Applied Technical Services
Marietta, GA 30062

To: Brandon Knight, President
Distributed Power, 2415 Burdette St.
Ferndale, MI 48220

From: Jonah Shifrin; Test Engineer.

Subject: Material properties of recycled aluminum from Haggerty Metal

Date: November 17, 2020

Distr: Dr. Sherry Wang, Manager

FORWARD

Your Company, Distributed Power, works to make access to solar power and the transition to green energy as easy as possible. To further reduce the carbon footprint in the use case of your solar panels you wish to use recycled aluminum as a primary build material sourced from Haggerty Metals from local demolition sites in Detroit, MI. In order to assess if the smelted recycled aluminum you have provided us with samples according to ASTM 399 test standards. Using these samples, you have requested we asses and report the Young's modulus, yield stress, ultimate tensile strength, poisons ratio, and plane strain fracture toughness of the recycled aluminum alloy. This requires we conduct tensile and fracture tests over multiple samples in order to report reliable datum estimates along with the relative errors of each metric. The purpose of this document is to document the methods, and procedure by which these metrics will be estimated as well as any important conclusions come to as a result.

SUMMARY

Data from six uniaxial-tensile-test was evaluated to generate stress-strain and principal curves from which Poisson's ratios, Young's moduli, yield stresses, and ultimate tensile stresses and their respective errors could be determined and averaged. Fracture tests were then conducted on 12 samples and the data analyzed to generate fracture toughness values for each sample. Each smaple's test results were then run through ASME E399 validation process to ascertain an average plain strain fracture toughness for the recycled aluminum sample. Table 1 below shows the averaged material properties and their respective errors as well as the standard material properties of 7075-T6 Aluminum [1].

Table 1. This table depicts the experimental material properties of the recycled sample (row one below headers) as well as the theoretical material properties of 7075-T6 aluminum (bottom row).

Data Set	Youngs Modulous [GPa]	Yield Stress [MPa]	Ultimate Tensile Stress [MPa]	Poisson's Ratio	Plane-Strain Fracture Toughness [MPA $m^{1/2}$]
Experimental	61.98 ± 0.21	508.40 ± $0.21x10^{-1}$	556.23 ± $0.21x10^{-1}$	0.36 ± $0.14x10^{-2}$	22.3 ± 3.2
Theoretical	71.7	503	572	0.33	20

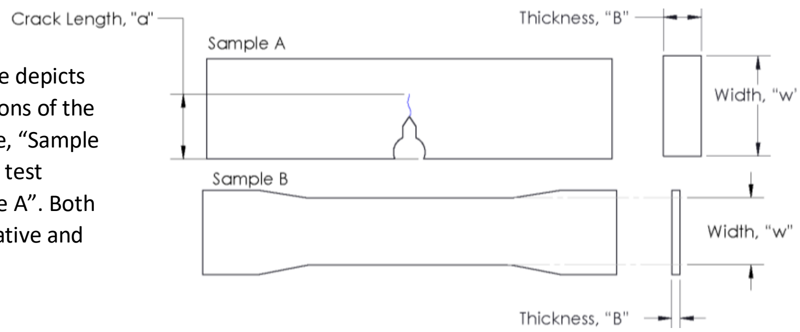
METHODS

The material properties: Young's modulus (E), yield stress (σy), ultimate tensile stress (UTS), poisons ratio (ν), and plane strain fracture toughness (K_{IC}), of the provided aluminum alloy samples were determined using uniaxial tensile testing and bending-moment-based fracture testing according to ASTM and ASME defined standards. Six samples were used in the Uniaxial tension test and four sets of four samples were used in the fracture test. Error calculations were done using the root mean square of accuracy resolution and repeatability error and the partial derivative method was used to propagate errors through equations one through fourteen.

Sample Measurements

For the tensile test, thickness (B) and width (w) of all six samples were measured using a *Mitutoyo 293-340-30 Digital Micrometer* with a resolution error of $5x10^{-4}$ [mm] [6] and accuracy error of $5x10^{-5}$ [mm] [6]. For the tensile test, these measurements were multiplied together to generate a cross sectional area for each sample. For the fracture test an additional metric of crack length (a) was measured. The described measurements are depicted in Figure 1 below. Crack length (a) was measured after the fracture test specimen broke under the applied force.

Figure 1. This figure depicts the sample dimensions of the tensile test dogbone, "Sample B", and the fracture test sample bar, "Sample A". Both drawings are qualitative and not to scale.



Tensile Test

A tensile test was conducted to determine the E, σy, UTS, and ν of the recycled aluminum alloy samples. After measuring the cross-sectional area of a dogbone sample, a 45° strain gauge (maximum strain error ±0.04) was placed on the approximate midsection of the sample to record material strains. The sample was then placed in the upper and lower grips of the *Instron 8516* (maximum error ±0.20 [kN]). The setup is depicted in Figure 2 below.

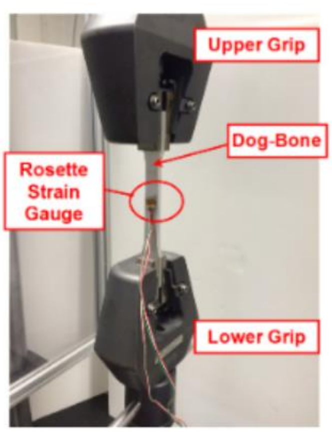


Figure 2. This figure depicts the lab setup for the tensile test using a recycled aluminum brass sample, Instron 8516 with an 80 [kN] load cell, and 45º strain rosette.

After placing a sample into the Instron an increasing uniaxial tension load was applied to the sample, recording load and strain on each strain gauges within the strain rosette. In order to generate the stress vs principal strain graph that E, σy, UTS can be derived from as well as the principal strain graph to find ν the recorded strain values need to be converted to principal strain using Mohrs circle for strain. The first step of this process is converting force applied (F_a) to pressure applied (P_a) using each sample's respective cross-sectional area (A). The relationship between these variables are described in Equation 1 [5] below.

$$P_a = \frac{F_a}{A} \qquad \text{Eqn. 1}$$

Next the strain rosette values must be converted to principal strains using the strain transformation equations [7], Equation 2 below. The plain strain equations relate the strain readouts of three strain gauges ε_a, ε_b, and ε_c with the principal strains in the directions of the defined coordinate system ε_x and ε_y and the shear strain γ_{xy} using the angle offsets from the defined x axis θ_a, θ_b, and θ_c.

$$\varepsilon_{a,b,c} = \varepsilon_x \cos^2\theta_{a,b,b} + \varepsilon_y \sin^2\theta_{a,b,c} + \gamma_{xy}\sin\theta_{a,b,c}\cos\theta_{a,b,c} \quad \text{Eqn. 2}$$

By defining the x and y axes the angle offsets θ_a, θ_b, and θ_c can be defined simply as 0º, 45°, and 90º respectively. After some algebraic manipulation Equations 2 through Equation 4 can be converted to Equation 3 through Equation 5 below [7].

$$\varepsilon_x = \varepsilon_a \quad \text{Eqn. 3}$$

$$\varepsilon_y = \varepsilon_c \quad \text{Eqn. 4}$$

$$\gamma_{xy} = 2 * \varepsilon_b - \varepsilon_a - \varepsilon_c \quad \text{Eqn. 5}$$

ε_x, ε_y, and γ_{xy} can now be used to find the true principal strains (aligned vertically with the Instron's applied force) using Equation 6 below [7]. Derived from Mohr's circle the variable $\varepsilon_{1,2}$ represents the max. and min. true principal strains; in a uniaxial tension test one of them will likely be negative (ε_2), the axis perpendicular to the applied force, and one will be positive, parallel to the applied force (ε_1).

$$\varepsilon_{1,2} = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad \text{Eqn. 6}$$

Using ε_1 as the axial strain value and $-\varepsilon_2$ as the transverse strain value, a stress-strain and transverse vs. axial strain plot can be made for the tested sample from which the described material properties E, σy, UTS, and ν can be derived for each sample. E is defined as the slope of the linear portion of the stress strain curve [3]. σy is found by applying a .2% strain translation to the linear fit. The intersection of the .2% strain line with the stress-strain curve is the yield stress, σy, of the sample. UTS can be found at the maximum stress of the stress strain curve. Finally, Poisson's ratio can be fond from the axial versus the opposite of transverse strain values. The slope of the line of best fit for this graph is the Poisson's ratio of the tested sample as articulated in Equation 7 [4] below.

$$\nu = \frac{-\varepsilon_2}{\varepsilon_1} \quad \text{Eqn. 7}$$

Fracture Test

A fracture test was conducted to determine the plain strain fracture toughness (K_{IC}) of the recycled aluminum samples. After measuring the cross-sectional area of each fracture test sample, the sample was placed into an *Instron 5984* (maximum error $1.3\text{x}10^{-2}$ [kN]) with the machined crack at the bottom and centered under the loading nose. A 2670 series Crack Opening Displacement Gauge, or COD, calibrated and zeroed at 5mm, was then placed in the bottom edge of the opening (maximum error $2.6\text{x}10^{-5}$ [mm]). The described setup is depicted in Figure 4 below.

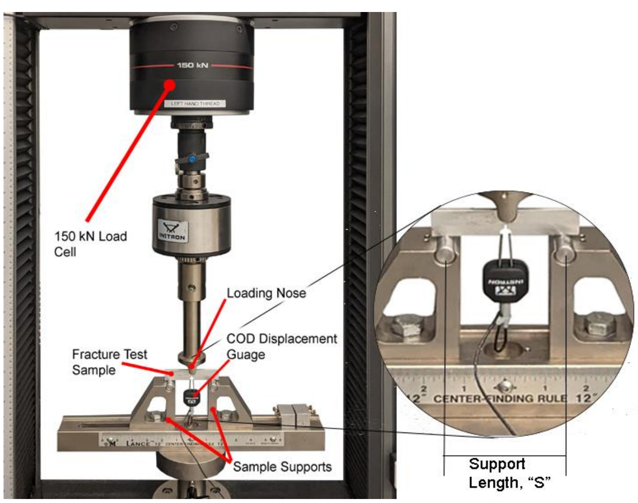


Figure 4. Depicts the procedural setup for each of the 16 fracture test samples. Here the load cell applies a known force through the loading nose, perpendicular to the length of the sample held up on either end by the sample supports. Support length (S) is a parameter used later to calculate fracture toughness (K_Q).

After the sample completely fractured the critical crack length (a) was measured using a *UM-ME 395 Digital Microscope* hooked up to *Arcsoft WebCam Companion* and *Bersoft Image Measurement* software. This setup had a resolution error of $5x10^{-3}$ [mm] and a maximum accuracy error of $5.58x10^{-2}$ [mm]. Using the described equipment five systematic measurements of crack length were taken for each sample (calibrated by the micrometer measured thickness of each sample). Measurements were taken from the machined crack edge of the sample to the visible critical crack length at the sides and approximate $1/4^{th}$ increments between the two, with regards to B. This process is depicted in Figure 3 below.

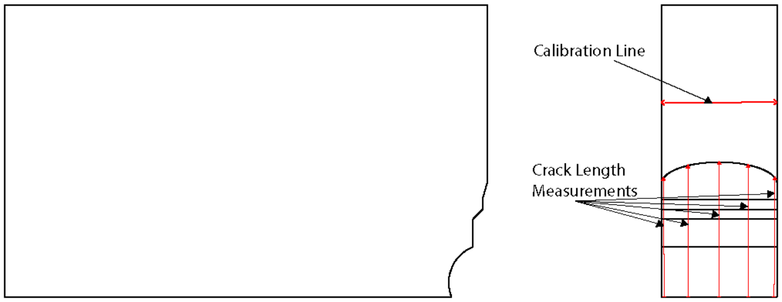


Figure 3. This figure shows a qualitative example of what a fractured fracture test specimen looks like. Two orthographics of the front and fractured faces of the sample are depicted on the left and right respectively. The left graphic is provided to be used in providing context for the right graphic to be compared to Figure 1 and Figure 3

To generate a K_{IC} estimate for the recycled brass fracture samples were grouped in 4 sets of 4 each set consisted of test samples of the following approximate thicknesses in mm: 3.0, 6.0, 8.0, 9.5. By Graphing COD displacement against applied force, a linear fit could be gained from the linear portion of each graph. The slope of this linear fit was then scaled by 95% and plotted on top of the experimental data. The intersection of the scaled line with the data set was determined as the fracture force (P_Q). The maximum applied force (P_{max}) was determined from the maximum applied force in the fracture test of each sample. From here, fracture toughness (K_Q) can be calculated using Equation 8 [2] and Equation 9 [2] below. The variables S, a, w, and B represent the support span, critical crack length, sample width, and the thickness of each sample, respectively.

$$K_Q = \left(\frac{P_Q * S}{B * w^{3/2}}\right) * f\left(\frac{a}{w}\right) \quad \text{Eqn. 8}$$

$$f\left(\frac{a}{w}\right) = \frac{3 * \left(\frac{a}{w}\right)^{\frac{1}{2}} * \left(1.99 - \frac{a}{w}\left(1 - \frac{a}{w}\right) * \left(2.15 - 3.93 * \frac{a}{w} + 2.7 * \left(\frac{a}{w}\right)^2\right)\right)}{2 * \left(1 + 2 * \frac{a}{w}\right) * \left(1 - \frac{a}{w}\right)^{3/2}} \quad \text{Eqn. 9}$$

Having calculated the fracture toughness of each sample the final steps in the procedure were to (1) generate a K_Q vs. B graph for each set of four samples for visual verification in which test irregularities and outliers can be determined and thrown out and (2) to run the validation tests to determine for which samples K_{IC} is approximately equal to K_Q. The validation procedure requires 2 steps as dictated by ASME E399 standards. Each step is articulated in Equation 10 [2] and Equation 11 [2] below. If Equation 10 is true than K_{IC} is approximately equal to K_Q. If Equation 10 is false for a given sample, Equation 11, in all three iterations, must be true otherwise an estimate of the plain strain fracture toughness for the given sample cannot be generated according to ASME E399 standards. The variable σy is the average yield stress from the Tensile tests.

$$\textbf{\textit{If}} \ \frac{P_{max}}{P_Q} < 1.1 \ \textbf{\textit{Then}} \ K_{IC} \cong K_Q \quad \text{Eqn. 10}$$

$$\textbf{\textit{If}} \ \frac{P_{max}}{P_Q} \geq 1.1 \ \textbf{\textit{And}} \ a, B, \& \ (w - a) \geq 2.5\left(\frac{K_Q}{\sigma_y}\right)^2 \ \textbf{\textit{Then}} \ K_{IC} \cong K_Q \quad \text{Eqn. 11}$$

Finally, all K_Q values that pass the visual assessment and ASME E399 validation tests are averaged to produce a final plain strain fracture toughness of the provided recycled aluminum sample.

RESULTS

The purpose of this set of experiments was to generate a list of material properties that would enable Distributed Power to assess the usability of Haggerty Metal's Recycled aluminum. Through the methods defined in the procedure this section will articulate the resulting values of Young's modulus (E), yield stress (σy), ultimate tensile stress (UTS), poisons ratio (ν), and plane strain fracture toughness (K_{IC}). The first four parameters are generated using a uniaxial tensile test of 6 dogbane samples whose material properties were found and averaged propagating error. The final parameter is calculated using four sets of four fracture tests using samples of varying thickness. Based on my analysis the material properties are as listed in Table 2 below.

Table 2. This table depicts the five averaged material properties of the recycled aluminum samples described above.

Youngs Modulous [GPa]	Yield Stress [MPa]	Ultimate Tensile Stress [MPa]	Poisson's Ratio	Plane-Strain Fracture Toughness [MPA $m^{1/2}$]
61.98 ± 0.21	508.40 ± 0.21x10^{-1}	556.23 ± 0.21x10^{-1}	0.36 ± 0.14x10^{-2}	22.3 ± 3.2

Tensile Test

For each dogbone sample a uniaxial tensile test was conducted, recording applied force and stress values of each of the strain gauges on the strain rosette. Using equations three, four, five, and six, the strain readouts from the rosettes were converted to true principal strains ε_1, axial strain, and ε_2, transverse strain. After converting applied force to applied pressure a stress-strain curve can be generated for each sample. Analyzing the linear portion of each stress strain curve allows a linear fit to be generated that's slope is reflective of E. A copy of the line of best fit is then translated 0.002 units to the right. The intersection of this line with the stress-strain curve is σy. Finally, the maximum stress in the sample before fracture is determined and set as the UTS value for the sample. The negative transverse principal strain ε_2 is then graphed against the axial principal strain. a linear fit model is the generated for this graph from which the slope is determined to be ν. The described procedure was conducted over 6 samples, the graphs from

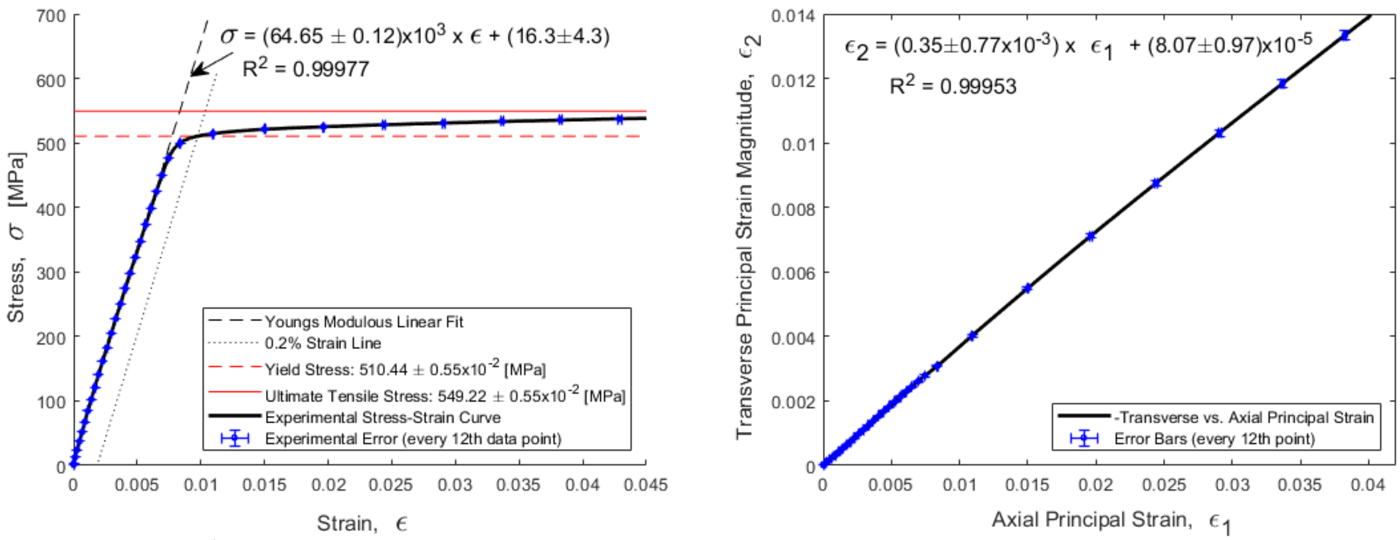


Figure 4. this figure depicts the stress-strain graph, graph a, and Poisson's ratio graph, graph b, for the sixth dogbone sample the black lines depict the experimental data, the blue objects are the error bars for every 12th data point collected in the data set. The maximum stress error was 5.5x10^{-3} [MPa] The maximum principal axial strain (x axis in both graphs) was 2.7x10^{-4}. The maximum transverse axial error was 2.7x10^{-4}. The E value was (64.65±0.12)x10^3 [MPa]. The σ_y value is 510.0.55±10^{-2} [MPa]. The UTS value is 549.22±0.55x10^{-2} [MPa]. The ν

The calculated yield stress, Young's modulus, ultimate tensile stress, and Poisson's ratio were determined for all six dogbone samples. The results are displayed Table 3 below.

Table 3. This table shows the results of the six tensile tests and the resulting material properties of E, σ_y, UTS, and ν.

Sample	Youngs Modulus [GPa]	Yield Stress [MPa]	Ultimate Tensile Stress [MPa]	Poisson's Ratio
1	64.74 ± 0.06	510.45 ± 0.74x10^{-2}	553.16 ± 0.74x10^{-2}	0.39 ± 0.39x10^{-3}
2	56.67 ± 0.02	508.32 ± 0.11x10^{-1}	562.82 ± 0.11x10^{-1}	0.40 ± 0.20x10^{-3}
3	59.62 ± 0.13	502.74 ± 0.11x10^{-1}	554.06 ± 0.11x10^{-1}	0.37 ± 0.68x10^{-3}
4	62.92 ± 0.13	509.98 ± 0.67x10^{-2}	563.57 ± 0.67x10^{-2}	0.36 ± 0.53x10^{-3}
5	64.82 ± 0.12	508.46 ± 0.95x10^{-2}	554.54 ± 0.95x10^{-2}	0.33 ± 0.46x10^{-3}
6	63.13 ± 0.12	510.44 ± 0.55 x10^{-2}	549.22 ± 0.55x10^{-2}	0.35 ± 0.77x10^{-3}
Avg.	61.98 ± 0.21	508.40 ± 0.21x10^{-1}	556.23 ± 0.21x10^{-1}	0.36 ± 0.14x10^{-2}

Fracture Test

To determine the plain strain fracture toughness (K_{IC}) of the recycled aluminum samples a fracture test was conducted as described in the procedure section. This included graphing applied load (F) against COD displacement to find the fracture force of each sample (P_Q). Fracture toughness (K_Q) is then calculated using the principle crack length (a), the fracture force (P_Q), the support span (S), critical crack length (a), sample width (w), and sample thickness (B). collected for each sample. This method for determining K_Q, defined by equations nine and ten was repeated for four sets of four samples. Figure 5 depicts the force vs. COD displacement for the 9.5 [mm] sample in the set.

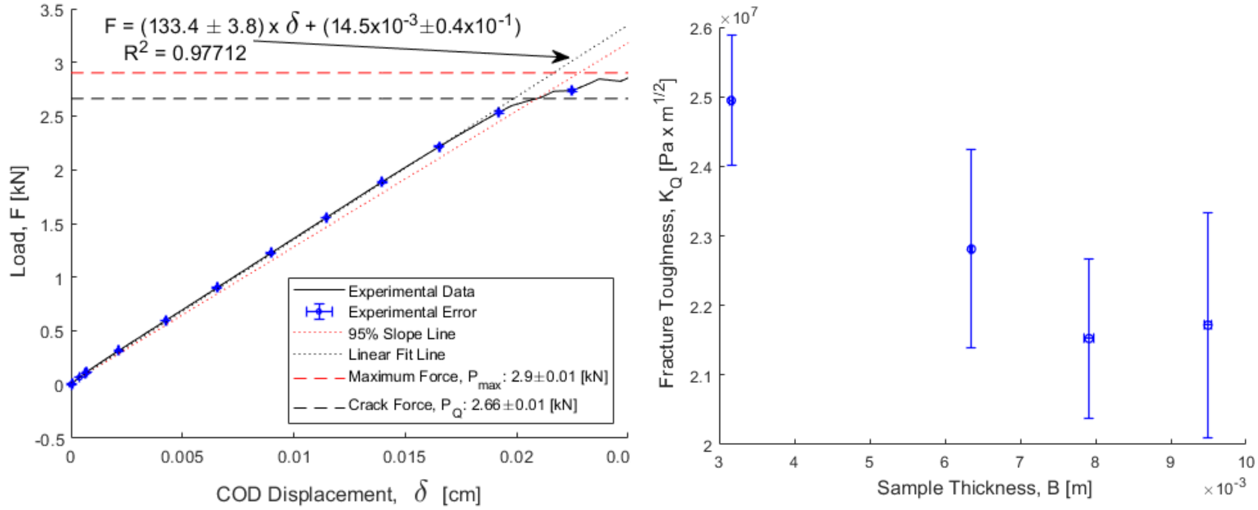


Figure 5. This figure depicts the force vs COD displacement of the 9.5 [mm] sample in the first set of samples on the left and the K_Q vs. B graph of the first trial set, with error bars, on the right. For the left graph, the black line is the experimental data with the blue icons indicating every 10th point's error values. The maximum Load error is 0.013 [kN]. The maximum COD error is 2.6x10^{-5} [cm]. The linear fit equation is in the top left corner of the graph. The P_Q value for this sample, as indicated by the dashed black line, is 2.66±0.01 [kN]. P_{max}, as indicated by the dashed redline is 2.90±0.01 [kN]. For the right graph, the blue icons are the error bars of at each point. The maximum K_Q error is 1.6 [MPa m$^{1/2}$] and the maximum the maximum thickness error is 6.4x10^{-2} [mm].

After acquiring the K_Q and generating KQ vs. B graphs for all 16 samples, the ASME E399 K_{IC} validation tests were conducted using equations 13 and 14. From the validation test it was determined the two thickest samples from trial one, three thickest from trial two, two thickest from trial three, and two thickest from trial four all passed. The crack length measurement procedure for trial set three was observed to not conform to the methodology dictated in the procedure as such trial three K_{IC} values were disregarded as outliers. The samples which passed the K_{IC} validation were then averaged for each set of samples as well as for an aggregate average. The described values can be seen in Table 4 below.

Table 4. This table describes the averaged K_{IC} values from each test set (with propagated error). The final K_{IC} estimate for the recycled aluminum sample is 22.3±3.2 [MPa m$^{1/2}$].

Trial	K_{IC} [MPa m$^{1/2}$]
1	21.6 ± 2.0
2	22.7 ± 1.8
3	N/A
4	22.7 ± 1.8
Avg.	22.3 ± 3.2

CONCLUSION

From the described experimental procedure and results, the requested material properties as are reported described in table 5 below. These results only represent the testing of a relatively small sample of tested recycled aluminum from Haggarty Metal and as such should be received with caution. Based on the testing results I would not be comfortable recommending the use of these material properties without first applying a safety factor of two. This safety factor would be applied to the material properties before industry standard safety factors. As such I would recommend the material properties be retested by another firm making sure to adhere to a defined measurement procedure for crack length measurement.

Table 5. This table depicts the five summary material properties requested in analysis of the recycled aluminum from Haggarty Metal

Youngs Modulous [GPa]	Yield Stress [MPa]	Ultimate Tensile Stress [MPa]	Poisson's Ratio	Plane-Strain Fracture Toughness [MPA m$^{1/2}$]
61.98 ± 0.21	508.40 ± 0.21x10^{-1}	556.23 ± 0.21x10^{-1}	0.36 ± 0.14x10^{-2}	22.3 ± 3.2

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