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Round Robin Tensile Testing of 50% Cold Worked Nitronic 60

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ABSTRACT

This report documents recent experiments on the structural properties of Nitronic 60, Level 5 (cold worked to approximately 50% reduction in diameter). Material from two different vendors was examined. Different cold working approaches by the two vendors resulted in inhomogeneous material properties that varied as a function of distance from the center of the rod.

Measurements were compared to Sandia specifications (7343200-7343207). The effect of several parameters on structural properties was examined, including lot-to-lot variability, lot diameter, radial location of tensile bars, tensile bar size, and cold working method. Most significantly, the apparent tensile strength, yield strength, and ductility were found to all vary with radial distance from the center of the bar.

ACKNOWLEDGEMENTS

This work was a collaborative effort. The work, advice, and guidance of Ed Wenski at the Kansas City National Security Complex and Don Susan at Sandia National Laboratories are greatly appreciated. IMR test labs and the National Security Complex were helpful in providing quality results for comparison purposes.

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EXECUTIVE SUMMARY

This report documents recent experiments on the structural properties of Nitronic 60, Level 5 (cold worked to approximately 50% reduction in diameter)[1]. Material from two different vendors was examined.

Vendor 1 used a proprietary gyratory forging technique to cold work the material. Five different lots of material, each with a different bar stock diameter, were tested from Vendor 1. Tensile tests were performed using multiple ASTM E8 tensile bar dimensions[2] including R1, R2, R3, and R5 and tested at three different laboratories including Sandia National Laboratories, the Kansas City National Security Complex, and an external material testing company, IMR Test Labs. The extreme levels of work hardening present in these bars resulted in a radial variation of hardness from the center of the sample to the surface. Samples were taken from the center of the bar, mid-radius, and outer edge when possible.

Vendor 2 used a more conventional cold die drawing technique. A more limited set of samples were analyzed from vendor 2 including one lot of material with R3 and R5 specimens.

Measurements were compared to Sandia specifications (7343200-7343207)[3]. The effect of several parameters on structural properties was examined, including lot-to-lot variability, lot diameter, radial location of tensile bars, tensile bar size, and cold working method. Most significantly, the tensile strength, yield strength, and ductility were found to all vary with radial distance from the center of the bar.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
HVN	Vickers Hardness Number

1. INTRODUCTION

Nitronic 60 is a nitrogen-strengthened austenitic stainless steel alloy with good galling, wear, and corrosion resistance[1]. It can also be cold worked to increase its strength for use in high stress applications. The extent of cold work imparted into Nitronic 60 is expressed as a 'level' followed by an integer value (1-7) which is approximately equal to the percent reduction in initial bar diameter when the level value is multiplied by ten. For example, Level 4 material is approximately 40% cold reduction. The material in this study is Level 5 Nitronic 60, meaning its initial bar diameter was reduced by half. This often results in inhomogeneous material properties across the bar diameter stemming from non-uniform strain accumulation during the cold working process. As such, acceptance testing several lots of this material can be challenging. Answering the question of whether a lot meets specifications may depend not only on the cold working process and the lot of material, but also on the specimen size, location, and method of data analysis. To understand the effects of these many parameters on structural material properties, a round robin experiment was performed at three different testing laboratories with four different ASTM tensile bar sizes on six lots of material from two different vendors.

2. HARDNESS TESTING

Grids of Vickers microhardness indentations were placed on cross sections of bars to interrogate the spatial variability in strength. The resulting microhardness measurements on two lots from vendor 1 and one lot from vendor 2 are shown in Figure 1. The gyratory forging process (vendor 1) results in significantly higher hardness at the center than near the edge of the bar (a difference of ~80 HVN). In contrast, the cold die drawing process (vendor 2) results in a more consistent hardness (a difference of ~60 HVN) throughout the cross section of the bar with somewhat higher hardness at the perimeter. The radial variation in hardness is attributed to strain gradients during the cold working operation. For gyratory forged material, deformation is applied to the outer diameter of the bar. This results in locally higher strains and peak temperatures from adiabatic heating which drives partial recovery and softening of the outer diameter region of material. These observations motivated an investigation of the effect of radial tensile bar location on measured properties.

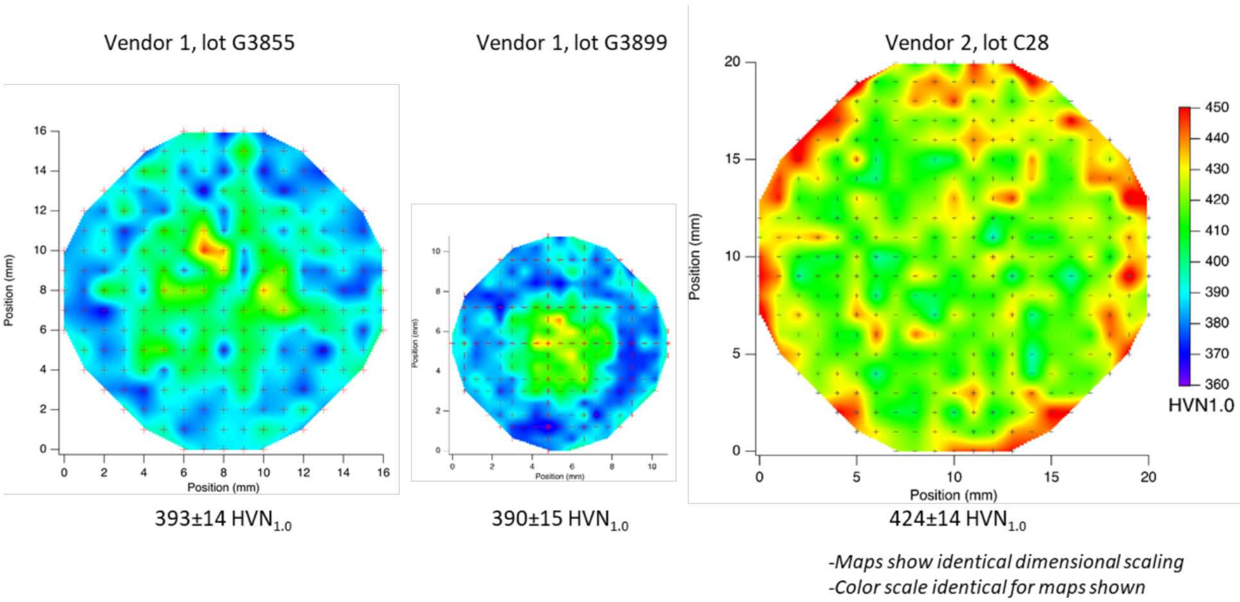

Figure 1. Microhardness maps of cross sections of different lots of Nitronic 60 bars. All three maps are shown at the same size and color scale. The gyratory forging process (left two) results in significantly higher hardness at the center whereas the cold die drawing process (right) results in a higher hardness at the perimeter.

3. MATERIAL

Five lots were obtained from vendor 1, each with a different diameter of bar stock as shown in Figure 2. ASTM standard E8 tensile bars with dimensions given in Sandia specification 9949050 were cut from each lot parallel to the bar axis[4]. Due to varying lengths of bar stock, a fully consistent set of different sizes of ASTM tensile bars was not possible. R5 tensile bars (the smallest size) were cut from the center, mid-radius, and outer edge of every lot from vendor 1. Outer edge R5 samples were cut from vendor 2. R3 tensile bars were taken from 4 of 5 lots from vendor 1 (at both edge and center) and from the center of the vendor 2 lot. ASTM size R1 (the largest size) and R2 tensile bars were taken from a few selected lots, as material allowed. The varying sizes and locations of tensile bars were compared to measured tensile properties. Sandia requirements for material properties are given in specifications 7343200-7343207, from which the values in Table 1 were copied[3]. Note that only Level 5 material was studied for this report. While not evaluated directly in this work, radial uniformity of Nitronic 60 is expected to increase with decreasing levels of cold work.

Table 1. Sandia specifications for Nitronic 60 of different levels[3]

Number	Level	Tensile Strength, ksi, min.	Yield Strength, 0.2% offset, ksi.	Elongation % in 4D, min.	Reduction in area, % min.
7343200	Annealed	95	50-65	35	55
7343201	Level 1	112	75 min	29	50
7343202	Level 2	131	92 min	20	48
7343203	Level 3	151	109 min	15	45
7343204	Level 4	183	126 min	11	42
7343205	Level 5	203	144 min	8	39
7343206	Level 6	225	161 min	6	35
7343207	Level 7	247	180 min	5	29

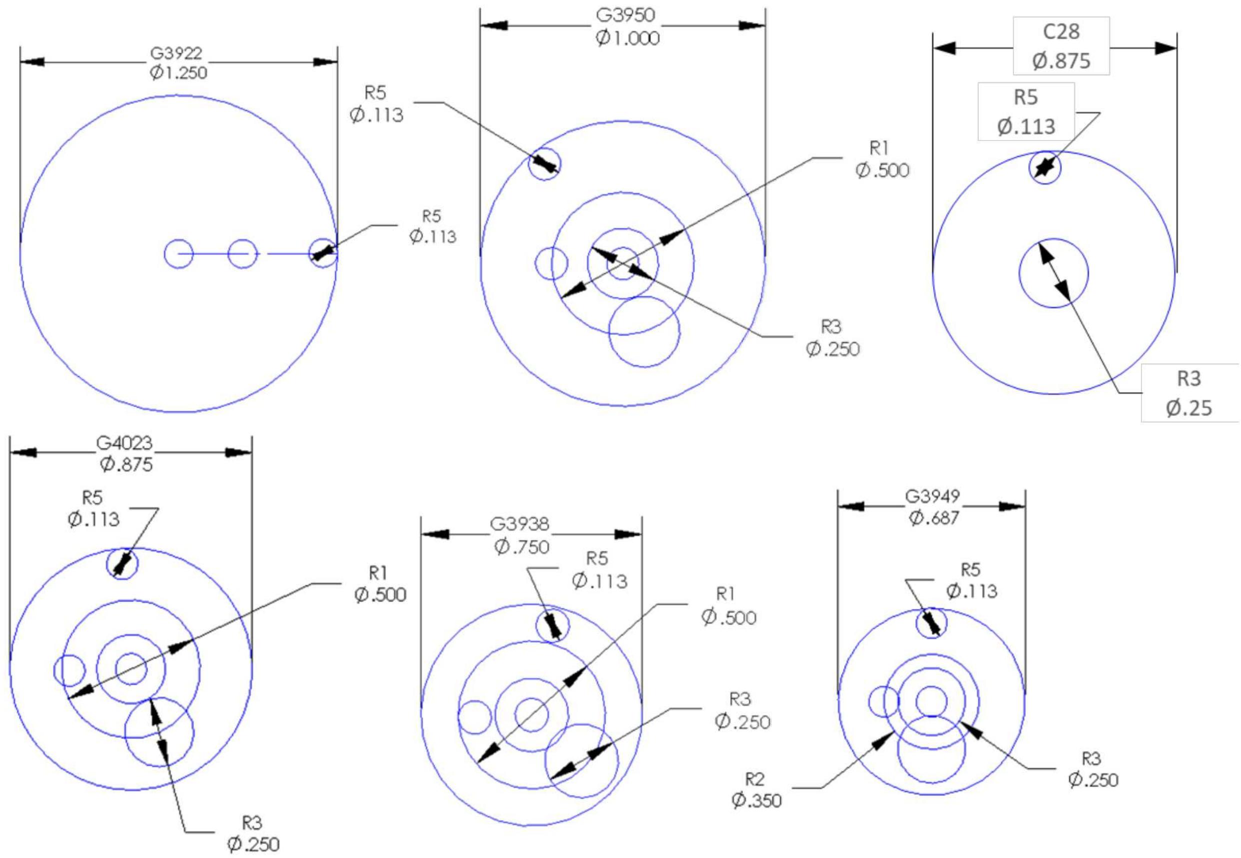

Figure 2. Diameters of each lot of material and the cross sectional sizes and locations of tensile bars taken from each lot.

4. TENSILE TESTING METHOD

Tensile testing was performed at three different laboratories. Although all three laboratories followed ASTM E8 and some procedures were standardized, there were inevitably a few minor differences between the testing techniques of each laboratory. In all cases, specimens were quasistatically loaded using a servohydraulic load frame with a load cell and knife-edge extensometer to measure stress and strain, respectively. The variability in measured properties was significant. All stress strain curves considered in this work are plotted in Figure 3. Specimens were loaded at a slow crosshead strain rate of 5×10^{-3} min^{-1} (8.3×10^{-5} s^{-1}) initially. At 4% strain, the strain rate was increased to 6×10^{-2} $\text{min}^{-}1$ (1.0×10^{-3} s^{-1}) in order to complete testing in a reasonable amount of time. This sudden increase in strain rate is responsible for the bumps in stress-strain curves at 4% strain. In some cases, such as most of the cyan curves with high tensile strength in Figure 3, this bump had no significant impact. For other curves, such as the red curves with lower tensile strengths in Figure 3, the bump exceeded the previous tensile strength of the material. For consistency, the maximum tensile strength before the 4% strain rate increase was used as the tensile strength for all samples.

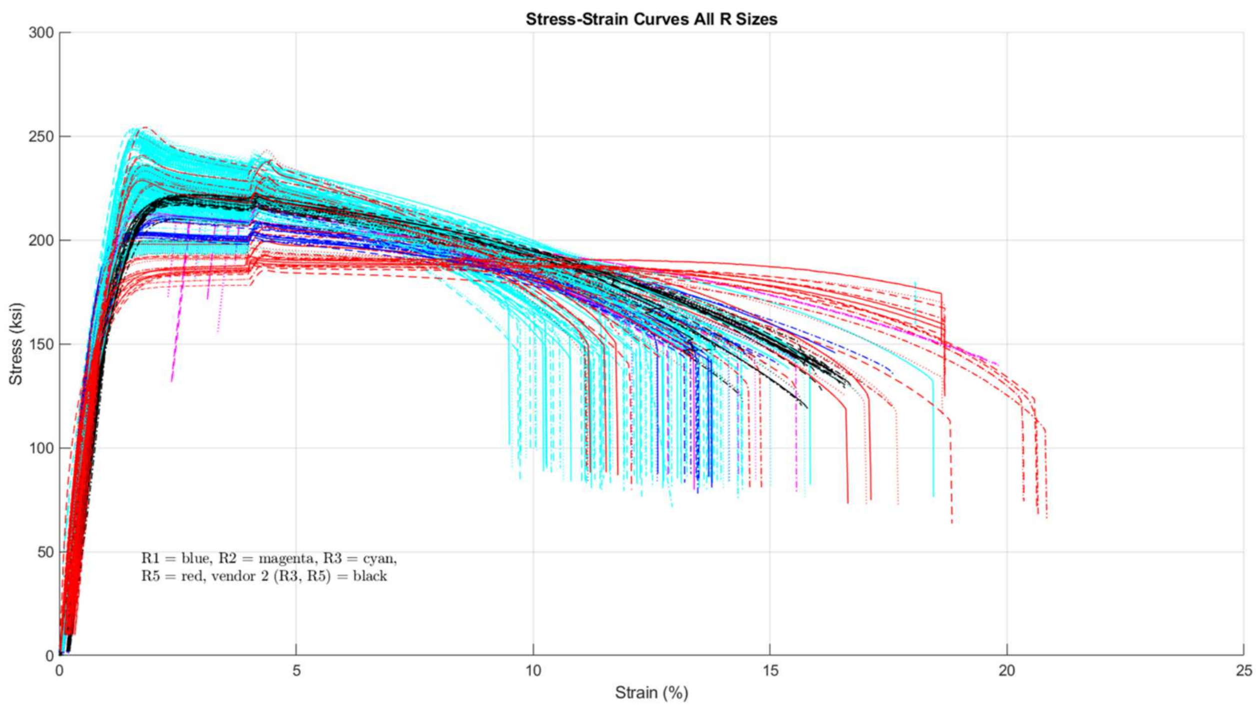

Figure 3. All stress-strain curves examined in this study. It is clear from this plot that the properties of this material, such as tensile strength and ductility, can vary considerably depending on specimen size, location, vendor, lot number. The bump in stress is due to a sudden increase in strain rate.

4.1. Tensile Results

To understand relationships between parameters and material properties, plots of elastic modulus, yield strength, ultimate tensile strength, elongation to failure, and reduction in area were made for all tested tensile bars in Figure 4 through Figure 8. These plots, with a somewhat complicated legend provide insight into the effect of many different parameters on structural properties. The horizontal axis groups data by lot. The bar diameter of each lot is listed above the lot number. Coloring (blue, red, or green) indicates which laboratory tested the samples (Sandia National Laboratories, Kansas

City National Security Complex, or IMR Test Labs, respectively). Different tensile bar sizes R1, R2, R3, and R5 are indicated by different marker types, diamonds, squares, triangles, and circles, respectively. Filled markers indicate tensile bars that were cut from the central axis of the bar while open symbols represent tensile bars cut from the mid-radius or edge of the bar. Mid-radius and edge samples were grouped together in marker style for simplicity and because the behavior of mid-radius samples was much closer to edge-cut samples than to center-cut samples.

4.1.1. Elastic Modulus

Despite being tested at different laboratories, all specimens were subjected to a consistent analysis procedure. Elastic modulus was calculated from the initial slope of the stress-strain curve, specifically by fitting a two-parameter linear regression line to data points between 10% and 25% of the ultimate strength value. Figure 4 demonstrates that the measured modulus of this material is quite variable. Most values range between 20 and 30 Msi—a 50% difference. Even more remarkable are the tails of this distribution. One point at the top of Figure 4 has a modulus above 50 Msi with no obvious reason for the discrepancy. Other specimens appear to have moduli below 18 Msi. Work hardening a bar until it is 50% of its initial diameter is an extensive amount of cold work; Figure 3 shows little strain between yield and ultimate tensile strength for most samples. This extreme amount of deformation apparently leads to inhomogeneity within the bar, as shown in the hardness maps of Figure 1. This inhomogeneity, in turn, leads to residual stresses within grains, micro-yielding in different regions of the tensile bar, curvature in the "linear elastic" portion of the stress strain curve, and variability in elastic modulus. By consistently defining the range over which elastic modulus is calculated, the variability can be quantified and understood.

Figure 9 shows stress-strain curves for two specimens (a) with a typical modulus of 29 Msi, and (b) with an abnormally high modulus of 51 Msi. The two curves appear to be consistent with one another except for the modulus difference. As shown in the zoom-in figures at the bottom of Figure 9, the linear fit appears to be a very good approximation of the initial slope. These specimens are both R5 edge specimens taken from lot 3950, so it is surprising that their moduli could be so different. They had the same tensile bar dimensions, were cut from the same radial location of the same bar, and were tested at the same laboratory. Thus, it appears this modulus variability is a true measure of material variability (i.e. not due to non-material causes). It is also apparent from these figures that a steeper elastic modulus results in a lower yield stress. The low-modulus specimen on the left in Figure 9 had a higher yield stress than the high-modulus specimen on the right. This difference of 136 vs 127 ksi is a substantial difference in strength but perhaps more modest than might be expected for a factor of 2 difference in modulus. Still, for specimens that lie near the specification limits, a different modulus measurement could mean the difference between accepting or rejecting a lot of material based on yield strength. This substantial variability in Young's modulus is thought to be a result of the processing of this material. The nominal value of Young's modulus for Nitronic 60 in the annealed, non-cold-worked condition is 26 Msi. Typically, cold work in austenitic stainless steels lowers Young's modulus so one might expect Level 5 Nitronic 60 to have a somewhat lower modulus, which agrees with the bulk of results shown here between 20–26 Msi.

There are several test artifacts that could lead to widely varying modulus measurements. A misaligned load frame, extensometer slip, or mismeasurement of cross sectional area could lead to errors in modulus, but those are not considered likely in this work. A misaligned load frame would likely be a systematic error affecting all specimens from a single laboratory, yet the laboratories agree with one another fairly well. Extensometer slip is typically obvious and often correctable (as was observed for a few samples in this work). A mismeasured cross sectional area causing double the modulus, such as the high point in Figure 4 would require half the cross sectional area and would result in an apparent 50% decrease in ultimate strength value, which was not observed. The inhomogeneous work hardening within each bar is the most likely cause of modulus variability. This inhomogeneity leads to the curved elastic behavior of this material. Underestimates of moduli can be caused by the concave-down curvature of the stress strain curve at the upper end of the modulus range due to local plasticity. Overestimates can be caused by a concave-up curvature at the very beginning of stress-strain curves due to early compliance changes on initial loading. The lower modulus range of 10% of tensile strength was chosen to eliminate this issue.

The effect of modulus calculation method was studied briefly with two methods for comparison. In method 1, an alternative data range for calculating the elastic modulus was also examined in this work: a range of 40–50 ksi, suggested by an external test laboratory. This is a reasonable range although in our opinion a wider range starting closer to zero is a more accurate estimation of the "real" elastic modulus. The upper end of this range is nearly the same as that used in this work (~25% of tensile strength), but the lower end is substantially higher (~20% of tensile strength).

In method 2, ultrasound transducers were placed on a small puck of material cut from each bar with 10 mm thickness and the diameter of the bar. Center, mid-radius, and edge samples were obtained using a 0.125 inch transducer for the dilatational wave and a 0.25 inch transducer for the shear wave. The dilatational and shear wave speeds were measured in the material, and Young's modulus was obtained from the calculated bulk and shear moduli. This technique allowed one measurement per average location rather than measuring each tensile specimen's modulus directly. Modulus measurements from the alternative range and the ultrasound methods are presented in Figure 10 and Figure 11, respectively. The alternative range method gives slightly different values that could impact borderline cases, but for practical purposes, these results are equivalent to the primary modulus method used in this report. The ultrasound method is known for being very precise, and that precision shows in the smaller scatter shown in this plot. It is quite possible that ultrasound modulus is more consistent and reliable, but it does pose some drawbacks. It is not widely used by many test labs, which limits its availability for acceptance testing. It is also not clear whether ultrasound modulus is exactly the quantity of interest for purposes of material certification since the modulus measurement is just an intermediate step to determining yield strength. This last point will be addressed later in the report.

4.1.2. Yield Strength

Values of yield stress for each specimen are plotted in Figure 5. The yield strength specification[3], 144 ksi, is indicated by the horizontal black line. Most specimens exhibit yield strengths above this line; however, a significant number of specimens are below this line. As one might expect from the vendor 1 hardness distribution in Figure 1, R5 tensile bars taken from the edge of the bar have some of the lowest yield strengths, and R5 specimens taken from the center of vendor 1 bars have some of the highest yield strengths compared to other specimen sizes and locations. Consequently, most of the specimens with yield stress below the specification are R5 samples taken from the edge of the bar.

The radial variability in hardness explains the effect of tensile specimen size and location on yield strengths observed in Figure 5. Beyond the R5 specimen observations, the R3 specimens near the bar center have consistently high yield strengths for vendor 1. R1 and R2 yield strengths are between the center and outer edge measurements from smaller samples. In vendor 1 lot 3950, all six R1 tensile bars are borderline on the specification with three failing the specification. This is partly due to the radial strength distribution, but it also appears to be a result of lot 3950 having lower overall yield strength among all specimens. For the vendor 1 lots examined in this report, there does appear to be a trend of yield strength vs bar diameter with 0.75 inch bars exhibiting the highest strength. Yield strength appears to decrease in both directions as bars become either larger or smaller than this. Whether this trend of decreasing yield strength on either side of 0.75 inches would hold for other lots is unknown. A similar, although less substantial, trend in elastic modulus can be observed in Figure 4.

One might expect the measured elastic modulus to have a negative correlation with yield strength. For a single stress-strain curve with a curved "linear elastic" region, a steeper elastic modulus would result in a lower yield stress, resulting in a lower 0.2% offset yield strength. It appears this is not the case in this material since the trends in Figure 4 and Figure 5 are in the same direction. Furthermore, Figure 9 demonstrated that the effect of variability in elastic modulus on yield strength is modest. Standardizing the modulus measurement allowed for fair comparisons between samples of different lots, but there is still some subjectivity in how the modulus is determined. To address this issue, a more direct measurement of yield was undertaken: unloading specimens to see if they have yielded.

A slight modification was made to the test procedure on many of the ~70 specimens tested at Sandia National Laboratories: specimens were unloaded at the yield strength specification and subsequently reloaded to failure. This unload/reload did not affect the overall stress-strain curve, but it did allow for a direct observation of whether the material had yielded at that stress. That is, if the unloading curve approaches a strain value less than 0.2% as the load approaches zero, then the material could be said to be unyielded by the ASTM 0.2% offset criterion. Figure 12 demonstrates the results of this experiment with one plot for each specimen size. Only the very beginning of the stress-strain curves are shown in these plots including the loading curves (starting near zero) and the unloading curves (coming down between 0 and 0.3% strain). It is apparent from this plot that most specimens have not yielded by the 144 ksi specification, but a few have yielded and a few are border cases. As might be expected, nearly all of the specimens that do not meet specifications are size R5 taken from the edge or mid-radius. There are a few R1 and R3 size specimens that appear to be right at the 0.2% threshold.

4.1.3. Tensile Strength

The ultimate tensile strengths of all specimens are plotted in Figure 6. It appears most vendor 1 R5 specimens taken from the center or mid-radius fail the tensile strength specification. Additionally, most vendor 1 R1 size specimens taken from the center also fail or are borderline cases. The vendor 1 outer edge R5 specimens failing tensile strength are understandable since the material at the edges had effectively less cold working. At the moment, it is not entirely clear why the R1 specimens failed to meet specifications. One might think they would be relatively strong since they were taken from the center, but they have large diameters extending to the mid-radius. Vendor 2 tensile strengths appeared to be relatively consistent and met tensile specifications, but there were not as many specimens or testing variables for this lot so the true scatter between cold working methods cannot be fairly compared.

4.1.4. Ductility

Ductility measured by elongation to failure is shown in Figure 7. All specimens met this requirement although a single R1 sample was a borderline case. The variability in elongation to failure is large here, but that is likely due to the fact that so many specimen sizes, locations, lots, and test labs were involved. Strength values of this material are concerning, but we can be confident in meeting ductility specifications.

Ductility measured by reduction in area (R of A) is shown in Figure 8. The 50–60% R of A values indicate good ductility and are in-line with elongation to failure measurements. One single R3 specimen taken from the mid-radius of lot G4023 failed to meet specifications. No clear explanation for this low value has been found so it is presumed to be an accurate indication of material behavior.

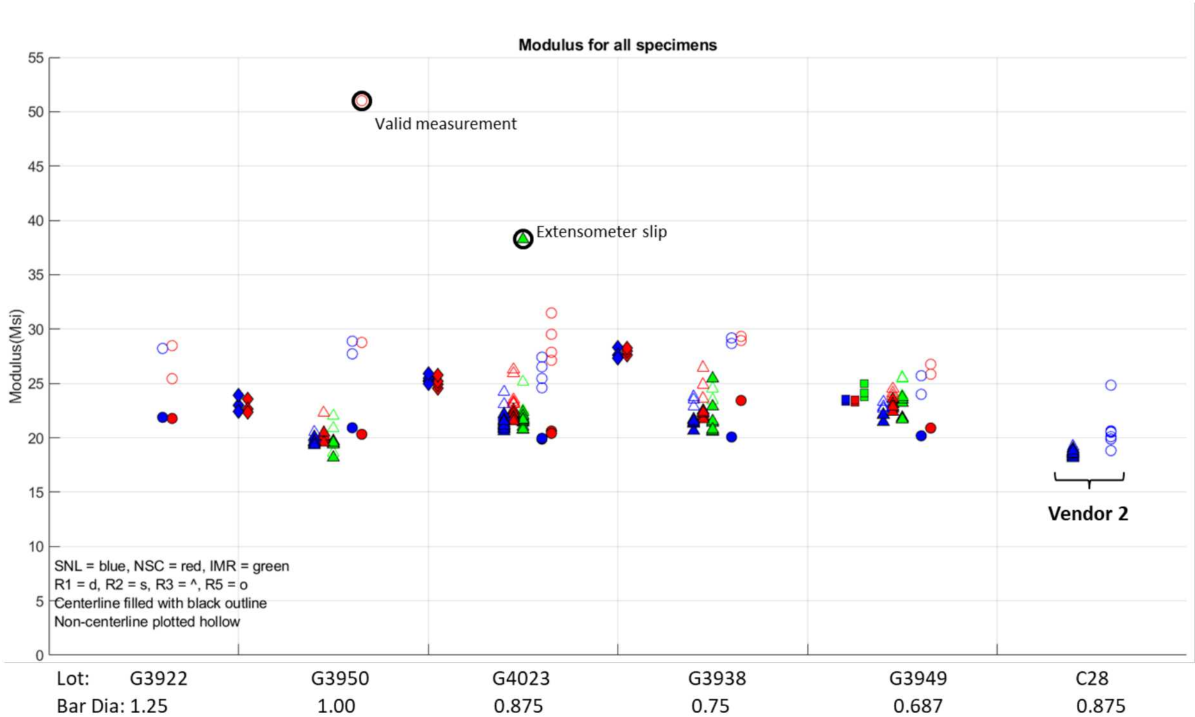

Figure 4. Elastic modulus for each tensile specimen, calculated from data between 10 and 25% of ultimate strength.

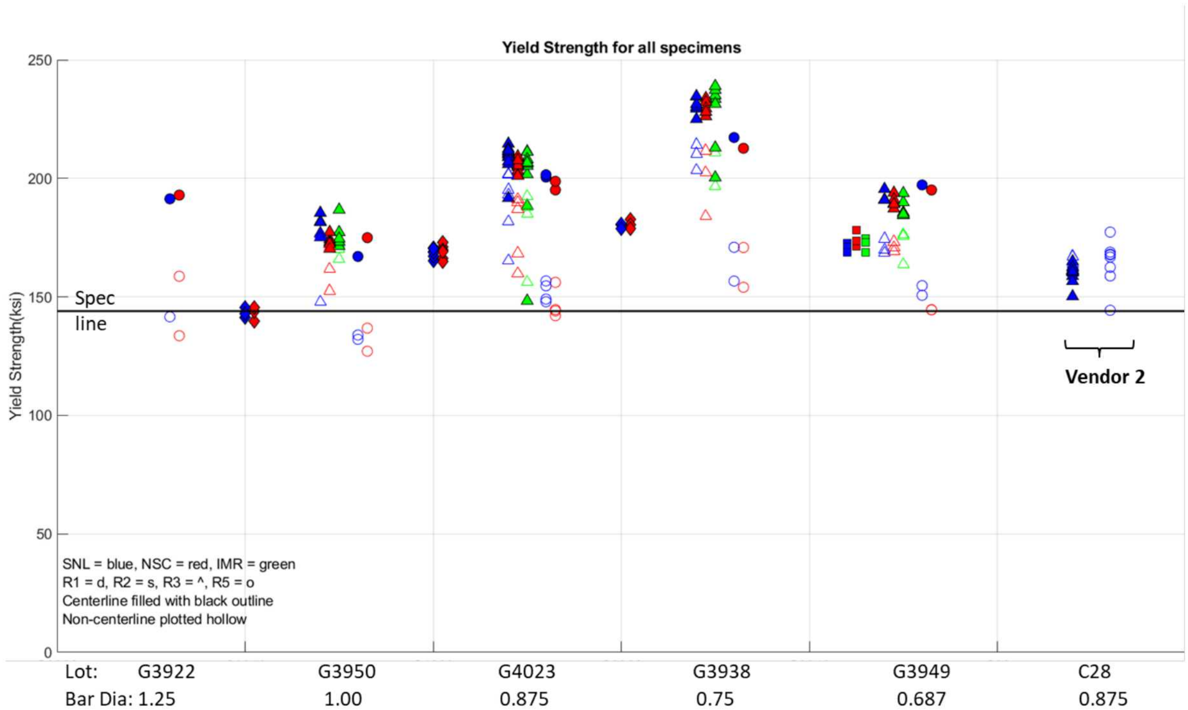

Figure 5. Yield strength for each tensile specimen plotted vs lot number (horizontal axis).

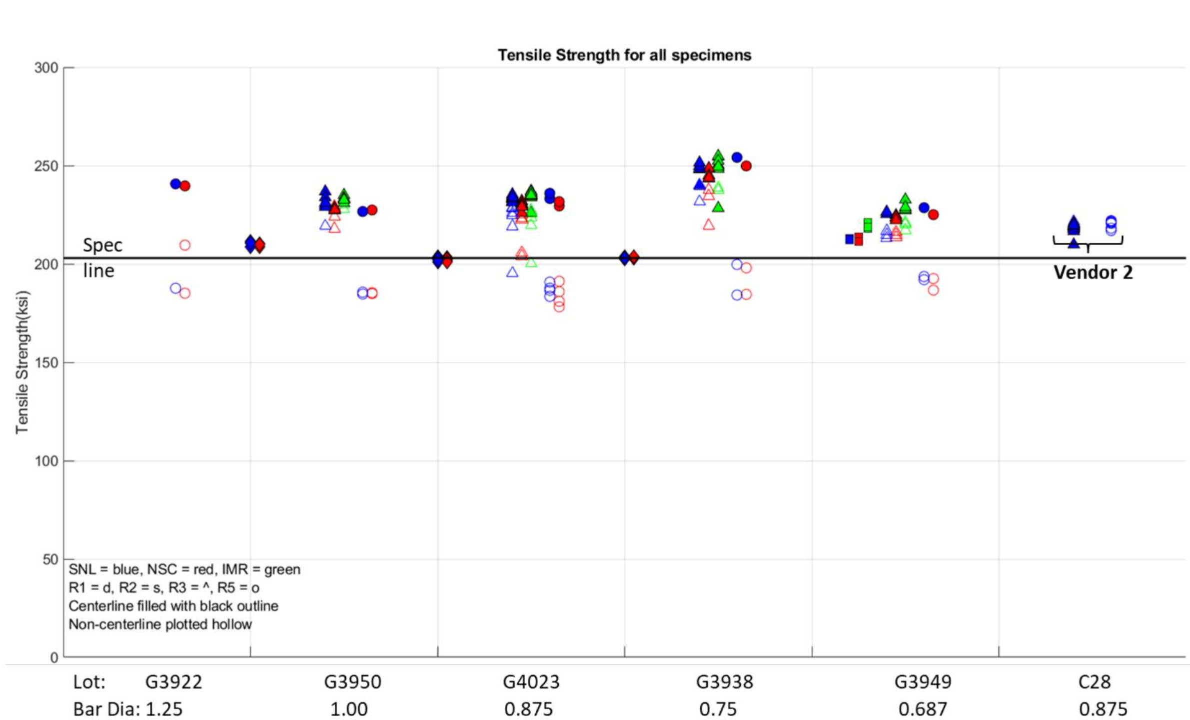

Figure 6. Tensile strength for each tensile specimen plotted vs lot number (horizontal axis).

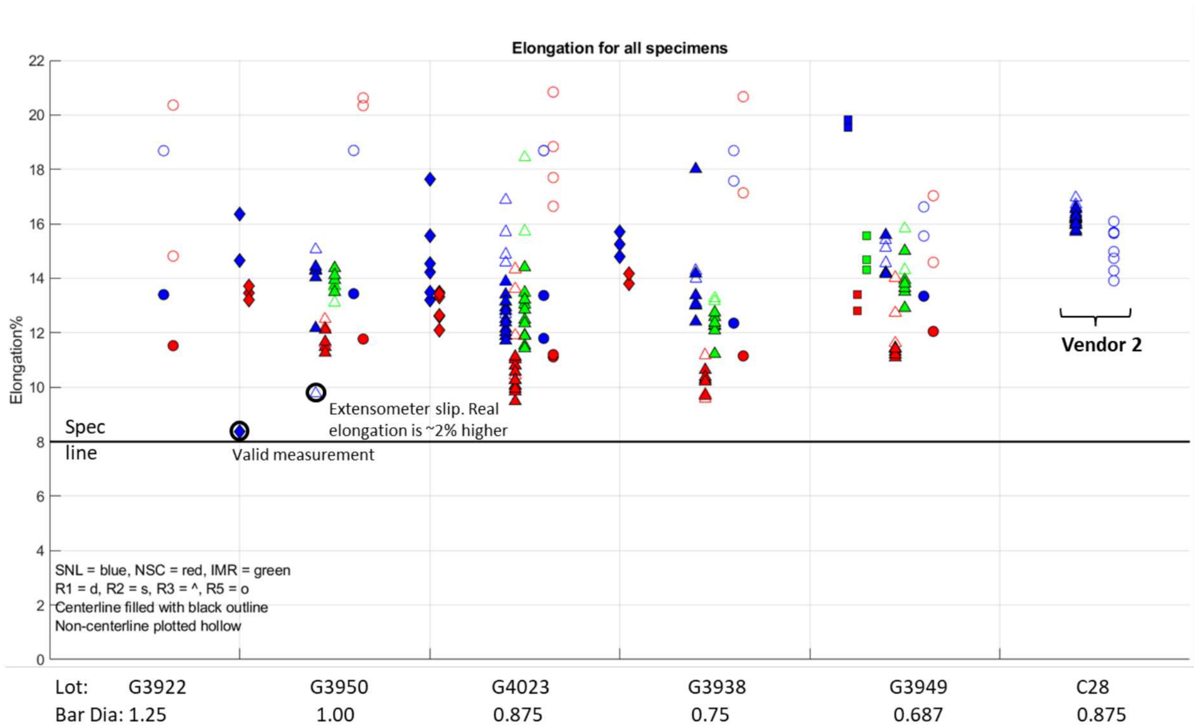

Figure 7. Elongation to failure for each tensile specimen plotted vs lot number (horizontal axis).

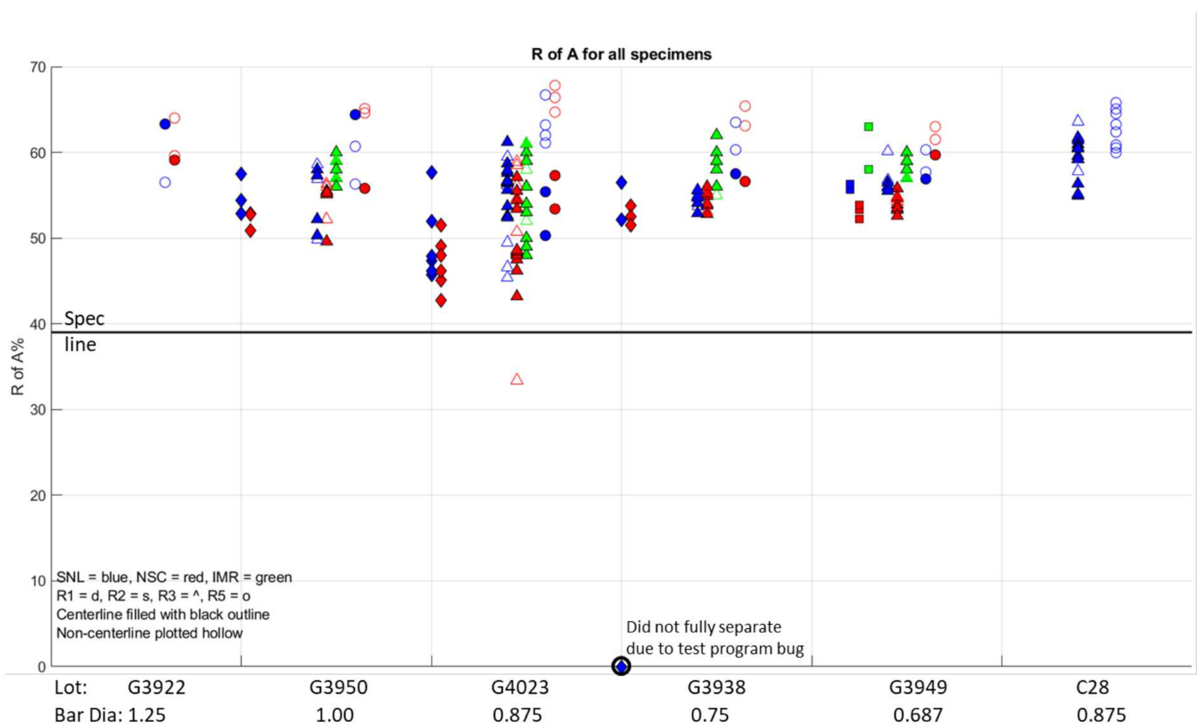

Figure 8. Reduction in area for each tensile specimen plotted vs lot number (horizontal axis).

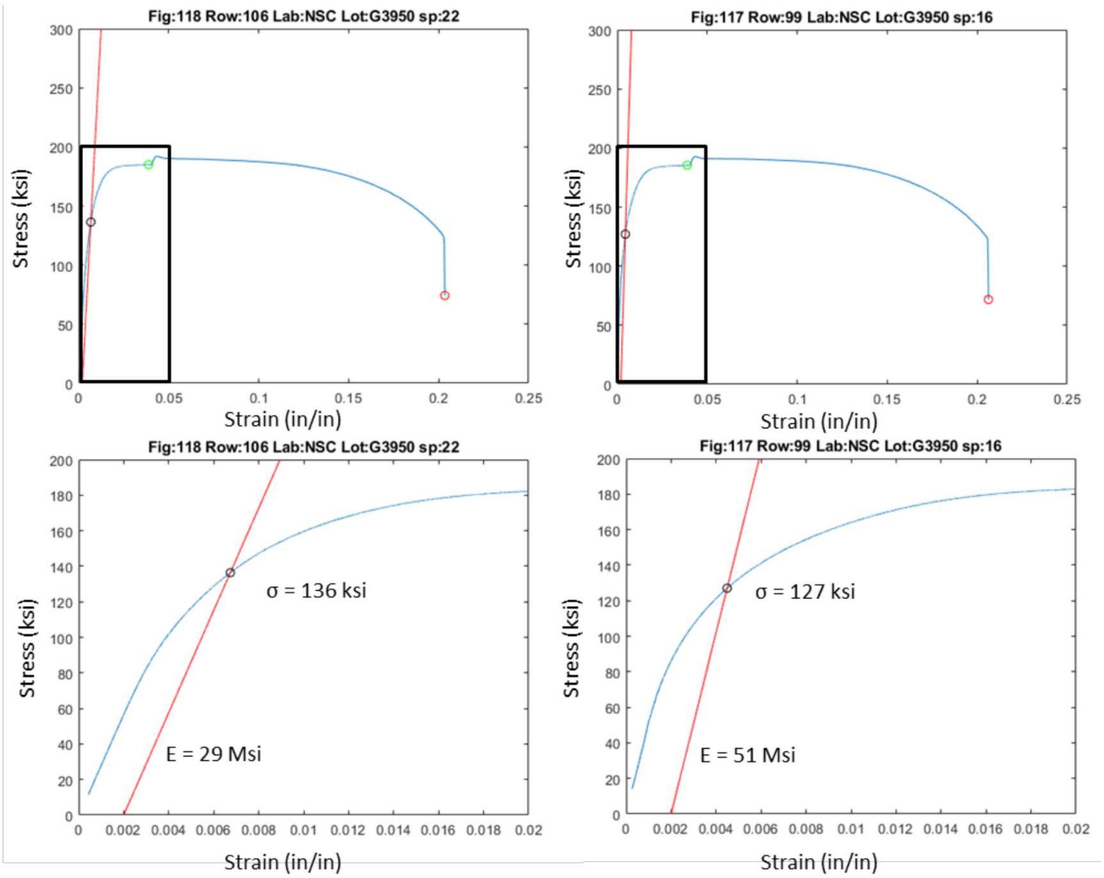

Figure 9. Two stress-strain curves showing (a) Typical specimen (b) Specimen with the highest elastic modulus from Figure 4. A magnified view of the linear elastic region shows significant curvature for both specimens.

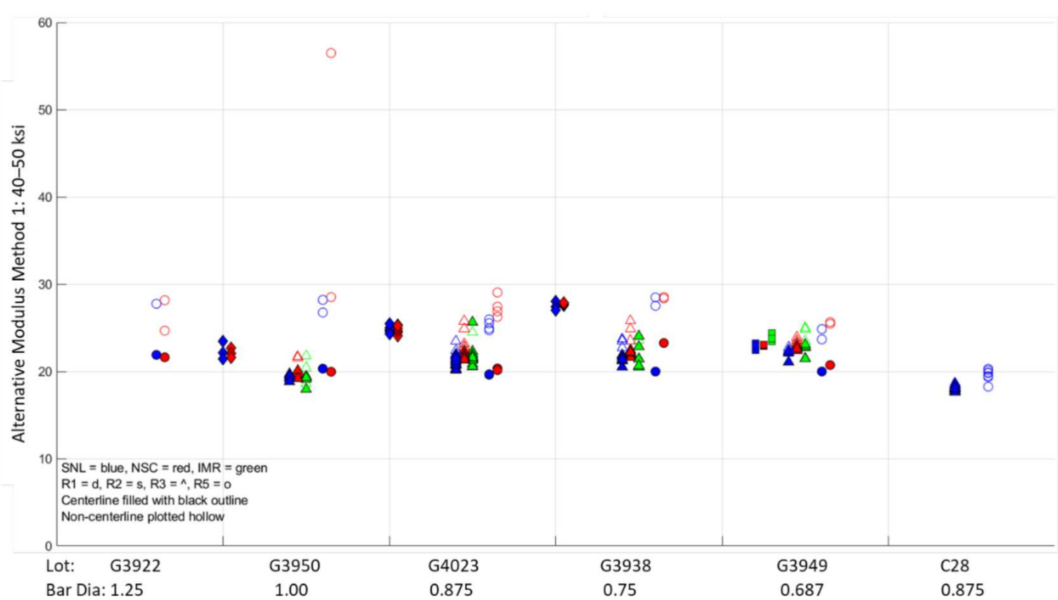

Figure 10. Elastic modulus measurements resulting from alternative method 1, a linear fit to data between 40–50 ksi.

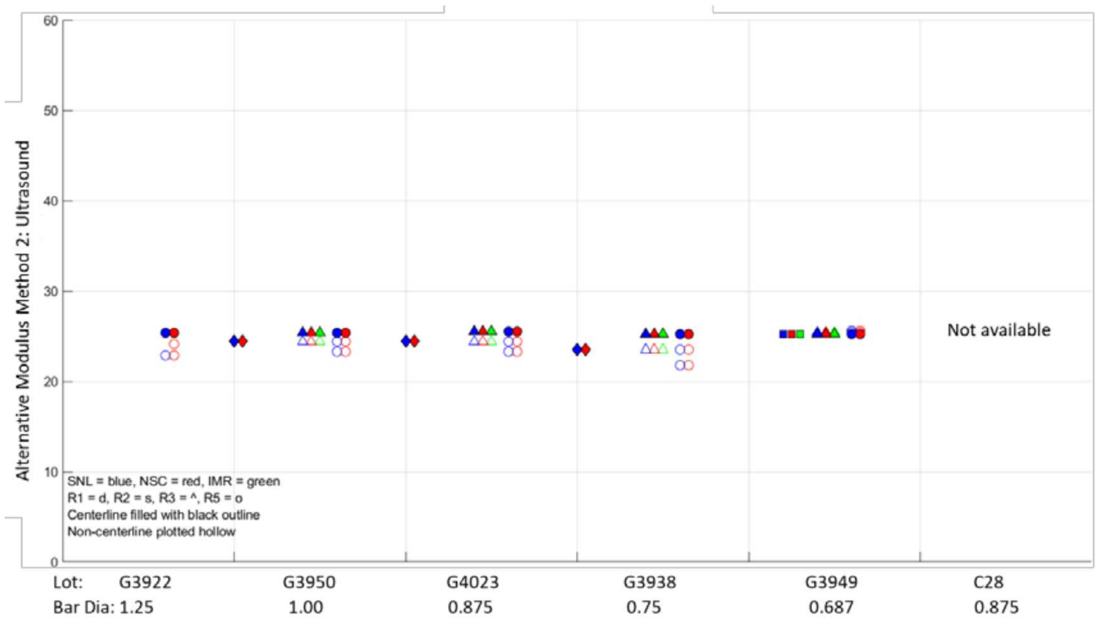

Figure 11. Elastic modulus measurements resulting from alternative method 2, ultrasonic wave speed measurements.

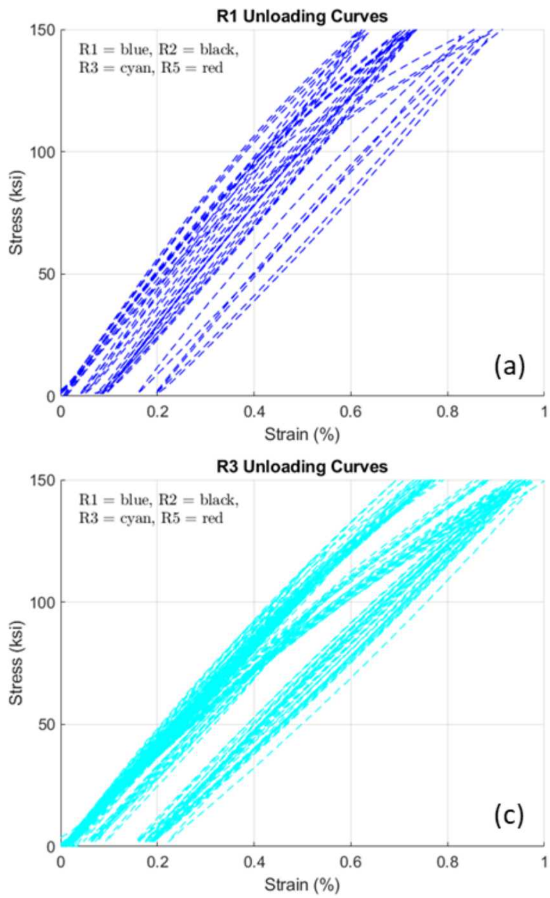

Figure 12. Initial loading, unloading, and reloading curves for many of the specimens tested at Sandia National Laboratories for specimen sizes (a) R1, (b) R2, (c) R3, (d) R5. These unloading curves provide a direct observation of yielding. Specimens were unloaded at the specification yield strength. If unloading to zero stress brings them back to less than 0.2% strain, it can be said that the specimens passed the specification. While most specimens behaved elastically up to the yield specification, many did not.

5. DISCUSSION

This work focuses on the effects of several factors on the measured material properties of Nitronic 60 Level 5: variability between lots, bar diameter, cold working method, tensile specimen size, and analysis methods. In brief, the measured strengths, ductility, and moduli depend on all of these factors. This section will provide a summary of the impact of each factor on tensile bar behavior and implications for component design. Most of the effects discussed here can be explained from the microhardness maps in Figure 1 showing radial distributions in hardness.

The diameter of the bar stock appears to have a slight effect on strength and ductility with moderate bar diameters near 0.75 inches exhibiting slightly higher strength and lower ductility than either larger or smaller bars. However, this could simply reflect lot-to-lot variability. Since only one lot of each diameter was examined, these apparent trends cannot be confirmed.

Specimen size can make an important impact on properties, primarily due to the inhomogeneous hardness throughout the cross section (Figure 1). Choosing a tensile bar size and location to use for acceptance testing can be challenging due to the many interacting variables that impact measured structural properties. It may be favorable to decide on a specific tensile specimen size and location for all tests. This choice must be thoughtfully considered. In gyratory forged bars, small tensile bars (R5) taken from the edge will give lower strengths (both yield and ultimate), higher ductility (both elongation and reduction of area), and higher modulus. In contrast, R3 specimens taken from the center exhibit higher strengths, lower ductility, and lower modulus. The cold die drawing technique appears to produce the opposite strength and ductility trends with radius, although to a lesser degree. Admittedly, a very limited sample size was used for vendor 2. As a consequence of these strength trends, one might consider which cold working technique to use when choosing material for a design. In applications where high strength at the outer edge of the component is desired, such as a gear, the cold die drawn material might be preferred (e.g. vendor 2). In applications where high ductility is desired at the outer edge, one might prefer gyratory forged material (e.g. vendor 1). The largest sizes of tensile bars (R1, R2) appear to exhibit lower strength than all but R5 edge samples. Choosing a tensile bar size and location that is conservative depends on the application.

The variability in all properties can be summarized on a Weibull plot. This is done for the ultimate tensile strength of the gyratory forged specimens (vendor 1) in Figure 13. Marker symbols match the convention of earlier figures. Approximate guiding lines have been drawn to extrapolate these data to the horizontal axis. More formal Weibull fits could be performed on this data, but this simple approach was chosen for now in the interest of time. The location where this line crosses the axis is the predicted tensile strength of the lowest 1% of specimens of that type. These numbers can be compared to specifications and designs can be adjusted as necessary. Note that the smaller tensile bars have considerably more variability, as indicated by their shallower slope. Furthermore, small tensile bars taken from the center appear to be consistently high strength while small bars taken from the edge or mid-radius have considerably lower strength. The large R1 and R2 samples were considerably more consistent with steeper slopes. The coloring generally is mixed in these plots, indicating that there was no strong systematic bias between testing laboratories. Note that only the R3 center, R5 center, and R2 specimens are projected to actually meet the tensile strength specification (203 Ksi) 99% of the time. One should expect material lots to fail specifications sometimes in acceptance testing if R1 center, R3 edge, or R5 edge specimens are used on gyratory forged material.

As a result of this study, specifications 7343200-7343207[3], revision J included substantial modifications. In particular, revision J defines the rate of testing as was done in this work (slow until

4% strain and determine tensile strength before increase). Revision J also defines range of data for determining modulus of elasticity.

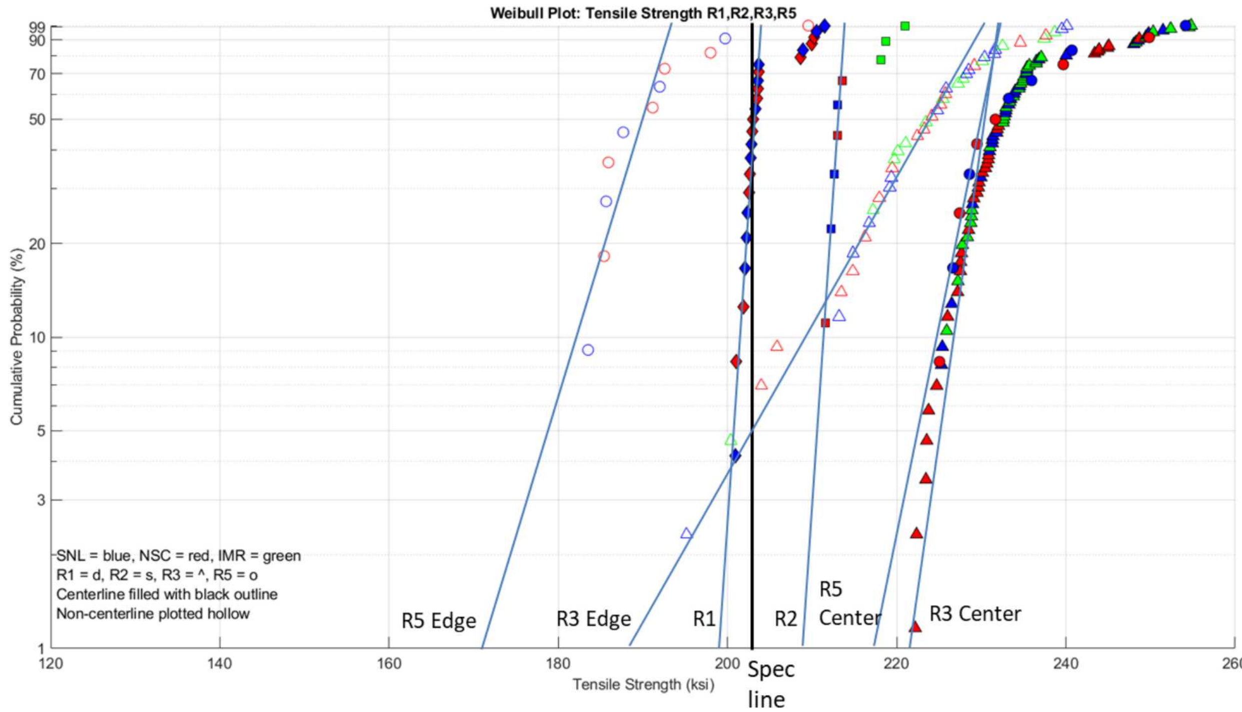

Figure 13. Weibull plot of ultimate tensile strength for all specimens. This plot demonstrates how the variability and minimum measured strength varies with choice of specimen size and location.

6. CONCLUSIONS

This study demonstrated that the material properties measured by a tension test in work hardened Level 5 Nitronic 60 depend strongly on specimen size, location, and the cold working technique. The gyratory forging technique used by vendor 1 resulted in strength decreasing radially with distance from the central axis of the bar. In contrast, the conventional drawing technique used by vendor 2 (cold drawing) resulted in the opposite trend in which strength increased with distance from the central axis. The resulting tensile properties can vary substantially, especially if using small tensile bars such as ASTM R3 or R5 sizes. The cold drawing technique may result in somewhat more homogeneous material, but there is not enough data in this study to conclusively address that issue.

The high level of work hardening in level 5 Nitronic 60 results in stress strain curves with a curved elastic region. This is thought to be related to the variability in strength with radius. That is, each tensile bar has a gradient of yield strength so that it gradually yields at different regions in the material rather than yielding at one specific load. The apparent elastic modulus changes dramatically with loading; as a result, unambiguously determining the elastic modulus is difficult. This ambiguity in elastic modulus can propagate to uncertainty in yield strength. To address this challenge, modulus calculations in this study were standardized to include initial loading data with loads from 10–25% of tensile strength. As a result of these findings, specifications 7343200-7343207[3], revision J were modified to explicitly define rate and modulus determination to match the procedures outlined in this document.

As for the variability of measured properties of the material tested in this work, significant lot-to-lot and intra-lot variability was observed. This is true of all measured properties including elastic modulus, yield strength, ultimate tensile strength, and elongation to failure. Occasional outliers were present, sometimes due to test anomalies, but other times with no explanation for extremely high or low values of structural properties. Elongation to failure measurements appeared to be above specification requirements for all specimens tested. Yield and ultimate tensile strengths in a significant number of samples failed specifications. In particular, gyratory forged R1 samples taken from the center of the bar and R5 samples taken from the edge of the bar were found to be the weakest, often with tensile strengths below specifications.

Weibull plots of ultimate tensile strength indicate that the tensile strength specification does not have sufficient margin if the tensile testing methodology is not well controlled. One must consider the application, specimen type, and location. R3 and R5 specimens taken from the center of bars will meet this specification, but most other types and locations will not. Even if a center-cut R3 tensile bar meets specification, it does not mean that components cut from the edge of that bar should be accepted since the strength of the component may not match the strength of the tensile bar. Considering the spatial variability in structural properties and the large variability one might measure in tensile strength, care must be taken when designing with and acceptance testing Level 5 Nitronic 60 material. It is recommended that tensile bars be taken from the same radial location as the high-stress region of the component being considered.

REFERENCES

[1] Nitronic 60 Data sheet, https://www.hpalloy.com/Alloys/descriptions/NITRONIC60.aspx

[2] ASTM E8, Standard test methods for tension testing of metallic materials, ASTM International

[3] Sandia internal specifications 7343200-7343207, "Stainless Steel, Bar and Wire, UNS S21800 (Nitronic 60)", Sandia National Laboratories.

[4] Sandia internal specification 9949050, "Tensile Test Specimens for Metals", Sandia National Laboratories.

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