure.

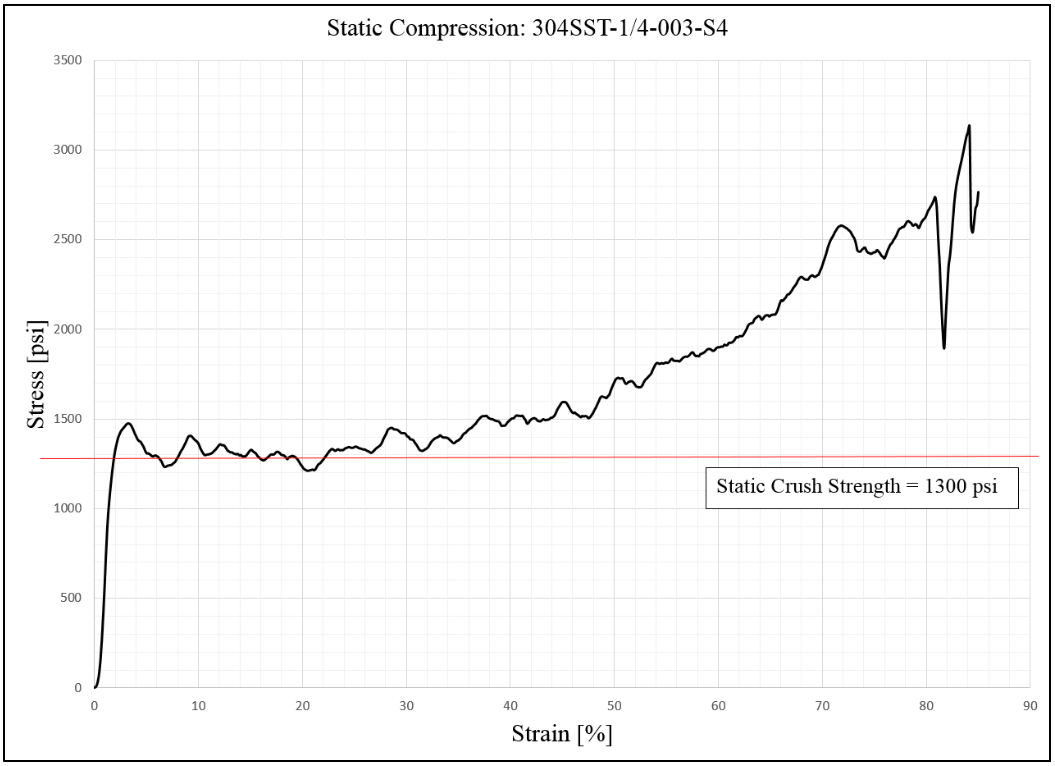

Figure 4: Static Crush Strength of Sample 4

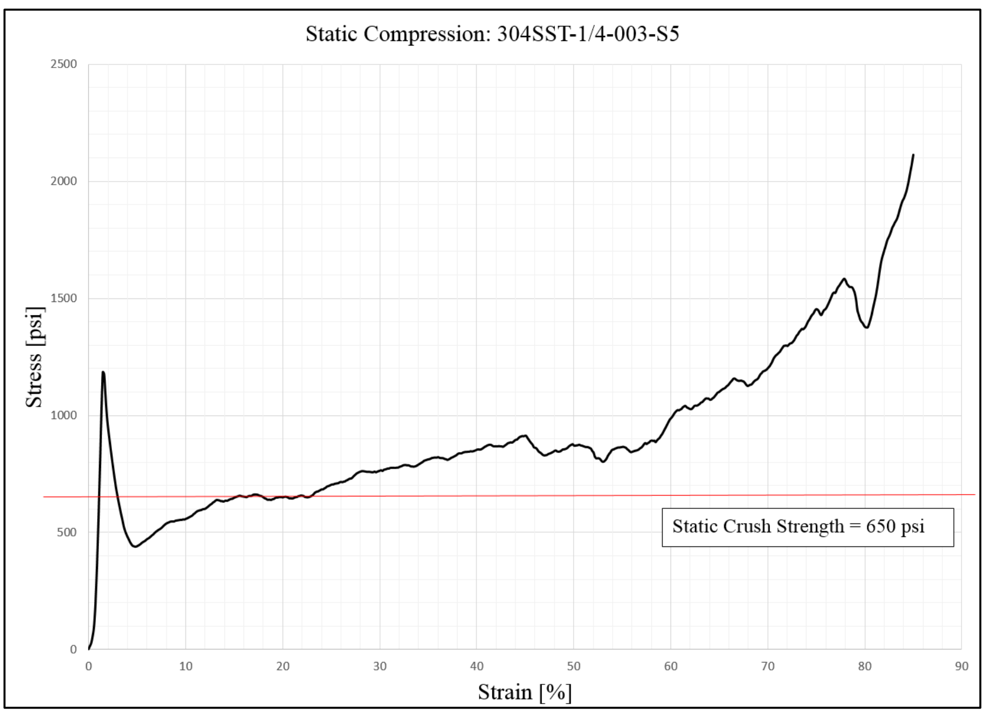

Figure 5: Static Crush Strength of Sample 5

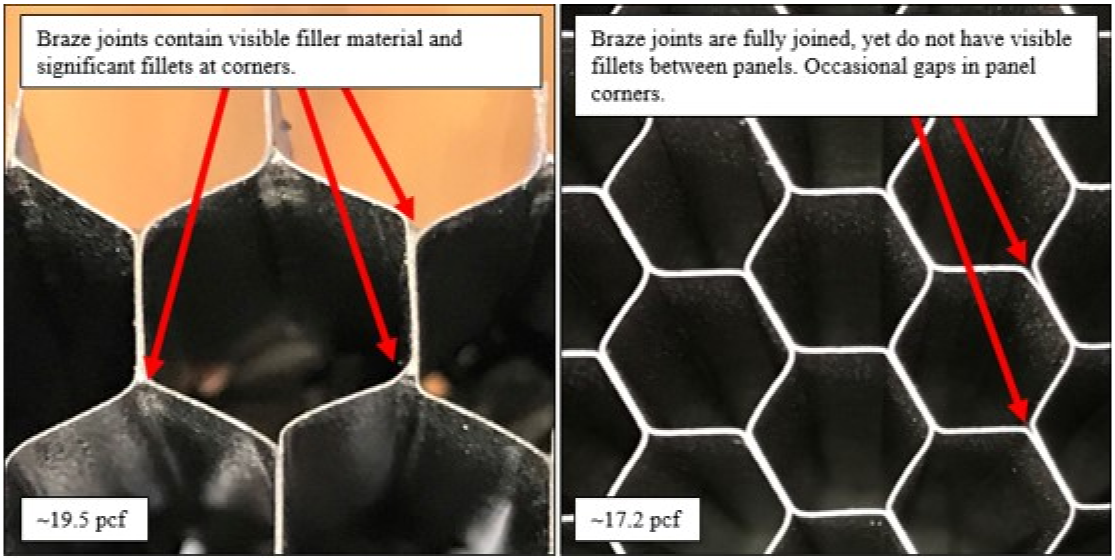

Figure 6: Brazing Comparison

The crush strengths of samples 4 and 5 were also compared to the analytical crush strength determined from the Wierzbicki model described previously. The model indicates that stainless steel honeycomb with a 0.003 inch ribbon thickness and 0.25 inch cell diameter should have a crush strength of around 500 psi. However, this model does not account for brazing material, which increases the ribbon thickness of the honeycomb structure. When the ribbon thickness is increased to 0.005 inch the analytical crush strength becomes 1170 psi which compares favorably to the 1300 psi crush strength of sample 5.

Comparison

The average dynamic crush strength of samples 1-4 was 1523 psi while the static crush strength of sample 4 was around 1300 psi for around a 16% decrease at lower strain rate. The difference between static and dynamic crush strengths of the stainless steel honeycomb structure comes from the effects of strain rate on the 304 Stainless Steel material properties rather than the structure of the honeycomb itself [3]. Figure 7 shows the effects of strain rate on a 304 Stainless Steel rod and shows that an increase in strain rate from 1 s^{-1} to 100 s^{-1} leads to gain of about 20% for yield strength of the material. This matches with the experimental determined difference between static and dynamic.

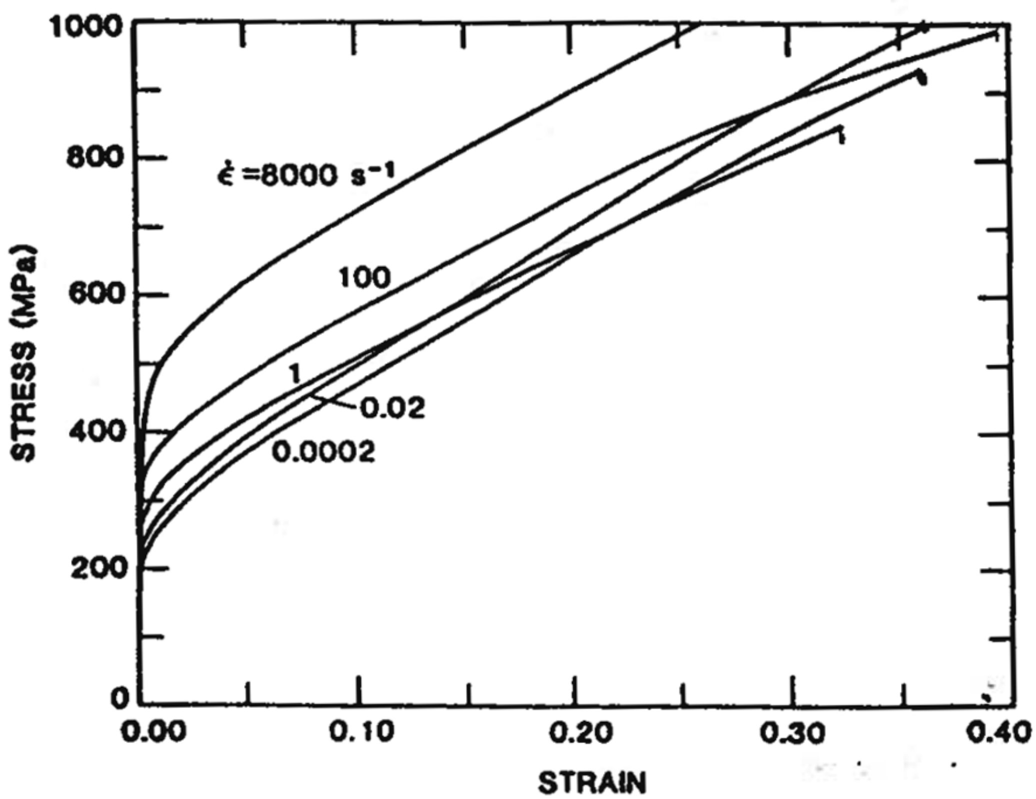

Figure 7: Effect of Strain Rate on 304 Stainless Steel

Conclusions

The average dynamic crush strength of 19.5 pcf density stainless steel honeycomb is 1523 psi while the static crush strength of a sample with the same density is around 1300 psi. The difference between the static and dynamic crush strengths is consistent with the effects of strain rate on 304 Stainless Steel. The quality of brazing can greatly affect the overall crush strength of the material as indicated by sample 5 having a crush strength around 50% less than that of sample 4, which had densities of 17.2 pcf and 19.6 pcf respectively. Also, the Wierzbicki model was shown to be inaccurate unless the effect of brazing is considered when determining ribbon thickness of the honeycomb.

References

[1] V. Jeyasingh, “Analytical Modeling of Metallic Honeycomb for Energy Absorption and Validation with FEA,” (2005).

[2] HexCell, “HexWeb Honeycomb Attributes and Properties,” (1999)

[3] M. G. Stout, P. S. Follansbee, “Strain Rate Sensitivity, Strain Hardening, and Yield Behavior of 304L Stainless Steel,” Transactions of the ASME, (1986).

Appendix A: 304 Stainless Steel Material Properties

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BROWN METALS COMPANY

Certificate of Test / Conformance
Certificate Number: 177886-1

BMC Lot Receipt
15-257

Customer:	**HONEYCOMB PRODUCTS INC**		
Material:	C.R. Stainless Steel	**Customer PO#:**	OV16022
Type:	304	**Date Shipped:**	5/8/2017
Finish:	1BA | Ra:3 µin.	**Sales Order #:**	232772
Size:	.003 X 2.500"	**Supplier Source (1) :**	ATI Flat Rolled Products (USA)
No. of Coils :	9	**Melt Mill Source (1):**	ATI Flat Rolled Products (USA)
Net Weight:	110.250#	**Heat Number:**	982985

UNS Number:	S30400
Specifications:	AMS-5513J |

MECHANICAL PROPERTIES

Condition/Temper	Annealed
Hardness(2)	HV177/181 (B 88)
Ultimate Tensile Strength(3)	103,200
Yield Strength @ .2% offset(3)	48,000
Percent Elongation in 2 inches	70.0 %
Bend Test	OK
Embrittlement (ASTM-A-262 Pr. E)	OK
ASTM Grain Size	9.0

CHEMICAL PROPERTIES

C	Mn	P	S	Si	Cr	Ni	Mo	Cu	N	Al	Co	Fe	Mg
.055	1.52	.032	.0002	.44	18.44	9.09	.40	.43	.04	.001	.28	Bal	.001

(1) Country of Origin specified in parenthesis. Material complies with **DFARS Sections 252.225-7008 & 252.225-7009 (JUL 2009)** if melted in the USA or a qualifying country according to DFARS. (2) Hardness conversion using ASTM-E-140.(3) Tensile & Yield Strength reported in PSI. (4) If requested, tolerances, camber and other measurement readings are reported in inches.

Date: May 8, 2017

Anthony Schlumpf
Brown Metals Company Quality Control Clerk

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Appendix B: Dynamic Crush Strength Test Procedure

SAVANNAH RIVER NATIONAL LABORATORY		WI#:	WI-RDE-2018-0006
R&D Engineering Work Instruction		Revision:	0
Packaging Technology & Transportation Engineering		Effective Date:	07/10/2018
Dynamic Impact Testing of Packaging Materials: 723-A		Page:	Page 1 of 6
		Kevin Frew	07/10/2018
		PI	*Date*
Additional Reviewer	*Date*	*Manager*	*Date*

1.0 PURPOSE

The purpose of this work instruction is to define the steps for dynamic impact testing of packaging materials using a 5ft vertical drop pipe and 43lb weight in 723-A. The intent is to use the impact results to determine the mechanical properties of the packaging materials.

The dynamic impact testing system consists of the following:

- Clear acrylic pipe (5ft long, 5.25in ID)
- Steel impact cylinder (43.8lb, 5in diameter, 8in tall) (i.e. platen)
- Aluminum A frame
- Rapid prototyped pipe stand (i.e. base)
- Rapid prototyped pipe mounts for A frame
- Tie down straps
- Electric hoist rigging system
- Electrically operated quick-release hook rated for 1000lbs or greater
- High speed video equipment (optional)

The system will be operated by personnel with incidental rigging qualification in conjunction with an SRNL R&D test engineer (PI) in either the Packaging Technology & Transportation Engineering (PT&TE) or Materials Evaluation organization.

2.0 SCOPE

The scope of this work instruction is limited to the Dynamic Impact Testing as described in this work instruction to be conducted at 723-A.

2.1 Definitions

SRNL - Savannah River National Laboratory

PI - Principal Investigator (the SRNL test engineer responsible for the testing and testing oversight)

3.0 PRECAUTIONS/LIMITATIONS

3.1 Safety

3.1.1 Implemented engineering controls are as follows:

- Protective acrylic tubing over impact site
- Electronic quick release hook rated for 1000lbs or greater
- Electric hoist

3.1.2 Administrative controls are as follows:

- Barricade around drop site
- Lifting/dropping of weight done only by personnel with incidental rigging qualification.
- Do **not** plug the release hook into an electrical outlet or an extension cord until:
    - All personnel have been cleared from the drop area (barricade)
    - The test item has been placed in the desired drop position at the desired drop height

3.1.3 Personnel within the barricaded drop site shall wear the following PPE:

- Safety glasses
- Safety shoes
- Protective gloves while handling the test specimens
- Ear protection during impact
- Hard hat

3.1.4 Follow all 8Q 26 General Laboratory Safety Procedures and General Site Safety Procedures.

3.1.5 Be aware of hazards such as pinch points and tripping hazards during performance of this work as addressed in the Hazard Assessment Package SRNL-L4500-2017-00082.

3.1.6 Ensure drop site access and the surrounding area is restricted by proper placement of barriers and barricades.

3.1.7 SRNL procedure L9.4-10526: Operation of the L.A.B. Equipment Release Hook 1000lb Model ER1000 or 3000lb Model ER3000 for Drop Testing may be referenced for quick release hook operation.

4.0 PREREQUISITE ACTIONS

4.1 At the beginning of each series of dynamic impact testing, ensure that all personnel involved in the testing are signed in on a working copy of the latest revision of the Hazards Assessment Package and that all involved understand the hazards and safety precautions to be taken during testing.

4.2 Ensure that all personnel involved in testing have participated in a pre-job briefing and have signed the associated paperwork.

4.3 Ensure that all personnel involved in testing have the appropriate PPE as described in section 3.1.3.

4.4 Record M&TE used in testing and the expiration date(s) of the calibration.

5.0 PERFORMANCE SECTIONS

5.1 Test Sample Preparation

5.1.1 ENSURE that samples fit within the effective area of the steel impactor. If oversized, contact PI prior to test. Sample heights may vary.

5.1.2 ENSURE all initial dimensional values are recorded prior to testing in the test spreadsheet (Attachment 7.1.2).

5.2 Test Site Preparation

5.2.1 ENSURE all personnel involved in the testing are signed in on a working copy of the Hazards Assessment Package (SRNL-L4500-2017-00082), latest revision.

Note:	Strapping may include ratchet tie down straps, elastic cords, etc. The strapping should ensure minimum movement of the pipe. Rapid prototyped attachments will be provided by PI; otherwise, stop work.

5.2.2 SECURE the acrylic pipe to the aluminum A frame in 723-A using provided rapid prototyped attachments and strapping AND position the base in-line with the acrylic pipe.

5.2.3 BARRICADE the area surrounding the impact site AND provide ample empty space for safe walking.

5.2.4 ENSURE that the electric hoist is secured to the top beam of the aluminum A frame.

Note:	Reference SRNL procedure L9.4-10526 steps 5.1.1 – 5.1.5 for quick release hook operation.

5.2.5 ATTACH the quick release hook to the hoist.

5.2.6 PLACE the steel impactor outside of the acrylic pipe AND attach it to the quick release hook via the threaded Crosby hook on the top surface.

5.2.7 CONFIGURE high speed video equipment to record the impact if applicable.

5.3 Drop Test Procedure

> Note: Loosen strapping if necessary. A load distributer may be installed if applicable.

5.3.1 RAISE the acrylic pipe manually AND secure the test sample to the base platform using double sided tape.

> Note: Ensure that the strapping is subsequently tightened if loosening occurs in 5.3.1.

5.3.2 LOWER the pipe to fit within the pipe base.

> Note: Never place hands, fingers, or feet underneath the metal impactor while hoisting.

5.3.3 HOIST the impactor to the desired height AND position it such that it is concentric and contained within the acrylic piping.

5.3.4 ENSURE that the acrylic pipe is level such that there are no significant frictional losses during the drop.

5.3.5 MEASURE the height of the drop from the top of the test specimen to the bottom of the impactor AND record the data in the test spreadsheet (Attachment 7.1.1).

5.3.6 CONFIGURE high speed video equipment if applicable.

5.3.7 ENSURE that all personnel are outside the barricade during the drop. Reentry may occur after impact.

> Note: Reference SRNL procedure L9.4-10526 steps 5.1.10 – 5.1.18 for quick release hook operation.

5.3.8 RELEASE the platen such that it falls down the drop cylinder with little frictional loss or tilting.

> Note: Loosen strapping if necessary.

5.3.9 LIFT the drop pipe AND remove the impactor.

5.3.10 RETRIEVE the sample.

5.3.11 LOWER the acrylic pipe to rest on the floor.

5.3.12 RECORD the post-test dimensional values in the test spreadsheet (Attachment 7.1.1).

Note: Reference SRNL procedure L9.4-10526 steps 5.1.1 – 5.1.5 for quick release hook operation.

5.3.13 REATTACH the impactor to the quick release hook.

5.3.14 RECONFIGURE high speed video equipment if applicable.

5.3.15 REPEAT section 5.3 for each test specimen.

6.0 REFERENCES

6.1.1 SRNL-L4500-2017-00082, Hazard Assessment Package for Dynamic Impact Testing of Packaging Materials

6.1.2 8Q 26, General Laboratory Safety Procedures

7.0 ATTACHMENTS

7.1.1 Test Spreadsheet

ATTACHMENT 7.1.1

Data Recorded By:			Dynamic Impact Testing (WI-RDE-2017-0006)					
Test Specimen	Initial Length [in]	Initial Width [in]	Initial Height [in]	Final Length [in]	Final Width [in]	Final Height [in]	Impactor Weight [lb]	Height of Drop [in]
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
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