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GRCop-84 Rolling Parameter Study

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GRCop-84 Rolling Parameter Study

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Abstract

This report is a section of the final report on the GRCop-84 task of the Constellation Program and incorporates the results obtained between October 2000 and September 2005, when the program ended. NASA Glenn Research Center (GRC) has developed a new copper alloy, GRCop-84 (Cu-8 at.% Cr-4 at.% Nb), for rocket engine main combustion chamber components that will improve rocket engine life and performance. This work examines the sensitivity of GRCop-84 mechanical properties to rolling parameters as a means to better define rolling parameters for commercial warm rolling. Experiment variables studied were total reduction, rolling temperature, rolling speed, and post rolling annealing heat treatment. The responses were tensile properties measured at 23 and 500 °C, hardness, and creep at three stress-temperature combinations. Understanding these relationships will better define boundaries for a robust commercial warm rolling process.

The four processing parameters were varied within limits consistent with typical commercial production processes. Testing revealed that the rolling-related variables selected have a minimal influence on tensile, hardness, and creep properties over the range of values tested. Annealing had the expected result of lowering room temperature hardness and strength while increasing room temperature elongations with 600 °C (1112 °F) having the most effect. These results indicate that the process conditions to warm roll plate and sheet for these variables can range over wide levels without negatively impacting mechanical properties. Incorporating broader process ranges in future rolling campaigns should lower commercial rolling costs through increased productivity.

Introduction

NASA Glenn Research Center (GRC) has developed a new copper alloy, GRCop-84 (Cu-8 at.% Cr-4 at.% Nb), for rocket engine thrust chamber liners and injector plates to improve rocket engine life and performance, decrease maintenance and improve safety. This system first identified in 1986 has been carefully characterized and shows promise in bettering the rocket performance compared to the current Space Shuttle Main Engine (SSME) main combustion chamber liner material, NARloy-Z (Cu-3 wt.% Ag-0.5 wt.% Zr) (ref. 1). Research to define the manufacturing processes for GRCop-84 liners was initiated in 2000, and the final production route selected is reported elsewhere (ref. 2).

An important step in the GRCop-84 liner manufacturing process is warm rolling used to transform extruded billet into plate and sheet. Hot rolling at 857 °C (1575 °F) was previously examined internally by NASA GRC and was found to produce unacceptably low properties. The observation that copper anneals at much lower temperatures (ref. 3) and GRCop-84 has a nearly pure Cu matrix led to successful attempts to warm roll GRCop-84 at 300 °C (572 °F).

To facilitate the large reductions needed to transform extruded billet into plate and sheet, the rolling should be performed at temperatures as high as possible without degrading properties. When performed at

*Currently with HC Stark.

elevated temperatures ductility generally improves, strength decreases and the propensity for cracking and tearing decreases. This allows for larger reductions during each rolling pass. The material should also be rolled as much as possible prior to reheating to increase productivity.

This work examines the sensitivity of GRCop-84 mechanical properties to warm rolling parameters as a means to better define boundaries for a commercial warm rolling process. Experiment variables studied were total reduction, rolling temperature, rolling speed and post rolling annealing heat treatment. The responses were tensile properties measured at 23 and 500 °C (73 and 932 °F), hardness and creep properties at three stress-temperature combinations. Understanding these processing-property relationships will better define boundaries for a robust commercial warm rolling process and allow selection of the most economically advantageous processing conditions.

Experimental Procedure

Design of Experiments

A design of experiments (DOE) examining the sensitivity of GRCop-84 mechanical properties to rolling parameters was developed prior to rolling and testing. Experimental variables were total reduction (65, 95, and 99%), rolling temperature (215, 300 and 415 °C/419, 572, and 779 °F), rolling speed (5.2 and 21.0 m/min) and post rolling annealing heat treatment (250, 350, and 450 °C/422, 662 and 752 °F). Late in the testing when new data became available a fourth post rolling heat treatment at 600 °C (1112 °F) was added to the test matrix and most of the lower temperature post rolling heat treatments were dropped. The measured responses were 23 and 500 °C tensile properties, hardness, creep rate and rupture life. The DOE is listed in table I and gives the assignment of samples to the test conditions as well as the test conditions.

Rolling Stock Preparation

The GRCop-84 used was from three billet ends from Large Extrusions 1 and 2, the first two large extrusions. The billet ends were the remnants from preparing these extrusions for strip rolling and still retained the copper extrusion can. HC Stark, Euclid, was commissioned to saw the billet ends into pieces approximately 50.8 by 101.6 mm (2 by 4 in.). The thicknesses of the samples were nominally 12.7 mm (0.5 in.), 22.22 mm (0.875 in.) and 38.1 mm (1.5 in.). The pieces were cut from the blocks according to the scheme shown in figure 1. Not all of the pieces were useable because after extrusion the copper can thickness varied, and some copper was also sucked into the billet center during extrusion. Pieces with any remnants of the copper can were discarded and not used in this study. Each piece was identified by the notation system also shown in figure 1.

Rolling

Each block was assigned a set of process conditions and production run order as shown in table II. The processing conditions were partially randomized to minimize the effects of lurking processing variables as much as possible. Due to a problem encountered during the rolling that made the original piece unfit for testing, piece 3b2b had to be replaced with another piece from the same parent material processed in the same manner. The designation was retained for ease of tracking the material.

Each block was heated in air using an electric laboratory box furnace located adjacent to the rolling mill for approximately 20 min. Initially thermocouples contacting the blocks were used to determine when the block reached temperature. It was observed that when the furnace recovered and reached temperature closely matched the time the thermocouple contacting the blocks also reached temperature. Eventually, just monitoring the furnace control thermocouple was used as the indicator that the specimens attained the desired temperature.

All rolling was performed at HC Starck on a 2 high rolling mill with 40.6 cm (16 in.) diameter rolls designated #8 Mill by HC Starck. A rolling reduction schedule was determined and used to set the screw position of the rolling mill for each pass. An example is shown in table III, and the complete set of reduction schedules can be found in appendix A. Each pass represents an approximate 10% reduction in thickness. After each roll pass, the piece was reheated to the desired temperature to achieve as close as possible a constant rolling temperature during the entire rolling sequence.

The final sheet dimensions after rolling were approximately 115 mm (4.5 in.) by 140 mm (5.5 in.) by 4.3 mm (0.170 in.) thick for the 65% total reduction, 115 mm (4.5 in.) by 305 mm (12 in.) by 1.0 mm (0.040 in.) for the 95% total reduction and 115 mm (4.5 in.) by 305 mm (12 in.) by 0.8 mm (0.030 in.) thick for the 99% total reduction. After rolling and annealing as indicated by the DOE, each sample was chemically cleaned using a nitric acid-water pickling solution and hand wiped to remove as much of the surface and embedded oxide as possible.

Post rolling heat treatments were conducted at 250, 350, and 450 °C (422, 662, and 752 °F) to assess the effects of varying annealing temperatures upon the mechanical strength and therefore the recrystallization of the warm rolled GRCop-84. Within the DOE the post rolling heat treatment temperatures were limited to those above the rolling temperature so, for example, samples warm rolled at 300 °C were not annealed at 250 °C.

It was later learned that the minimum annealing temperature for complete recrystallization for 23% cold worked GRCop-84 is 600 °C (1112 °F) (ref. 5). Annealing at temperatures between 300 and 600 °C (572 and 1112 °F) produces a range in mechanical properties. The degree of recrystallization and hence the strength of the sheet was also found to be dependent on the amount of cold work below 600 °C. For <15% reductions the effect of cold work on the recrystallization temperature could be substantial. This confounds any attempt to identify the influence of the rolling parameters from remaining cold work in this study. Therefore, only a limited number of the planned 250, 350, and 450 °C (422, 662, and 752 °F) annealed specimens were actually tested.

Selected post rolling heat treatments at 600 °C was added to the DOE for comparison to the revised annealing procedure (ref. 5). These treatments were done by placing the specimens in sealed stainless steel envelopes obtained from the Sentry Company, (Foxboro, MA). Annealing of the samples was done in an argon atmosphere by backfilling and sealing the envelopes prior to thermal exposure. The samples were annealed at 600 °C for 30 min followed by an air cool.

Test Specimen Fabrication

From each rolling condition, longitudinal and transverse specimens were machined by wire EDM and used for the tensile and creep tests. The specimen design is shown in figure 2 and conforms to ASTM E8 (ref. 4). A reduced section that had a slight taper towards the middle was employed to ensure that the fracture would occur within the gauge length. The taper falls within the guidelines for ASTM E8. Longitudinal and transverse specimens from each rolled strip were assigned to the various tensile and creep test conditions as shown in table I.

Tensile Testing

Room and elevated temperature mechanical testing was performed at NASA GRC. Room temperature tensile testing following ASTM E8 was conducted in air using Instron 1125 and TT-series load frames upgraded for automated data acquisition and control. All tensile tests were conducted using strain rate control and a strain rate of 0.005 mm/mm/min (0.005 in./in./min). An MTS 632.13E-20 clip-on extensometer was used to measure the strain up to 15%. Above 15% the extensometer was removed, and the crosshead displacement was used to control the test and calculate strain. The yield strength was determined using a 0.2% offset.

Elevated temperature tensile testing was conducted at 500 °C (932 °F) in flowing argon using the same load frames. The samples were heated at a rate of at least 550 °C/h (990 °F/h) to temperature, held at temperature for 10 min to stabilize the temperature and tensile tested. An MTS 632.59B-04 high temperature extensometer was used to measure the strains up to 15%. Above 15% the crosshead displacement was used to control the test and determine the strain. A 0.2% offset was again used to calculate the yield strength.

The rolled sheets were tested in both the longitudinal direction and transverse direction to determine if the sheets developed measurable anisotropy.

Hardness

Hardness measurements were made using a New Age Tester Model ME-2 following ASTM E18 (ref. 5). The Rockwell B scale (HR_B) was used for all hardness measurements. The hardness tester was calibrated before each use with certified hardness standards.

Creep

Testing was conducted at NASA GRC using five constant load vacuum creep units built by the Brew Corporation. Chamber pressures of less than 1.1 Pa (8×10^{-6} torr) were obtained for all tests with most being conducted at less than 0.13 Pa (1×10^{-6} torr). Sample heating rates were 1000 °C/h (1800 °F/h) or more to test temperature. The samples were held for 5 min prior to starting the test to stabilize the temperature. The load was applied by hanging weights on the lever arm and lowering the jack that supported the weight pan. An electric drill was used to drive the jack screw to smoothly and consistently lower the jack and apply the load. A computer data acquisition system took readings of time, displacement and temperature at regular intervals. Typically readings were taken ever 1 sec for the first 10 min of life, every 10 sec until 2 hr of life, and every 300 sec from 2 hr until failure.

Samples were tested at 500 °C/105 MPa (932 °F/15.2 ksi), 650 °C/44.3 MPa (1202 °F/6.4 ksi) and 800 °C/17 MPa (1472 °F/2.5 ksi). The rolled sheets were tested in both the longitudinal direction and transverse direction at each condition to determine if any differences in rate or life were detectable.

Results and Discussion

Metallography

Selected SEM images of microstructures are shown in figure 3 comparing total reduction, rolling temperature and rolling speed with no post rolling annealing treatment. All of the microstructures appear to have similar grain sizes and distributions of Cr_2Nb particles. No easily discerned microstructural differences were observed between the various rolling conditions.

Tensile Strength

The complete tensile data set is presented in appendix B. To understand the influence of the rolling parameters examined in this study, the data was subdivided into two data sets: those that did not receive a post rolling heat treatment and those that did. The results of the set that did not receive a post rolling anneal heat treatment will be discussed first. The data was reordered in several ways to examine the influence of each rolling parameter.

Rolling Temperature

When the tensile properties of the unannealed sheet are arranged by rolling temperature as summarized in table IV and shown in figure 4, it was observed that room temperature yield strengths, ultimate tensile strengths and elongations were statistically equal at a 95% confidence level for all three rolling temperatures as determined by paired t-Test comparisons of the means. Orientation was not a statistically significant factor at a 95% level either.

Similarly at elevated test temperatures of 500 °C (932 °F), yield strength values between the various rolling temperatures (fig. 4(a)) and orientations were statistically equal at a 95% confidence level as determined by paired t-Tests. Ultimate strengths (fig. 4(b)) showed differences between 215, 300, and 415 °C at a 95% confidence level with 215 °C rolling temperature level being greater than 300 °C rolling temperature level and the 300 °C rolling temperature level being less than the 415 °C rolling temperature level. However, orientation did not produce statistically significant differences.

Fairly wide scatter was observed for the tensile elongations that may confound the ability to detect differences in the response with rolling temperature and other rolling parameters. Between the various rolling temperatures (fig. 4(c)), at a 95% confidence level the 215 °C rolling temperature elongation was less than the 300 °C rolling temperature elongation. The 300 °C rolling temperature elongation was equal to the 415 °C rolling temperature elongation at a 95% confidence level. At all three rolling temperatures orientation again did not have an effect at a 95% confidence level.

Based on these results, it was determined that rolling temperature over the range tested, 215 to 415 °C, had no effect on the room temperature tensile properties and minimal but statistically significant effects on the elevated temperature tensile properties of GRCop-84. Orientation played no role in the tensile properties indicating the sheets were isotropic and did not develop a strong texture. These results indicates any of the rolling temperatures are acceptable, and the temperature window for warm rolling GRCop-84 is at least 215 to 415 °C.

Total Reduction

When the tensile properties for the unannealed sheet are reordered by total reduction as summarized in table V and shown in figure 5 it was observed that room temperature yield strengths, ultimate strengths and elongations were different at a 95% confidence level based upon paired t-Tests. It was determined that the properties following a 65% total reduction were greater than the properties following both a 95 and 99% total reduction, but the properties following 95 and 99% total reductions were not statistically different. There was no difference at the 95% confidence level between the longitudinal and transverse orientations.

Similarly the 500 °C (932 °F), yield strengths for all total reductions (fig. 5(a)) were statistically equal at a 95% confidence level as determined by paired t-Tests. Ultimate tensile strength (UTS) (fig. 5(b)) showed differences where the UTS for a 65% total reduction is equal to the UTS for a 95% total reduction, but the UTS for a 95% total reduction is less than the properties for a 99% total reduction at a 95 % confidence level. Orientation did not show any statistically significant differences at a 95% confidence level.

For the data collected, the tensile elongation (fig. 5(c)) for a 65% total reduction is greater than the elongation for a 95% total reduction, and the elongation for a 95% total reduction is greater than the elongation for a 99% total reduction at a 95% confidence level. Orientation again did not have an effect at a 95% confidence level.

The higher strengths seen at the 65% total reduction level compared to the 95 and 99% reductions were not expected. Further investigation to determine the cause of the differences by comparing the microstructures (fig. 3) failed to identify reasons for these differences.

One possible explanation is there is a general trend observed in many materials that greater reductions tend to lower properties. In the extreme case, the number of grains through the thickness can be reduced to the point where grain boundary properties determine the macroscopic properties. This typically occurs around 50 grains through the thickness. Decreased properties were one concern for making GRCop-84 sheet. GRCop-84 sheet has not exhibited much reduction in properties, but this could be one area where a small yet detectable difference exists.

Based on these results, there were very minimal but statistically significant differences in the tensile properties over the range examined indicating that total reduction does have an influence on the mechanical properties of GRCop-84. The difference is small and will likely be minimized by subsequent annealing and production steps. No root cause was identified for the subtle difference of the room temperature strength of the 65% total reduction sheets. Orientation has no measurable effects on any of the properties tested. In practical terms, the processing window for total reduction is large and unlikely to have a real effect for combustion chamber applications.

Rolling Speed

When the tensile properties of the unannealed sheet is arranged by rolling speed as summarized in table VI and shown in figure 6 it was observed that room temperature and 500 °C yield strengths, ultimate strengths and elongations were statistically equal as determined by a t-test comparison of means at a 95% confidence level. Furthermore, orientation does not have any measurable effect on properties a the same confidence level.

Based upon these results, the rolling speed does not have an effect on properties over the range tested. There is a caveat that continued lowering of the rolling speed will eventually have an effect due to cooling of the rolling stock with time as it is being rolled and greater quenching of the rolling stock at slower rolling speeds. From a practical viewpoint, the speeds used are typical of those used in commercial production. Actual rolling times with the size plates and sheets used for the GRCop-84 task are typically much less than two seconds, so temperature differences from end to end due to cooling are minimal and should be covered by the range of rolling temperatures used in this study.

The results show that there is a large processing window for rolling speed for GRCop-84.

Tensile Fracture Surface

Selected SEM images of the tensile fracture surfaces are shown in figure 7 comparing total reduction, rolling temperature and rolling speed with no post rolling annealing treatment. No significant differences were observed between the various rolling conditions. This indicates that none of the factors examined caused any observable changes in the fracture mechanism of GRCop-84. The fracture surfaces are also consistent with other fracture surfaces observed during tensile testing of other GRCop-84 samples (ref. 6).

Post Rolling Anneal Temperature

When the tensile properties for the as-rolled sheets are compared to the sheets given a post rolling heat treatment at various temperatures it was observed that the post rolling heat treatment had the intended effect in lowering room temperature strength and increasing ductility as shown in table VII and figure 8. Furthermore, the 600 °C (1112 °F) heat treatment produced a lower average strength and higher average ductility compared to the lower temperature heat treatments.

These measured room temperature strengths after the heat treatments are slightly higher than the annealed yield strengths determined for GRCop-84 with 23% cold reduction by Ellis and Garg (ref. 7). Ellis and Garg reported average room temperature yield strengths of 220 MPa (31.9 ksi) were achieved for a 600 °C/30 min/AC anneal. This work using a 600 °C heat treatment showed a 33% higher average room temperature yield strength of 293 MPa (42.5 ksi). One possible reason for this difference is that the 15% reductions per pass and reheats after each pass did not induce enough residual strain energy to cause complete recrystallization. There is evidence in the work done by Ellis and Garg as well as others that the amount of residual cold work has a strong influence on the recrystallization (ref. 6).

No differences between as-rolled and heat treated properties were observed at 500 °C. The similar strengths at all of the 500 °C tensile tests results from the low flow strength and high dislocation mobility which appears to overwhelm any influence that changes in the annealing heat treatments might contribute. The 500 °C test temperature also acts as an additional heat treatment that could overwhelm the effects of lower temperature heat treatments as well if the time at temperature is sufficient to partially or completely anneal the GRCop-84 specimens.

These results appear to indicate that a minimum reduction or stored energy imparted by working at a sufficiently low temperature is required to achieve complete recrystallization in GRCop-84. This is consistent with the results for pure copper (refs. 3 and 8). In practice GRCop-84 plates and sheets will be warm rolled without reheating after every pass. The finishing temperature will be around 200 °C based upon past experience (ref. 2). The amount of remaining work after the warm rolling even if dynamic recrystallization occurs appears to be sufficient to allow complete recrystallization at 600 °C (ref. 7). It is unclear how much lower the annealing temperature can be for warm rolled material, but the results of this study indicate using a 600 °C annealing temperature is preferable to using lower temperatures since it ensures complete annealing. The work by Ellis and Garg (ref. 5) also shows that higher temperatures are generally suitable as well. However, they are not preferred due to cost and grain growth.

Taken together these results indicate that the annealing temperature must be at least 600 °C and that the amount of work remaining in the material after rolling will play a significant role in determining the final tensile properties.

Hardness

The entire hardness data set is presented in appendix C. A summary of the hardness measurements is presented in table VIII and shown in figure 9. Paired t-Test comparison of means was not performed for the hardness data, but qualitatively the same responses observed for the tensile properties were also observed for hardness. The hardness as a function of total reduction confirms the result observed in tensile testing that the 65% total reduction sheet is stronger. The change in hardness as a function of post rolling heat treatment temperature trends are similar to that presented for tensile properties as shown in figures 8(a) and (b).

The results also show that the hardness of the material can be used for production quality assurance during warm rolling if needed. A wider range of hardnesses and strengths would be required to develop a correlation between the two properties, but, for example, hardness ranges can be used to differentiate between properly and improperly annealed GRCop-84.

Creep

The creep lives were determined at three temperature-stress combinations, and the data is presented in appendix D. The summary of the results is presented in table IX. Because no effect of orientation was observed in tensile testing and two of the three creep test temperatures were expected to result in complete recrystallization, no effort was made to determine if there was an orientation effect on creep properties.

Figure 10 shows a Monkman-Grant plot of creep life versus creep rate. The data from all three temperature-stress combinations falls on a single trend line indicating a consistent creep behavior within this data set. The 95% confidence interval for the least squares regression is also plotted in figure 10. Most of the data points fall within the 95% confidence limits as expected for a large data set such as this one, and no probable outliers or indications of adverse changes from the various processing routes were observed.

A plot of creep life versus applied stress is presented in figure 11. Variation of creep properties is larger than desired because of temperature issues that were later corrected (ref. 9). However the results can still be used to compare means for large differences and detect gross changes in the creep properties of GRCop-84.

The results show that the creep life is independent of rolling temperature. Examining creep life as a function of total reduction and rolling speed showed similar lack of correlation. Figure 11 also includes baseline as-extruded GRCop-84 data (refs. 10 and 11) for comparison. The creep life for the sheet falls at or below the lower 95% confidence interval. This is consistent with other observations of sheet creep lives (refs. 12 and 13). No root cause has been determined for the lower creep properties for rolled sheet yet.

The average creep rate when this data is pooled at each test temperature-stress level is also presented in table IX. No discernable differences in the creep rate were observed. A plot of creep rate versus stress (fig. 12) similarly illustrates no dependency of creep rate upon rolling temperature. The plot also includes GRCop-84 as-extruded average creep rate (ref. 8) for comparison. The creep rate for the sheet falls above the as-extruded average which is again consistent with other sheet creep results (refs. 11 and 12).

The elevated temperatures used for creep testing minimize the differences in properties that might be observed as was noted with the 500 °C tensile properties. However, the lack of detectable changes indicates that processing has no effect on the creep properties of GRCop-84, and the processing window for GRCop-84 is again very wide.

Implications for GRCop-84 Plate and Sheet Production

The data taken as a whole consistently indicate that GRCop-84 can be processed over a very wide range of rolling conditions and still provide consistent mechanical properties. If any of the rolling related parameters examined greatly affected the final properties, everything from the starting rolling stock thickness to the rolling temperature to the rolling speed would need to be controlled much more closely during production. While possible to do so, the extra control will add time and complexity to the production process and therefore cost.

As one example, if GRCop-84 required a rolling temperature between 300 and 350 °C experience indicates that the pieces would need to be reheated approximately every third pass when 63 mm (2.5 in.) thick starting stock is converted to 13 mm (0.5 in.) thick plate. With the wide rolling temperature window demonstrated for GRCop-84 by this study, the starting stock can be converted to plate without reheating. This cut the time required to make the plates by half or more. Since the rolling was done as a toll operation and mill time was what was being bought in this program, the decrease in time required for the rolling reduced the rolling cost by approximately 50%. Similar reductions in cost would be expected for commercially produced GRCop-84 plate.

The rate of scrap production is generally greater for processes that have very tight tolerances. By having a very wide production window the expected rejection rate for failing to meet production parameter requirements is expected to be small. In practice over three commercial rolling campaigns no warm rolled plate or sheet had to be scrapped. The lack of waste material directly translates into cost savings and an overall lower GRCop-84 plate and sheet cost.

Conclusions and Recommendations

Three rolling parameters were varied within limits consistent with typical commercial production processes. The experimental variables selected - total reduction, rolling speed and rolling temperature - have very slight to no influence on tensile, hardness and creep properties at the values tested.

Post rolling heat treatments had the expected result of lowering room temperature hardness and strength while increasing room temperature elongations. In the temperature range tested, a 600 °C (1112 °F) heat treatment had the most effect.

These results indicate that the process conditions to warm roll GRCop-84 sheet can range over wide levels without negatively impacting mechanical properties. Incorporating broader process ranges in future rolling campaigns should lower commercial rolling costs through decreased scrap and increased productivity.

It is recommended that the warm rolling temperature range be increased to 200 to 400 °C (392 to 752 °F), and the rolling speed should be set between 5 meters per minute and 21 meters per minute in future rolling campaigns. The total reduction can be whatever is needed to achieve the final thickness from the starting stock. Annealing should be conducted at 600 °C to ensure complete recrystallization and a full anneal in the warm rolled GRCop-84.

Future Work

Two areas should be examined further:

1. The cause of the higher strengths and hardness for the 65% total reduction compared to the 95 and 99% total reductions is unknown. Additional microscopy may help reveal the cause.
2. The tensile strengths of sheets annealed at 600 °C (1112 °F) following a 15% warm reduction in this study were greater than comparable 23% cold work sheet tested elsewhere in this project. Further examination of the relationship between the amount of residual work and annealing temperature may be required to ensure consistent complete annealing.

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TABLE I.—DESIGN OF EXPERIMENTS (DOE) CONDITIONS AND SPECIMEN ASSIGNMENT

	Tensile				Creep			Rolling conditions			
Sample ID	RT-1	RT-2	500 °C -1	500 °C-2	500	650	800	Rolling temperature, (°C)	Reduction, (%)	Speed, (m/min)	Anneal, (°C)
3a5c	T4	T6	T5	T8	T3	T2	T1	215	65	5.2	0
3a5d	L4	T1	L2	T2	L1	L3	L5	215	65	5.2	0
1a2b	L4	T1	L2	T2	L1	L3	L5	215	65	21.0	0
1a2c	L4	T1	L2	T2	L1	L3	L5	215	65	21.0	0
1a3c	L2	T1	L4	T2	L1	L3	L5	215	95	5.2	0
3a4b	L2	T1	L1	T2	L1	L3	L5	215	95	5.2	0
3a4c	L4	T1	L2	T2	L1	L3	L5	215	95	21.0	0
8a8a	L3	L2	L1	T1	T2	L5	L4	215	99	21.0	0
1a2d	L3	L2	L1	T1	T2	L5	L4	300	65	5.2	0
2a2b	T2	L4	T1	L1	L3	L5	L2	300	65	5.2	0
2a2c	L5	T1	L3	L4	L1	T2	L2	300	65	21.0	0
1a4b	L3	L2	L1	T1	T2	L5	L4	300	95	5.2	0
1a5c	L3	T1	L3	L4	L1	T2	L2	300	95	5.2	0
1a4c	L1	T2	L3	T1	L5	L2	L4	300	95	21.0	0
2a3b	L2	T1	T2	L3	L4	L1	L5	415	65	5.2	0
2a3d	T1	L5	L3	L2	T2	L1	L4	415	65	21.0	0
1a3b	L1	L5	T1	L2	T1	T2	L4	415	95	5.2	0
1a5b	T1	L5	L3	L6	L2	L4	T2	415	95	21.0	0
3a2b	L2	T1	L5	T2	L1	L3	L4	415	99	21.0	0
3a2b-250	L5	T1	L3	L4	L1	T2	L2	415	99	21.0	250
1a4b-350	T2	L4	T1	L1	L3	L5	L2	300	95	5.2	350
1a5c-350	L4	T2	L1	L5	L3	T1	L2	300	95	5.2	350
3a2b-350	L4	T2	L1	L5	L3	T1	L2	415	99	21.0	350
2a4c-450	L4	T1	L2	T2	L1	L3	L5	215	65	5.2	450
2a4d-450	L3	L5	L2	T1	T2	L1	L4	215	65	5.2	450
2a5b-450	T1	L5	L3	L1	L2	L4	T2	215	65	21.0	450
2a5c-450	L1	L3	T1	T2	L5	L4	L2	215	65	21.0	450
1a3c-450	L4	T1	L2	T2	L1	L3	L5	215	95	5.2	450
3a4b-450	L4	T1	L2	T2	L1	L3	L5	215	95	5.2	450
3a4c-450	L4	T1	L2	T2	L1	L3	L5	215	95	21.0	450
8a8a-450	L5	T1	L3	L4	L1	T2	L2	215	99	21.0	450
2a5d-450	L2	T1	L5	T2	L1	L3	L4	300	65	5.2	450
2a2d-450	L4	T2	L1	L5	L3	T1	L2	300	65	21.0	450
1a4b-450	L3	L5	L2	T1	T2	L1	L4	300	95	5.2	450
1a5c-450	L2	T1	T2	L3	L4	L1	L5	300	95	5.2	450
1a4c-450	T1	L5	L3	L2	T2	L1	L4	300	95	21.0	450
2a3c-450	L1	T2	L3	T1	L5	L2	L4	415	65	5.2	450
2a4b-450	L3	L5	L1	L2	T1	T2	L4	415	65	21.0	450
1a3b-450	L3	L5	L2	T1	T2	L1	L4	415	95	5.2	450
1a5b-450	T2	L4	T1	L1	L3	L5	L2	415	95	21.0	450
3a2b-450	L4	T1	L2	T2	L1	L3	L5	415	99	21.0	450

TABLE II.—SPECIMEN FABRICATION PRODUCTION ORDER AND PROCESS CONDITIONS

Process order	Roll temperature, (°C)	Total reduction, (%)	Roll speed, (mpm)	Final anneal, (°C)	Start thickness, (in.)	Final thickness, (in.)	Piece identity	No. pres
1	215	95	5.2	no	0.875	0.040	3A4B	3
2	215	95	21.0	no	0.875	0.040	3A4C	3
3	215	65	5.2	no	0.500	0.172	3A5C	1
4	215	65	5.2	no	0.500	0.172	3A5D	1
5	215	65	21.0	no	0.500	0.172	1A2B	1
6	215	65	21.0	no	0.500	0.172	1A2C	1
7	415	95	21.0	no	0.875	0.040	1A5B	3
8	215	99	21.0	no	1.500	0.033	3B2B	0
9	415	99	21.0	no	1.500	0.033	3A2B	4
10	300	95	5.2	no	0.875	0.040	1A5C	3
11	300	95	5.2	no	0.875	0.040	1A4B	3
12	300	95	21.0	no	0.875	0.040	1A4C	3
13	415	95	5.2	no	0.875	0.040	1A3B	3
14	300	65	5.2	no	0.500	0.172	1A2D	1
15	300	65	5.2	no	0.500	0.172	2A2B	1
16	300	65	21.0	no	0.500	0.172	2A2C	1
17	300	65	21.0	no	0.500	0.172	2A2D	1
18	415	65	5.2	450	0.500	0.172	2A3B	1
19	415	65	5.2	450	0.500	0.172	2A3C	1
20	415	65	21.0	450	0.500	0.172	2A3D	1
21	415	65	21.0	450	0.500	0.172	2A4B	1
22	215	65	5.2	450	0.500	0.172	2A4C	1
23	215	65	5.2	450	0.500	0.172	2A4D	1
24	215	65	21.0	450	0.500	0.172	2A5B	1
25	215	65	21.0	450	0.500	0.172	2A5C	1
26	300	65	5.2	450	0.500	0.172	2A5D	1
27	215	95	5.2	450	0.875	0.040	1A3C	2
							Total	44

TABLE III.—BASELINE ROLLING SCHEDULES

		Total reduction		
Pass	Per pass reduction, %	65%	95%	99%
0	---	0.500	0.900	1.500
1	7.5	0.463	0.833	1.388
2	10	0.416	0.749	1.249
3	10	0.375	0.674	1.124
4	10	0.337	0.607	1.011
5	10	0.303	0.546	0.910
6	10	0.273	0.492	0.819
7	10	0.246	0.442	0.737
8	10	0.221	0.398	0.664
9	10	0.199	0.358	0.597
10	10	0.179	0.323	0.538
11	10	0.161	0.290	0.484
12	10	0.145	0.261	0.435
13	10	END	0.235	0.392
14	10	---	0.212	0.353
15	10	---	0.190	0.317
16	10	---	0.171	0.286
17	10	---	0.154	0.257
18	10	---	0.139	0.231
19	10	---	0.125	0.208
20	10	---	0.112	0.187
21	10	---	0.101	0.169
22	10	---	0.091	0.152
23	10	---	0.082	0.137
24	10	---	0.074	0.123
25	10	---	0.066	0.111
26	10	---	0.060	0.100
27	10	---	0.054	0.090
28	10	---	0.048	0.081
29	10	---	0.044	0.073
30	10	---	0.039	0.065
31	10	---	END	0.059
32	10	---	---	0.053
33	10	---	---	0.048
34	10	---	---	0.043
35	10	---	---	0.039
36	10	---	---	0.035
37	10	---	---	0.031
38	10	---	---	0.028
--	---	---	---	END

TABLE IV.—TENSILE PROPERTIES AS A FUNCTION OF ROLLING TEMPERATURES

	Rolling temperature, (˚C)	Test temperature, (˚C)	Average	Std dev	Sample size	Hypothesis	t value	Accept hypothesis 95% CL
Yield strength (MPa)	215	23	457.2	35.5	10	215 = 300	0.764	Y
	300	23	466.7	17.0	10	300 = 415	1.637	Y
	415	23	455.8	12.4	10	415 = 215	0.116	Y
	215	500	139.7	11.8	10	215 = 300	0.187	Y
	300	500	140.4	5.0	10	300 = 415	1.058	Y
	415	500	142.7	4.3	10	415 = 215	0.744	Y
Ultimate strength, (MPa)	215	23	526.6	37.6	10	215 = 300	0.346	Y
	300	23	530.9	12.7	10	300 = 415	0.855	Y
	415	23	526.4	10.6	10	415 = 215	0.011	Y
	215	500	162.0	5.3	10	215 = 300	2.419	**N**
	300	500	156.9	4.0	10	300 = 415	2.570	**N**
	415	500	164.0	7.8	10	415 = 215	0.672	Y
Elongation, %	215	23	12.5	1.6	9	215 = 300	1.580	Y
	300	23	14.5	3.3	10	300 = 415	0.474	Y
	415	23	13.8	2.9	10	415 = 215	1.141	Y
	215	500	13.0	2.0	10	215 = 300	3.493	**N**
	300	500	16.1	2.0	10	300 = 415	1.171	Y
	415	500	18.3	5.5	10	415 = 215	2.983	**N**

TABLE V.—TENSILE PROPERTIES AS A FUNCTION OF ROLLING REDUCTIONS

	Total rolling reduction, %	Test temperature, (˚C)	Average	Std dev	Sample size	Hypothesis	t value	Accept hypothesis 95% CL
Yield strength, (MPa)	65	23	474.5	21.7	14	65 = 95	3.575	**N**
	95	23	447.5	18.0	14	95 = 99	0.238	Y
	99	23	444.4	7.3	2	99 = 65	1.895	Y
	65	500	141.4	5.5	14	65 = 95	0.378	Y
	95	500	140.3	9.8	14	95 = 99	0.189	Y
	99	500	141.7	7.3	2	99 = 65	0.058	Y
Ultimate strength, (MPa)	65	23	538.7	23.0	14	65 = 95	2.5833	**N**
	95	23	517.6	20.0	14	95 = 99	0.5297	Y
	99	23	525.4	7.8	2	99 = 65	0.7894	Y
	65	500	160.0	4.9	14	65 = 95	0.1032	Y
	95	500	159.8	5.2	14	95 = 99	4.0383	**N**
	99	500	176.2	7.3	2	99 = 65	4.1645	**N**
Elongation, %	65	23	15.3	2.0	14	65 = 95	3.9422	**N**
	95	23	11.8	2.5	13	95 = 99	1.1236	Y
	99	23	13.9	0.1	2	99 = 65	0.9416	Y
	65	500	17.7	4.9	14	65 = 95	2.1181	**N**
	95	500	14.7	2.1	14	95 = 99	2.5960	**N**
	99	500	10.8	0.1	2	99 = 65	1.9440	Y

TABLE VI.—TENSILE PROPERTIES AS A FUNCTION OF ROLLING SPEED

	Rolling speed, (m/min)	Test temperature, (˚C)	Average	Std dev	Sample size	Hypothesis	t value	Accept hypothesis 95% CL
Yield strength, (MPa)	5.2	23	465.5	23.6	18	5.2 =21	1.646	Y
	21.0	23	451.5	21.6	12			
	5.2	500	141.3	8.3	18	5.2 =21	0.324	Y
	21.0	500	140.4	6.9	12			
Ultimate strength, (MPa)	5.2	23	529.2	26.8	18	5.2 =21	0.350	Y
	21.0	23	526.1	16.7	12			
	5.2	500	161.0	5.2	18	5.2 =21	0.039	Y
	21.0	500	161.1	8.3	12			
Elongation, (%)	5.2	23	13.2	3.3	17	5.2 =21	1.062	Y
	21.0	23	14.3	1.6	12			
	5.2	500	15.8	4.1	18	5.2 =21	0.029	Y
	21.0	500	15.9	4.2	12			

TABLE VII.—TENSILE PROPERTIES AFTER POST ROLLING HEAT TREATMENT

	Post rolling heat treatment, (°C)	Test temperature, (˚C)	Average	Std dev	Sample size	Hypothesis	t value	Accept hypothesis 95% CL
Yield strength, (MPa)	0	25	459.9	23.5	30	0 = 350	9.710	N
	350	25	295.1	12.7	2	0 = 450	12.374	N
	450	25	324.1	40.2	8	0 = 600	17.387	N
	600	25	293.0	42.9	15	350 = 450	0.969	Y
	---	---	-----	----	--	350= 600	0.068	Y
	---	---	-----	----	--	450 = 600	1.713	Y
	0	500	140.9	7.7	30	0 = 350	0.363	Y
	350	500	138.9	1.5	2	0 = 450	1.028	Y
	450	500	138.0	4.9	8	350 = 450	0.259	Y
Ultimate strength, (MPa)	0	25	528.0	23.0	30	0 = 350	5.996	N
	350	25	428.9	7.8	2	0 = 450	9.496	N
	450	25	438.5	26.4	8	0 = 600	13.697	N
	600	25	430.5	23.0	16	350 = 450	0.492	Y
	---	---	-----	---	--	350= 600	2.394	Y
	---	---	-----	---	--	450 = 600	0.767	Y
	0	500	161.0	6.5	30	0 = 350	0.074	Y
	350	500	161.3	0.0	2	0 = 450	0.035	Y
	450	500	160.9	5.3	8	350 = 450	0.110	Y
Elongation, %	0	25	13.6	2.8	29	0 = 350	4.394	N
	350	25	22.8	4.8	2	0 = 450	4.140	N
	450	25	18.7	4.0	8	0 = 600	9.170	N
	600	25	26.0	6.2	15	350 = 450	1.281	Y
	---	---	-----	---	--	350= 600	0.687	Y
	---	---	-----	---	--	450 = 600	3.002	N
	0	500	15.7	4.1	30	0 = 350	1.652	Y
	350	500	20.9	7.3	2	0 = 450	0.160	Y
	450	500	16.1	4.4	8	350 = 450	1.249	Y

TABLE VIII.—HARDNESS DATA

		Hardness, (HR_B)	Std dev	Sample size
Rolling temperature, (°C)	215	81.9	7.3	4
	300	82.4	2.8	5
	415	80.8	1.2	5
Total reduction, %	65	84.6	2.7	7
	95	78.5	2.7	6
	99	80.1	---	1.0
Rolling speed, (m/min)	5.2	81.6	4.9	9
	22	81.9	1.9	5
Post rolling heat treatment temperature, (°C)	0	81.7	4.0	14
	350	68.5	6.5	3
	450	68.7	4.2	16
	600	56.0	5.5	16

TABLE IX.—CREEP PROPERTIES

Test condition		Creep rate, (1/s)	Creep life, (h)
500 °C/105 MPa	Average	9.57E-05	2.8
	Std Dev	2.20E-04	2.4
	Sample Size	17	17
650 °C/44.3 MPa	Average	6.04E-05	3.1
	Std Dev	1.37E-04	3.0
	Sample Size	19	19
800 °C/17 MPa	Average	1.22E-05	17.7
	Std Dev	2.66E-05	18.2
	Sample Size	14	14

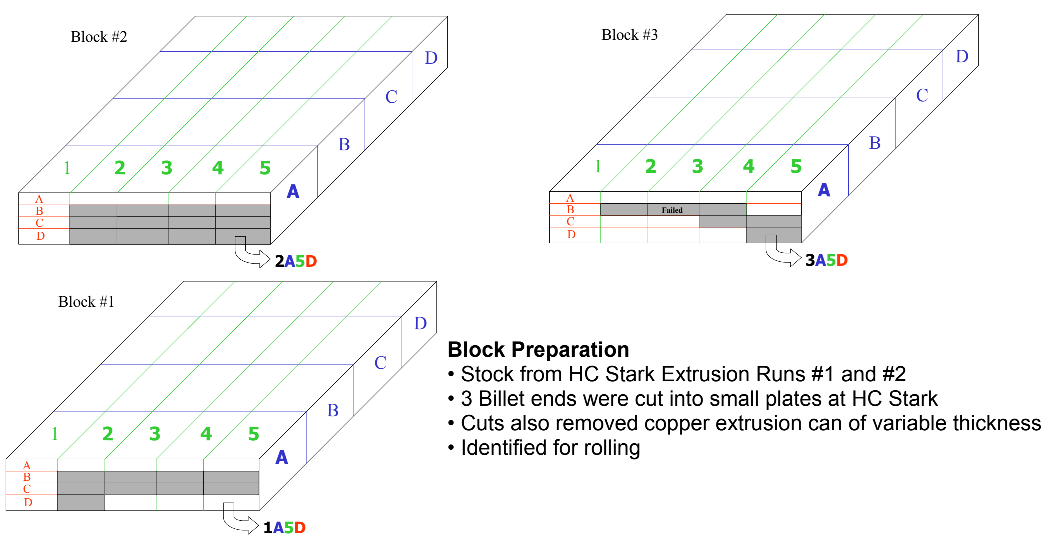


Figure 1.—Rolling block cutting and identification system used.

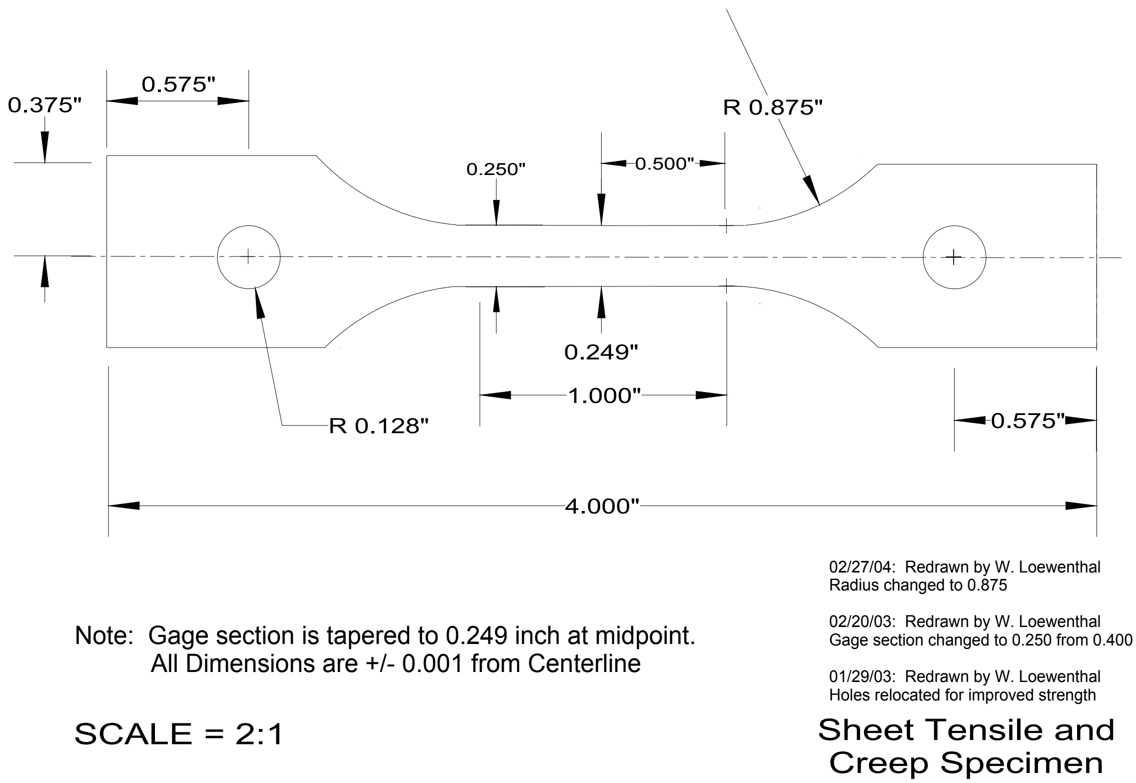
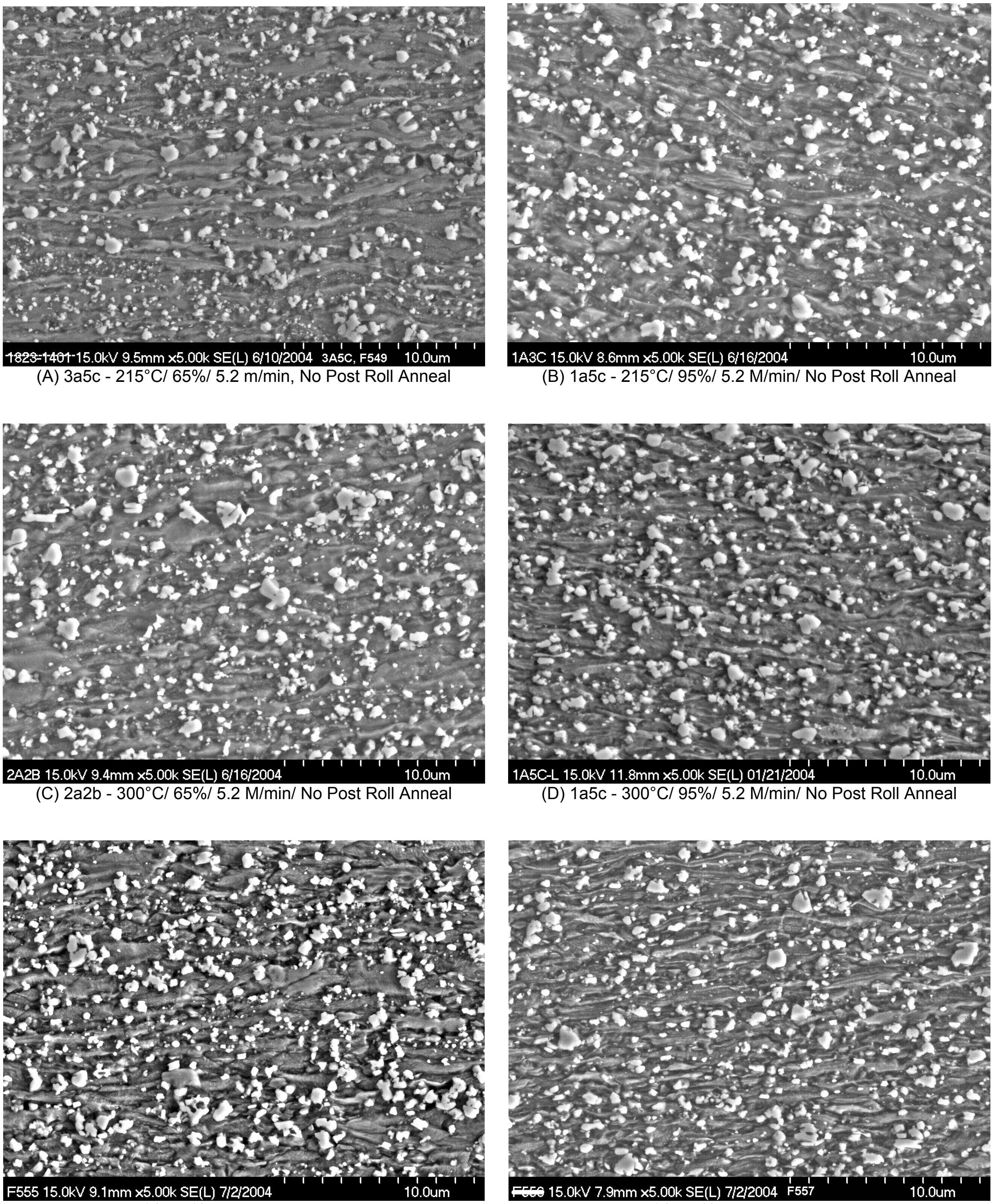


Figure 2.—Longitudinal and transverse tensile and creep specimen design.



(A) 3a5c - 215°C/ 65%/ 5.2 m/min, No Post Roll Anneal

(B) 1a5c - 215°C/ 95%/ 5.2 M/min/ No Post Roll Anneal

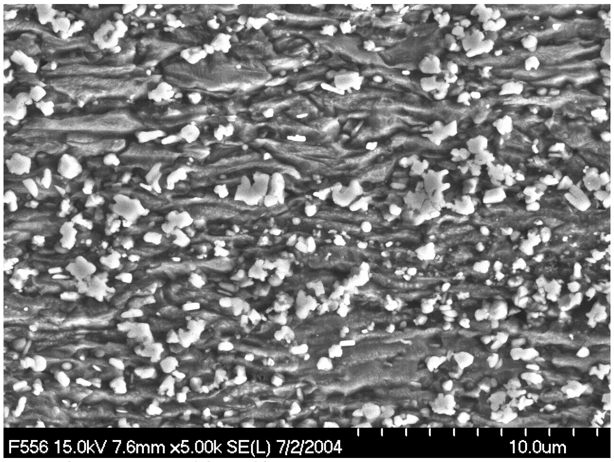
(C) 2a2b - 300°C/ 65%/ 5.2 M/min/ No Post Roll Anneal

(D) 1a5c - 300°C/ 95%/ 5.2 M/min/ No Post Roll Anneal

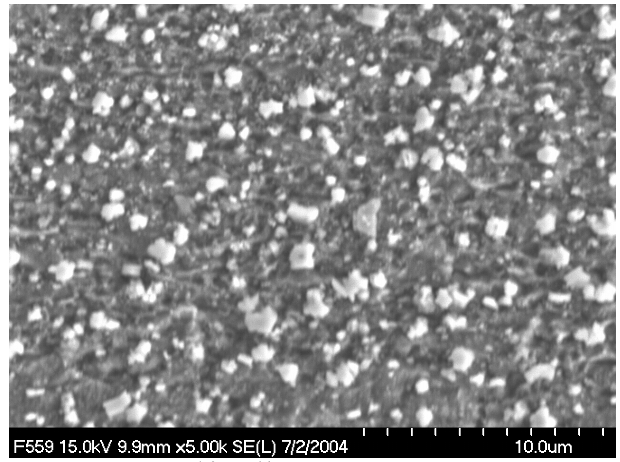
(E) 2c3b - 415°C/ 65%/ 5.2 M/min/ No Post Roll Anneal

(F) 1a3b - 415°C/ 95%/ 5.2 Mpm/ No Post Roll Anneal

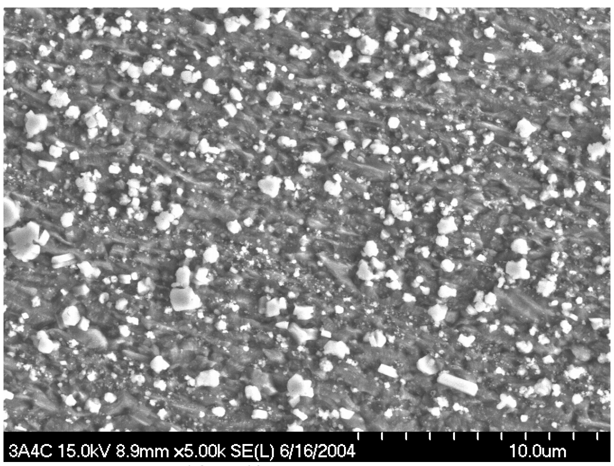
Figure 3.—Scanning Electron Microscope (SEM) images of as-rolled GRCop-84 samples.



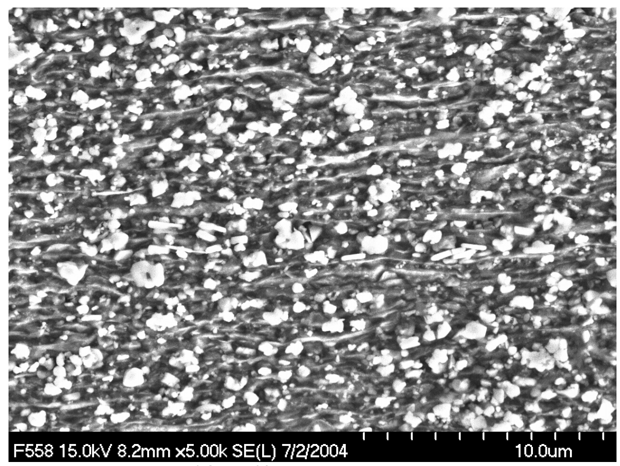
(G) 2a3d - 415°C/ 65%/ 5.2 Mpm/ No Post Roll Anneal



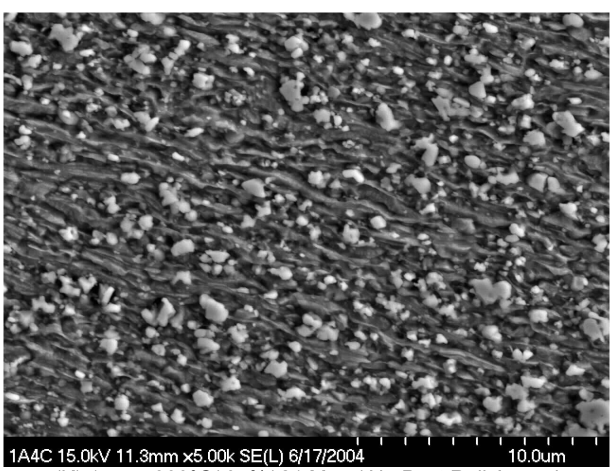
(H) 3a2b - 415°C/ 99%/ 21 Mpm/ No Post Roll Anneal



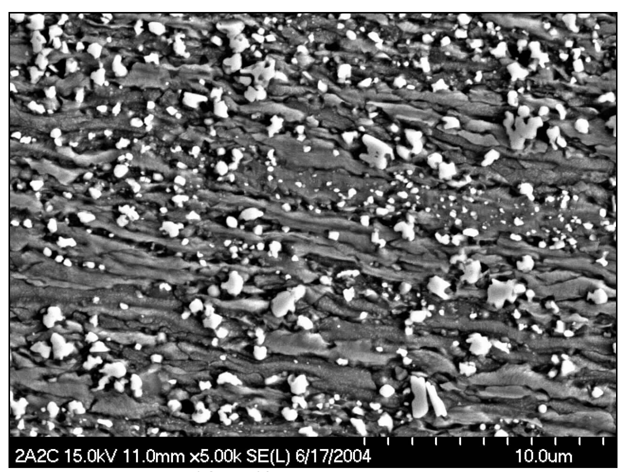
(I) 3a4c - 215°C/ 95%/ 21 Mpm/ No Post Roll Anneal



(J) 1a5b - 415°C/ 95%/ 21 Mpm/ No Post Roll Anneal



(K) 1a4c - 300°C/ 95%/ 21 Mpm/ No Post Roll Anneal



(L) 2a2c - 300°C/ 65%/ 21 Mpm/ No Post Roll Anneal

Figure 3.—Concluded.

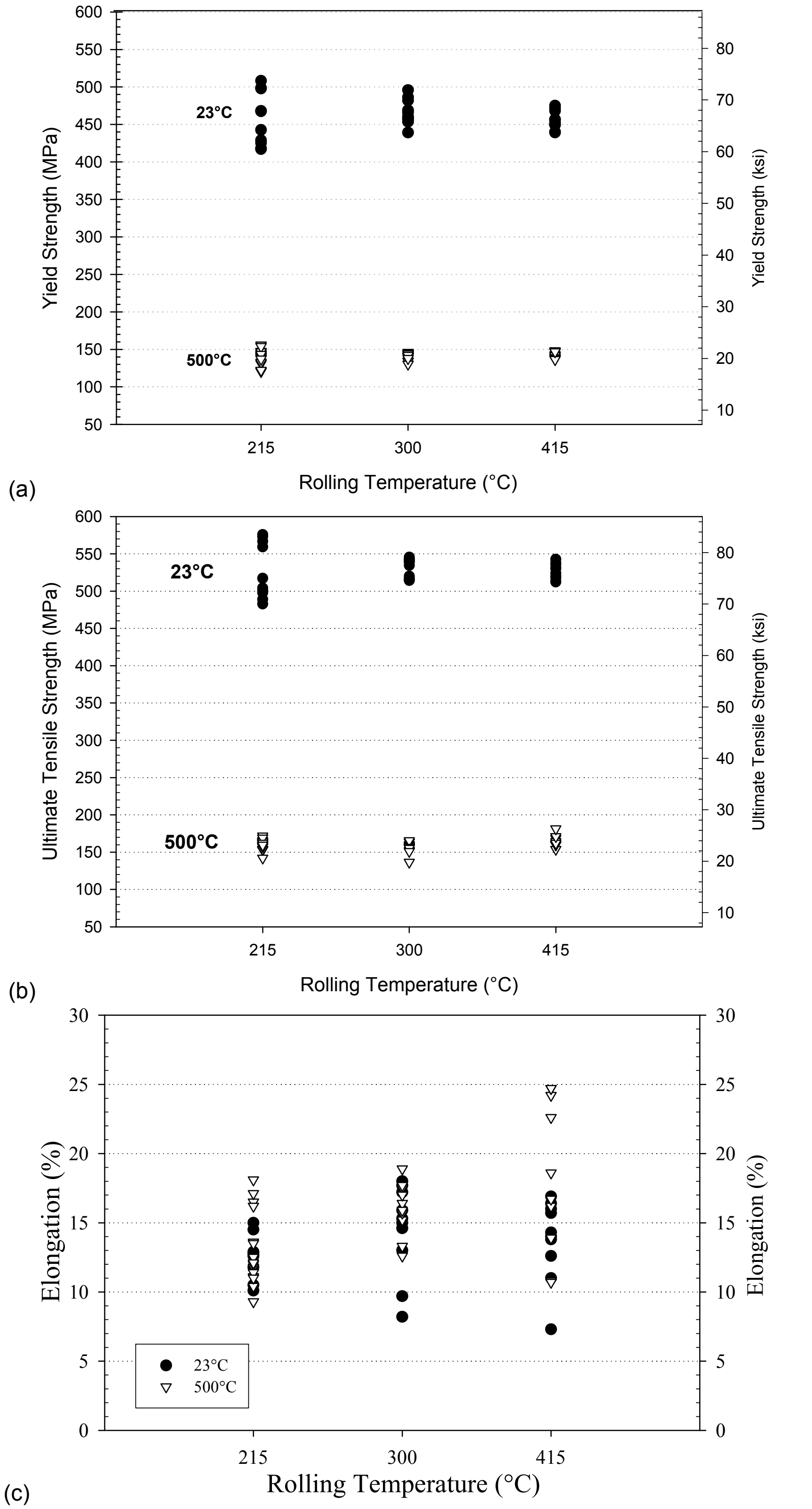


Figure 4.—(a) Effect of rolling temperature on as-rolled 0.2% offset yield strength. (b) Effect of rolling temperature on as-rolled ultimate tensile strength. (c) Effect of rolling temperature on tensile elongation.

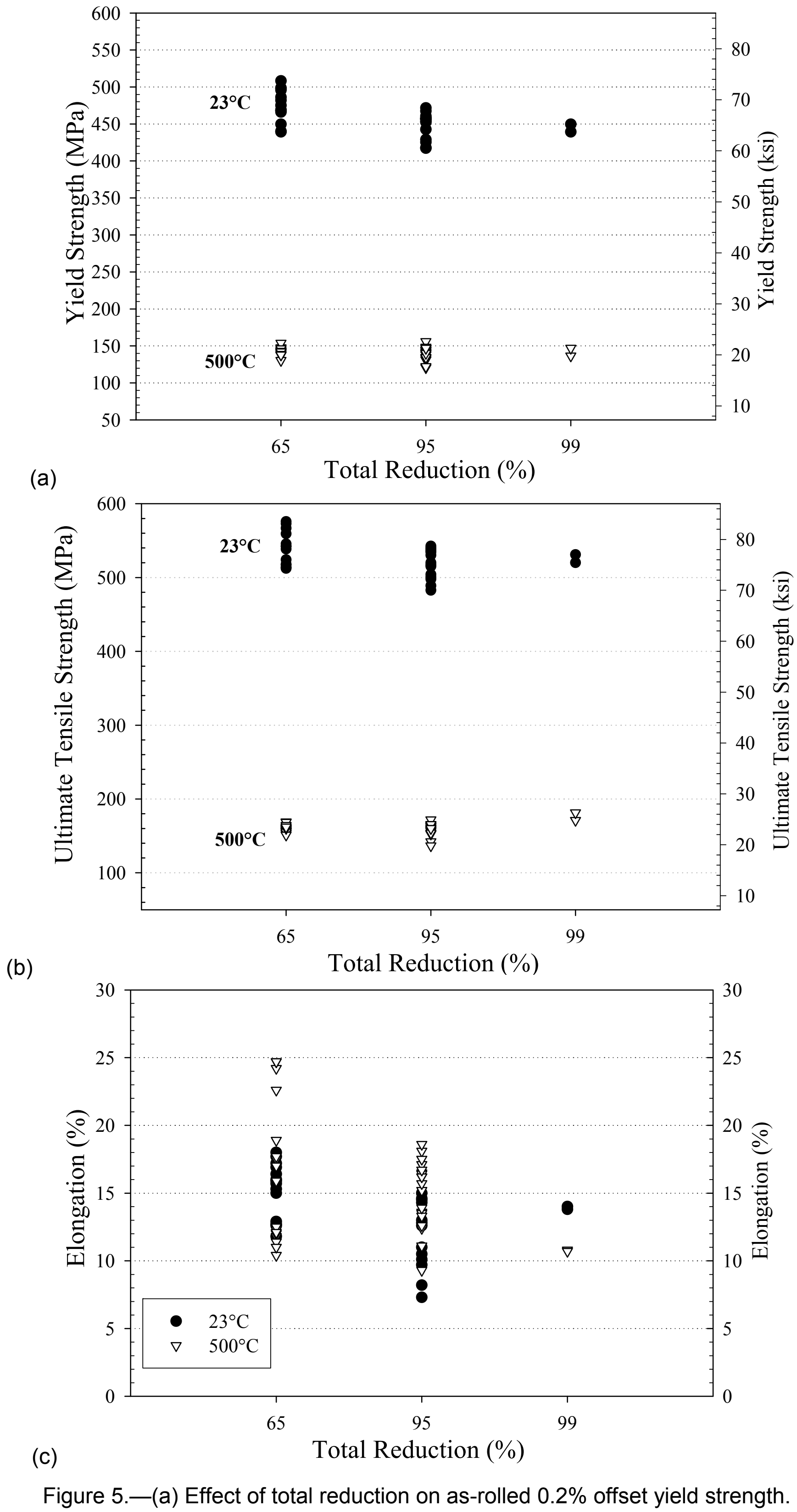


Figure 5.—(a) Effect of total reduction on as-rolled 0.2% offset yield strength. (b) Effect of total reduction on as-rolled ultimate tensile strength. (c) Effect of total reduction on as-rolled tensile elongation.

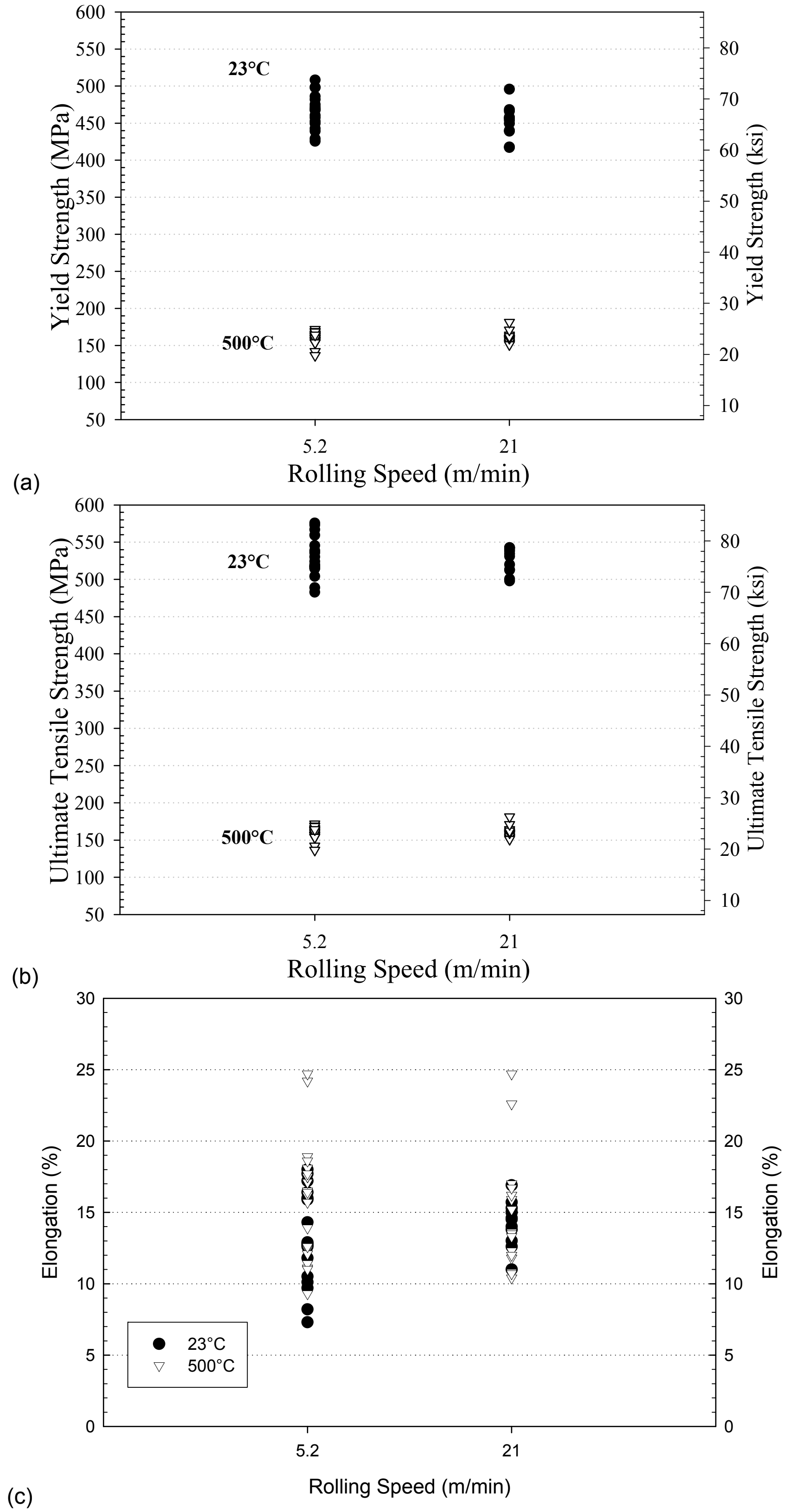
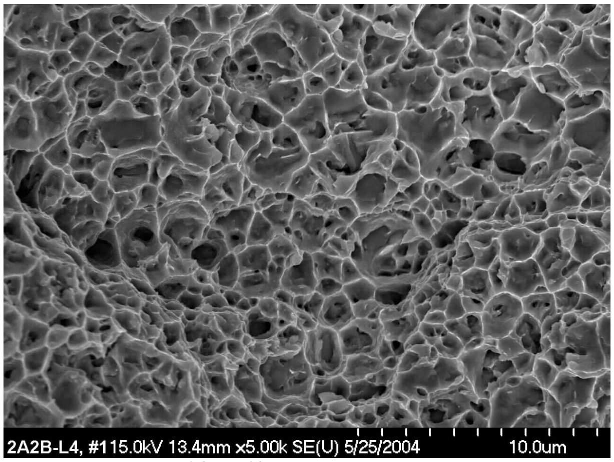
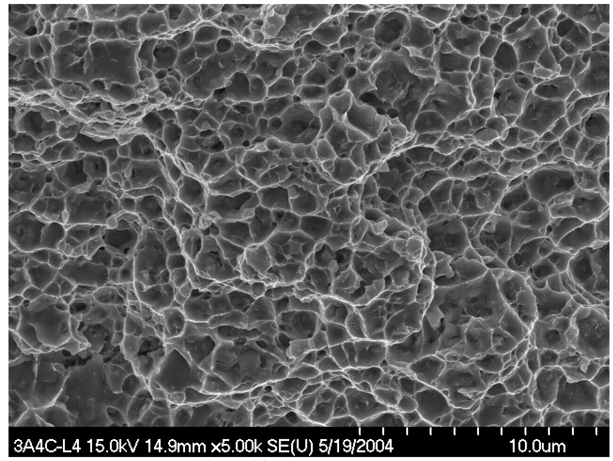


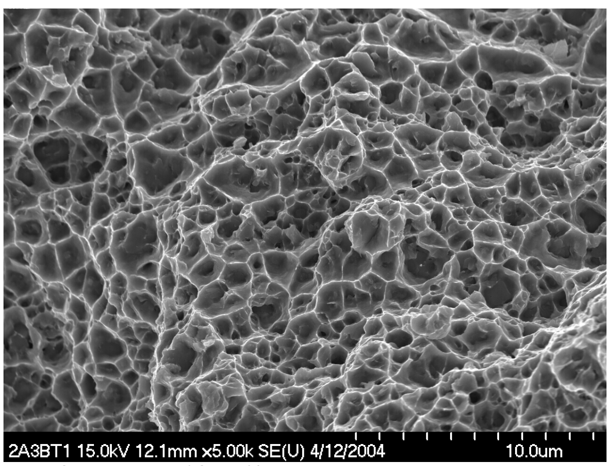
Figure 6.—(a) Effect of rolling speed on as-rolled 0.2 % offset yield strength.
(b) Effect of rolling speed on as-rolled ultimate tensile strength.
(c) Effect of rolling speed on as-rolled tensile elongation.



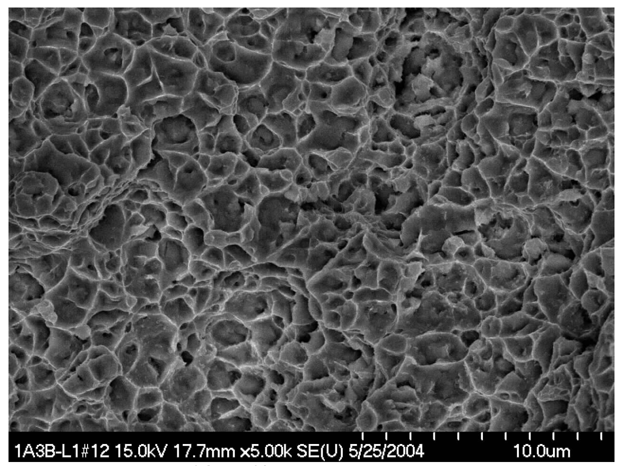
(A) 2a2b - 300°C/ 65%/ 5.2 Mpm/ No Post Roll Anneal



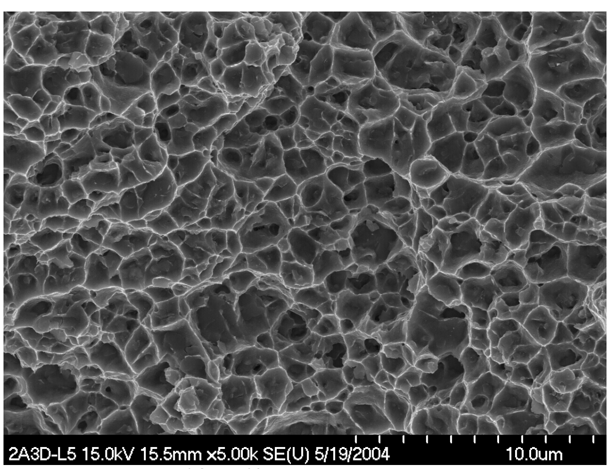
(B) 3a4c - 215°C/ 95%/ 21 Mpm/ No Post Roll Anneal



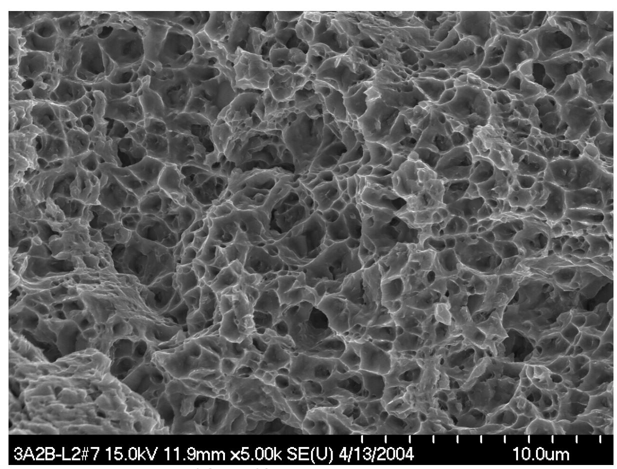
(C) 2c3b - 415°C/ 65%/ 5.2 Mpm/ No Post Roll Anneal



(D) 1a3b - 415°C/ 95%/ 5.2 Mpm/ No Post Roll Anneal

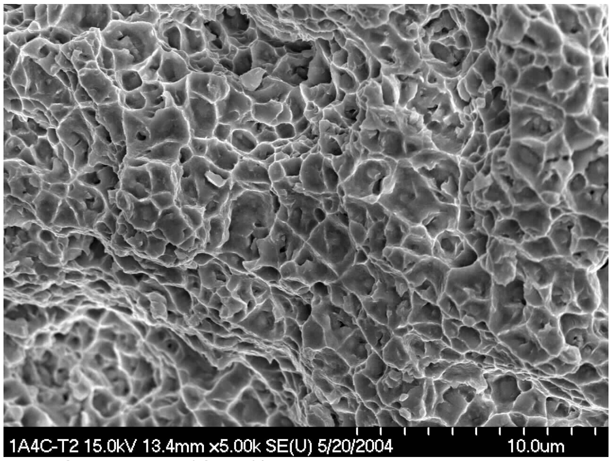


(E) 2a3d - 415°C/ 65%/ 5.2 Mpm/ No Post Roll Anneal

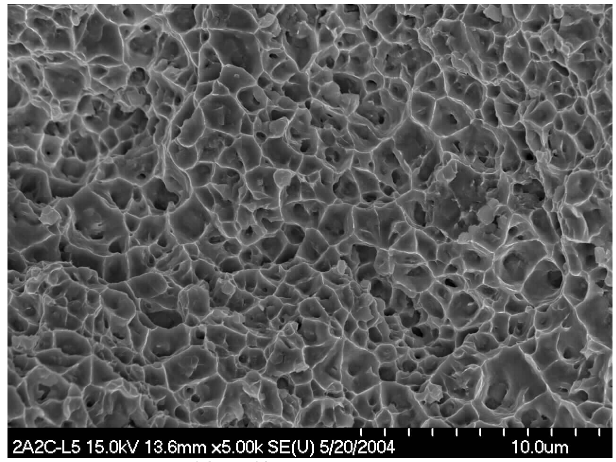


(F) 3a2b - 415°C/ 99%/ 21 Mpm/ No Post Roll Anneal

Figure 7.—Scanning Electron Microscope (SEM) images of Group-84 room temperature tensile test fractures at various rolling conditions.



(G) 1a4c - 300°C/ 95%/ 21 Mpm/ No Post Roll Anneal



(H) 2a2c - 300°C/ 65%/ 21 Mpm/ No Post Roll Anneal

Figure 7.—Concluded.

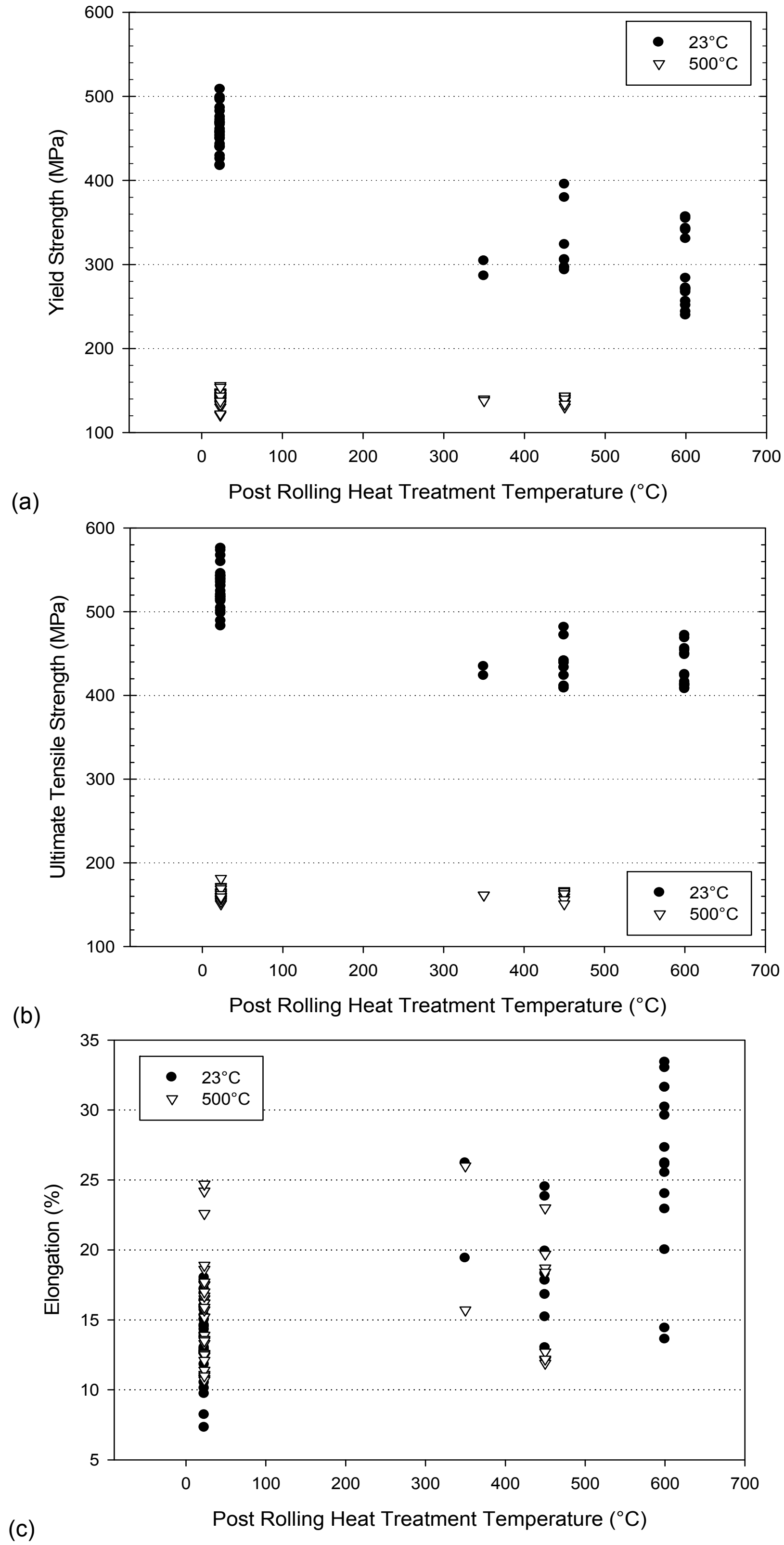
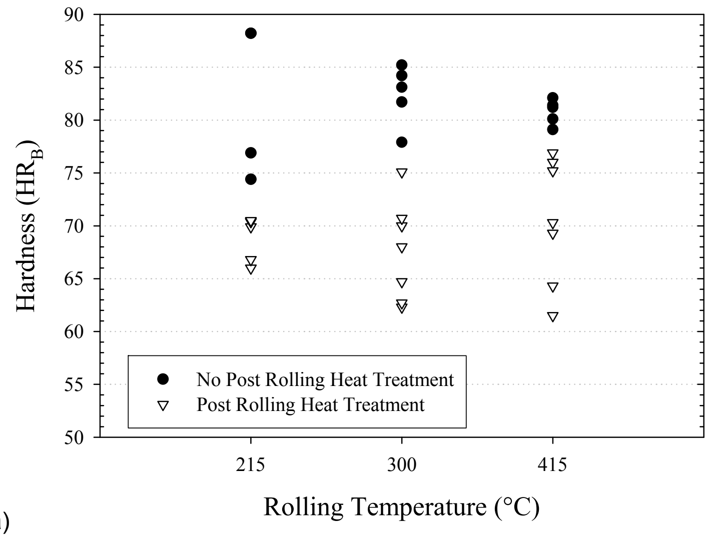
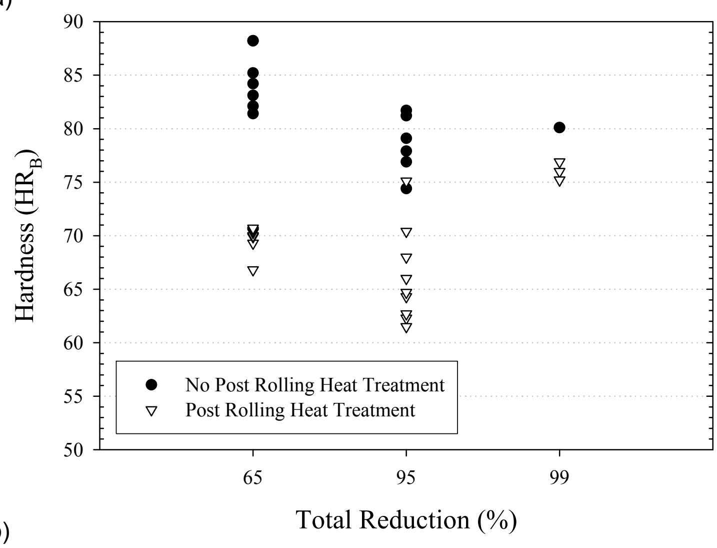


Figure 8.—(a) Effect of post rolling heat treatment temperature on yield strength. (b) Effect of post rolling heat treatment temperature on ultimate tensile strength. (c) Effect of post rolling heat treatment temperature on tensile elongation.

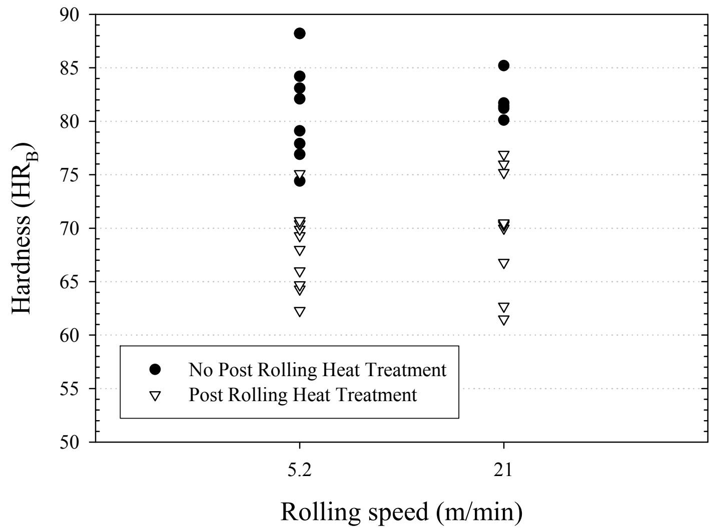


(a)

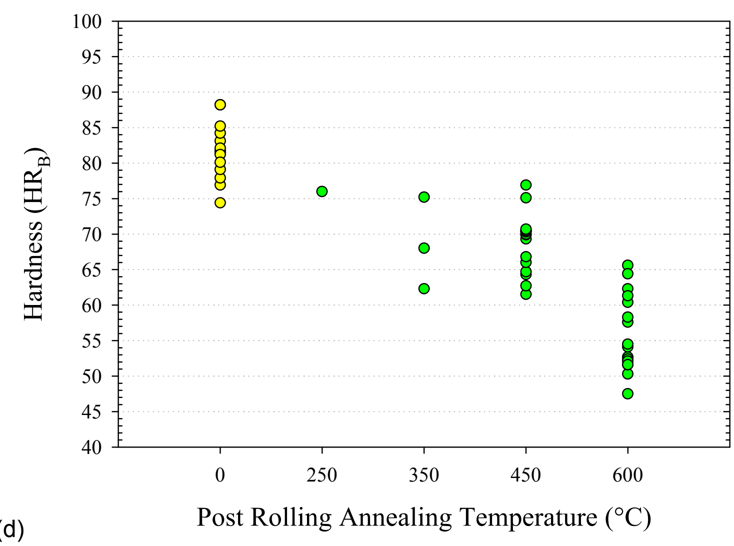


(b)

Figure 9.—(a) Effect of rolling temperature on hardness (b) Effect of total reduction on hardness (c) Effect of rolling speed on hardness (d) Effect of post rolling heat treatment temperature on hardness.



(c)



(d)

Figure 9.—Concluded.

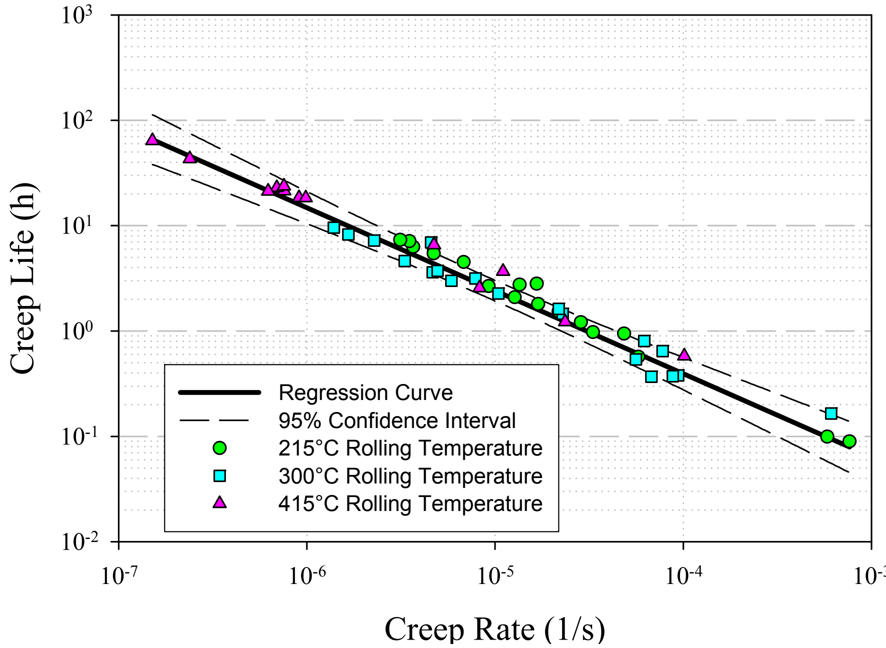


Figure 10.—Rolled GRCop-84 monkman-grant plot.

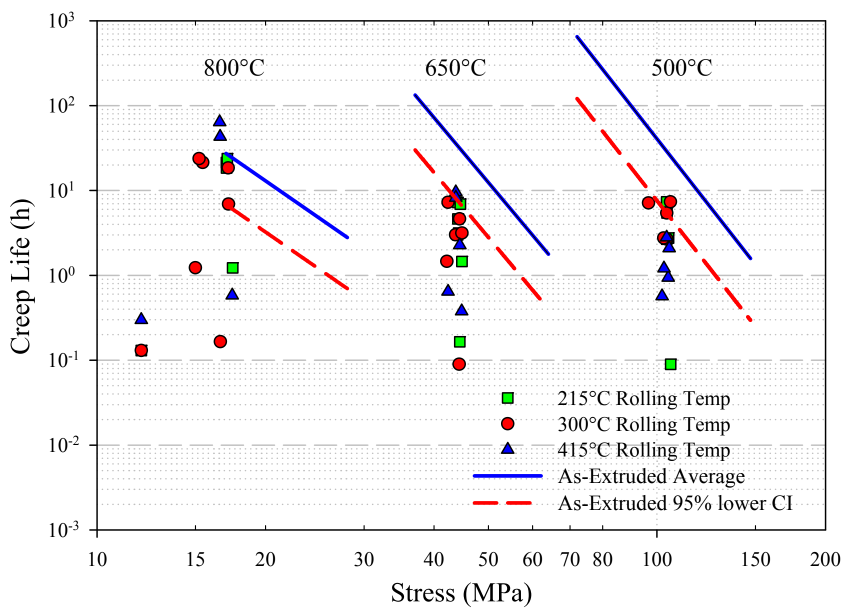


Figure 11.—Effect of rolling temperature on creep life.

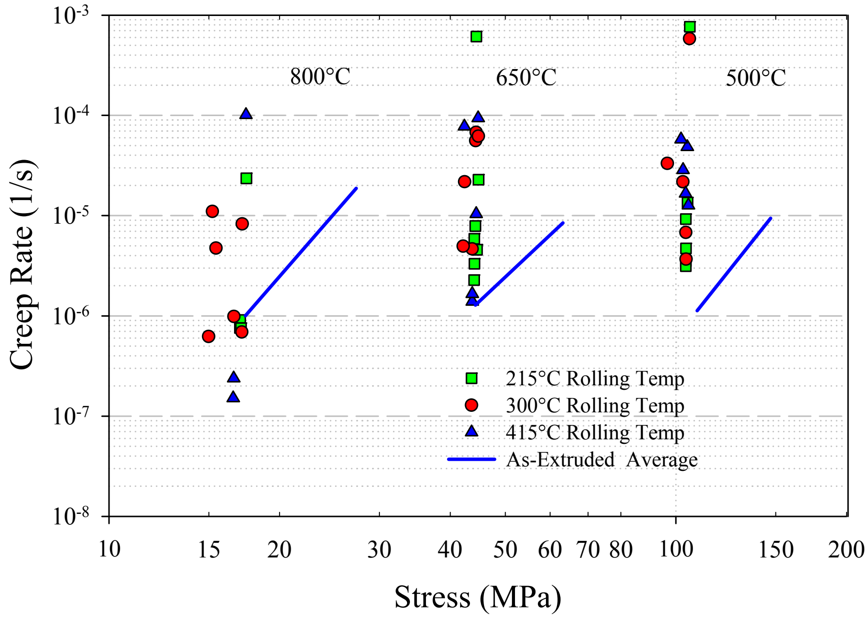


Figure 12.—Effect of rolling temperature on creep rate.

Appendix A—Actual Rolling Reduction Schedule Tables

Production Run #1
Piece: 3A4B

Pass	Thickness (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.900	7.5	6.75	0.833	0.832	0.032	0.801	2.125			
2	0.833	10	8.33	0.749	0.742	0.032	0.717	2.375			
3	0.749	10	7.49	0.674	0.688	0.032	0.642	2.625			
4	0.674	10	6.74	0.607	0.615	0.032	0.575	3.000			
5	0.607	10	6.07	0.546	0.560	0.032	0.514	3.125			
6	0.546	10	5.46	0.492	0.505	0.032	0.460	3.500			
7	0.492	10	4.92	0.442	0.475	0.032	0.411	3.750			
8	0.492	10	4.92	0.442	0.452	0.032	0.411	4.000			
9	0.452	7.5	3.39	0.418	0.415	0.034	0.384	4.500			
10	0.418	10	4.18	0.376		0.034	0.342				
11	0.376	10	3.76	0.339	0.344	0.034	0.305	5.250			
12	0.339	10	3.39	0.305		0.034	0.271				
13	0.305	10	3.05	0.274	0.277	0.034	0.240	6.500			
14	0.274	10	2.74	0.247		0.034	0.213				
15	0.247	10	2.47	0.222	0.226	0.034	0.188	7.875			
16	0.222	10	2.22	0.200		0.034	0.166				
17	0.200	10	2.00	0.180	0.180	0.034	0.146	9.875			
18	0.180	10	1.8	0.162		0.034	0.128				
19	0.162	10	1.62	0.146	0.142	0.034	0.112	12.750			
20	0.146	10	1.46	0.131	0.132	0.034	0.097	13.500			
21	0.131	10	1.31	0.118		0.034	0.084				
22	0.118	10	1.18	0.106	0.104	0.034	0.072	17.125		4.125	
23	0.102	7.5	0.77	0.094	0.089	0.036	0.058	6.500			
24	0.094	10	0.94	0.085	0.076	0.036	0.049	7.250			
25	0.085	10	0.85	0.076	0.068	0.036	0.040	8.000			
26	0.076	10	0.76	0.069		0.036	0.033				
27	0.069	10	0.69	0.062	0.55	0.036	0.026	10.000			
28	0.062	10	0.62	0.056	0.52	0.036	0.020	11.000			
29	0.056	10	0.56	0.050	0.046	0.036	0.014	12.250			
30	0.050	10	0.50	0.045	0.4	0.036	0.009	14.250			

Production Run #2
Piece: 3A4C

Pass	Thickness (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809	0.840	0.026	0.784				
2	0.809	10	8.09	0.728	0.760	0.026	0.703				
3	0.728	10	7.28	0.656	0.690	0.026	0.630	2.250			
4	0.656	10	6.56	0.590	0.627	0.026	0.565	3.000			
5	0.590	10	5.90	0.531	0.561	0.026	0.506	3.250			
6	0.531	10	5.31	0.478	0.513	0.026	0.452	3.500			
7	0.478	10	4.78	0.430	0.465	0.026	0.405	3.750			
8	0.430	10	4.30	0.387	0.417	0.026	0.362	4.063			
9	0.314	10	3.14	0.283	0.326	0.035	0.248	5.063			
10	0.283	10	2.83	0.254	0.280	0.035	0.219	6.000			
11	0.254	10	2.54	0.229	0.250	0.035	0.194	6.750			
12	0.229	10	2.29	0.206	0.224	0.035	0.171	7.500		4.250	
13	0.206	10	2.06	0.185	0.200	0.035	0.150	8.250			
14	0.185	10	1.85	0.167	0.179	0.035	0.132	9.250		4.500	
15	0.167	10	1.67	0.150	0.158	0.035	0.115	10.250			
16	0.150	10	1.50	0.135	0.140	0.035	0.100	11.500			
17	0.135	10	1.35	0.122	0.127	0.035	0.087	12.500			
18	0.122	10	1.22	0.109	0.115	0.035	0.074	14.000			
19	0.109	10	1.09	0.099	0.103	0.035	0.064	16.750			
20	0.099	10	0.99	0.089	0.091	0.035	0.054	17.000			
21	0.089	10	0.89	0.080	0.084	0.035	0.045	19.500			
22	0.080	10	0.80	0.072	0.077	0.035	0.037	6.500			
23	0.072	10	0.72	0.065	0.072	0.035	0.030	7.500			
24	0.065	10	0.65	0.058	0.063	0.035	0.023	8.250			
25	0.058	10	0.58	0.052	0.050	0.035	0.018	9.000			
26	0.058	10	0.58	0.052		0.035	0.018				
27	0.058	10	0.58	0.052		0.035	0.018				
28	0.058	10	0.58	0.052	0.046	0.035	0.018	11.250			
29	0.058	10	0.58	0.052		0.035	0.018				
30	0.058	10	0.58	0.052	0.042	0.035	0.018	12.000			
31	0.058	10	0.58	0.052		0.035	0.018				
32	0.058	10	0.58	0.052	0.040	0.035	0.018	12.750		4.500	

Production Run #3
Piece: 3A5C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416	0.445	0.034	0.382	2.375			
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.370	0.034	0.303	3.000			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.312	0.034	0.239	3.500			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.255	0.034	0.187	4.375			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179	0.210	0.034	0.145	5.250			
11	0.179	10	1.79	0.161	0.173	0.034	0.127	6.250			
12	0.179	10	1.79	0.161	0.172	0.034	0.127	6.250			

Production Run #4
Piece: 3A5D

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416	0.445	0.034	0.382	2.375			
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.368	0.034	0.303	3.063			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.310	0.034	0.239	3.625			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.255	0.034	0.187	4.250			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179	0.210	0.034	0.145	5.250			
11	0.179	10	1.79	0.161	0.172	0.034	0.127	6.375			
12	0.179	10	1.79	0.161	0.172	0.034	0.127	6.375			

Production Run #5
Piece: 1A2B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416	0.444	0.034	0.382	2.500			
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.365	0.034	0.303	3.000			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.305	0.034	0.239	3.500			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.252	0.034	0.187	4.500			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179	0.209	0.034	0.145	5.375			
11	0.179	10	1.79	0.161	0.173	0.034	0.127	6.500			
12	0.179	10	1.79	0.161	0.173	0.034	0.127	6.500			

Production Run #6
Piece: 1A2C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416	0.442	0.034	0.382	2.500			
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.634	0.034	0.303	3.125			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.302	0.034	0.239	3.750			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.250	0.034	0.187	4.375			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179	0.207	0.034	0.145	5.250			
11	0.179	10	1.79	0.161	0.172	0.034	0.127	6.375			
12	0.179	10	1.79	0.161	0.172	0.034	0.127	6.375			

Production Run #7
Piece: 1A5B

Pass	Thickness, (in.)	Target reduction (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809		0.034	0.775				
2	0.809	10	8.09	0.728	0.747	0.034	0.694	2.500			
3	0.728	10	7.28	0.656		0.034	0.622				
4	0.656	10	6.56	0.590	0.610	0.034	0.556	3.000			
5	0.590	10	5.9	0.531		0.034	0.497				
6	0.531	10	5.31	0.478	0.500	0.034	0.444	3.750			
7	0.478	10	4.78	0.430	0.450	0.034	0.396	4.125			
8	0.430	10	4.3	0.387		0.034	0.353				Cross Rolled
9	0.387	10	3.87	0.348	0.373	0.034	0.314	5.125			
10	0.348	10	3.48	0.314		0.034	0.280				
11	0.314	10	3.14	0.282	0.303	0.034	0.248	6.125			
12	0.282	10	2.82	0.254		0.034	0.220				
13	0.254	10	2.54	0.229	0.249	0.034	0.195	7.500			
14	0.229	10	2.29	0.206		0.034	0.172				
15	0.206	10	2.06	0.185		0.034	0.151				
16	0.167	10	1.67	0.150		0.034	0.116	11.500			
17	0.150	10	1.5	0.135	0.165	0.034	0.101				
18	0.135	10	1.35	0.121		0.034	0.087	15.500			
19	0.121	10	1.21	0.109	0.128	0.034	0.075				
20	0.109	10	1.09	0.098		0.034	0.064	17.500			
21	0.098	10	0.98	0.089	0.101	0.034	0.055				Cut into 3 pcs
22	0.089	10	0.89	0.080		0.034	0.046				5 5/8"
23	0.080	10	0.8	0.072		0.034	0.035				
24	0.080	10	0.8	0.072		0.034	0.035				
25	0.080	10	0.8	0.072		0.034	0.015				
26	0.080	10	0.8	0.072	0.065	0.034	0.015	8.500			
27	0.072	10	0.72	0.065		0.034	0.000				
28	0.072	10	0.72	0.065		0.034	0.000				
29	0.072	10	0.72	0.065		0.034	0.000				
30	0.072	10	0.72	0.065		0.034	0.000				
31	0.072	10	0.72	0.065	0.040	0.034	0.000	14.000			

Production Run #8
Piece: 3B2B (Replacement Piece)

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length (in.)	Time	Actual width, (in.)	Comments
1	1.500	7.5	11.25	1.388		0.034	1.354				
2	1.388	10	13.88	1.249		0.034	1.215	2.250			
3	1.249	10	12.49	1.124		0.034	1.090	2.500			
4	1.124	10	11.24	1.011		0.034	0.977	3.000			
5	1.011	10	10.11	0.910	0.944	0.034	0.876	3.250			
6	0.910	10	9.1	0.819	0.854	0.034	0.785	3.500			
7	0.819	10	8.19	0.737	0.775	0.034	0.703	3.750			
8	0.737	10	7.37	0.664	0.675	0.034	0.630	4.250			x-roll
9	0.683	7.5	5.12	0.632	0.655	0.035	0.597	3.250			
10	0.632	10	6.32	0.569	0.609	0.035	0.534	3.750			
11	0.569	10	5.69	0.512	0.540	0.035	0.477	4.125			
12	0.512	10	5.12	0.461	0.473	0.035	0.426	4.500			
13	0.461	10	4.61	0.415	0.427	0.035	0.380	5.000			
14	0.415	10	4.15	0.373	0.380	0.035	0.338	5.500			
15	0.373	10	3.73	0.336	0.370	0.035	0.301	6.000			
16	0.336	10	3.36	0.302	0.335	0.035	0.267	7.000			
17	0.302	10	3.02	0.272	0.275	0.035	0.237	7.500			
18	0.272	10	2.72	0.245	0.260	0.035	0.210	8.250			
19	0.245	10	2.45	0.220	0.250	0.035	0.185	9.000			
20	0.220	10	2.2	0.198	0.216	0.035	0.163	10.000			
21	0.198	10	1.98	0.178	0.180	0.035	0.143	11.500			
22	0.161	10	1.61	0.145	0.168	0.035	0.110	13.000			Cut into 2 pieces
23	0.145	10	1.45	0.130		0.034	0.090				
24	0.130	10	1.3	0.117	0.165	0.034	0.080				
25	0.117	10	1.17	0.105	0.153	0.034	0.070				
26	0.105	10	1.05	0.095	0.148	0.034	0.060				
27	0.095	10	0.95	0.085	0.135	0.034	0.050				
28	0.085	10	0.85	0.077	0.125	0.034	0.040				
29	0.077	10	0.77	0.069	0.098	0.034	0.030				
30	0.069	10	0.69	0.062	0.082	0.034	0.010				
31	0.062	10	0.62	0.056		0.034	0.010				
32	0.056	10	0.56	0.050	0.030	0.034	0.000	20.000			made 40 passes at 0.000" Screw

Production Run #9
Piece: 3A2B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	1.500	7.5	11.25	1.388		0.034	1.354				
2	1.388	10	13.88	1.249	1.250	0.034	1.215	2.188			
3	1.249	10	12.49	1.124		0.034	1.090				
4	1.124	10	11.24	1.011	1.050	0.034	0.977	2.750			
5	1.011	10	10.11	0.910		0.034	0.876	3.125			
6	0.910	10	9.1	0.819	0.835	0.034	0.785	3.500			
7	0.819	10	8.19	0.737	0.730	0.034	0.703				
8	0.737	10	7.37	0.664	0.683	0.034	0.630	4.063			
9	0.683	7.5	5.12	0.632		0.035	0.597				
10	0.632	10	6.32	0.569	0.577	0.035	0.534	5.000			
11	0.569	10	5.69	0.512		0.035	0.477				
12	0.512	10	5.12	0.461	0.480	0.035	0.426	6.000			
13	0.461	10	4.61	0.415		0.035	0.380				
14	0.415	10	4.15	0.373	0.390	0.035	0.338	7.250			
15	0.373	10	3.73	0.336		0.035	0.301				
16	0.336	10	3.36	0.302	0.320	0.035	0.267	8.750			
17	0.302	10	3.02	0.272		0.035	0.237				
18	0.272	10	2.72	0.245	0.258	0.035	0.210	10.750			
19	0.245	10	2.45	0.220		0.035	0.185				
20	0.220	10	2.2	0.198	0.213	0.035	0.163	13.063			
21	0.198	10	1.98	0.178		0.035	0.143				
22	0.161	10	1.61	0.145	0.153	0.035	0.110	16.750			Cut 4 pcs 4"long
23	0.145	10	1.45	0.130	0.140	0.034	0.090	4.750			
24	0.130	10	1.3	0.117		0.034	0.080				
25	0.117	10	1.17	0.105	0.122	0.034	0.070	5.500			
26	0.105	10	1.05	0.095		0.034	0.060				
27	0.095	10	0.95	0.085	0.106	0.034	0.050	6.750			
28	0.085	10	0.85	0.077		0.034	0.040				
29	0.077	10	0.77	0.069	0.081	0.034	0.030	8.250			
30	0.069	10	0.69	0.062		0.034	0.010				
31	0.062	10	0.62	0.056	0.066	0.034	0.010	10.000			
32	0.056	10	0.56	0.050		0.034	0.000				
33	0.056	10	0.56	0.050	0.056	0.034	0.000	12.000			
34	0.056	10	0.56	0.050		0.034	0.000				
35	0.056	10	0.56	0.050	0.048	0.034	0.000	14.000			
36	0.056	10	0.56	0.050		0.034	0.000				
37	0.056	10	0.56	0.050		0.034	0.000				
38	0.056	10	0.56	0.050		0.034	0.000				
39	0.056	10	0.56	0.050		0.034	0.000				
40	0.056	10	0.56	0.050		0.034	0.000				
41	0.056	10	0.56	0.050		0.034	0.000				
42	0.056	10	0.56	0.050		0.034	0.000				
43	0.056	10	0.56	0.050		0.034	0.000				
44	0.056	10	0.56	0.050		0.034	0.000				
45	0.056	10	0.56	0.050		0.034	0.000				
46	0.056	10	0.56	0.050	0.030	0.034	0.000	19.000			

Production Run #10
Piece: 1A5C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809		0.034	0.775				
2	0.809	10	8.09	0.728	0.755	0.034	0.694	2.500			
3	0.728	10	7.28	0.656		0.034	0.622				
4	0.656	10	6.56	0.590	0.617	0.034	0.556	3.000			
5	0.590	10	5.9	0.531		0.034	0.497				
6	0.531	10	5.31	0.478	0.505	0.034	0.444	3.625			
7	0.478	10	4.78	0.430	0.435	0.034	0.396	4.125			
8	0.430	10	4.3	0.387		0.034	0.350				Cross Rolled
9	0.387	10	3.87	0.348	0.357	0.034	0.300	5.000			
10	0.348	10	3.48	0.314		0.034	0.250				
11	0.314	10	3.14	0.282	0.303	0.034	0.200				
12	0.282	10	2.82	0.254	0.195	0.034	0.150	19.250			
13	0.185	10	1.85	0.167		0.034	0.133				
14	0.167	10	1.67	0.150		0.034	0.116				
15	0.150	10	1.5	0.135	0.153	0.034	0.101	11.375			
16	0.135	10	1.35	0.121		0.034	0.087				
17	0.121	10	1.21	0.109		0.034	0.075				
18	0.109	10	1.09	0.098		0.034	0.064				
19	0.098	10	0.98	0.088	0.112	0.034	0.054	15.500			
20	0.088	10	0.88	0.080		0.034	0.040				
21	0.080	10	0.8	0.072		0.034	0.030				
22	0.065	10	0.65	0.058	0.070	0.034	0.024	24.000			Cut into 3 pieces 8" long
23	0.047	10	0.47	0.042		0.034	0.008				
24	0.047	10	0.47	0.042	0.064	0.034	0.008				
25	0.047	10	0.47	0.042		0.034	0.000				
26	0.047	10	0.47	0.042	0.058	0.034	0.000	10.000			
27	0.047	10	0.47	0.042		0.034	0.000				
28	0.047	10	0.47	0.042		0.034	0.000				
29	0.047	10	0.47	0.042		0.034	0.000				
30	0.047	10	0.47	0.042	0.045	0.034	0.000				
31	0.047	10	0.47	0.042		0.034	0.000				
32	0.047	10	0.47	0.042		0.034	0.000				
33	0.047	10	0.47	0.042		0.034	0.000				
34	0.047	10	0.47	0.042		0.034	0.000				
35	0.047	10	0.47	0.042	0.040	0.034	0.000				

Production Run #11
Piece: 1A4B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809		0.034	0.775				
2	0.809	10	8.09	0.728		0.034	0.694				
3	0.728	10	7.28	0.656	0.690	0.034	0.622	2.750			
4	0.656	10	6.56	0.590		0.034	0.556				
5	0.590	10	5.9	0.531		0.034	0.497				
6	0.531	10	5.31	0.478	0.508	0.034	0.444	3.750			
7	0.478	10	4.78	0.430	0.460	0.034	0.396	4.125			
8	0.430	10	4.3	0.387		0.034	0.353				Cross Rolled
9	0.387	10	3.87	0.348		0.034	0.314				
10	0.348	10	3.48	0.314	0.350	0.034	0.280	5.500			
11	0.314	10	3.14	0.282		0.034	0.248				
12	0.282	10	2.82	0.254		0.034	0.220				
13	0.254	10	2.54	0.229	0.265	0.034	0.195	7.125			
14	0.229	10	2.29	0.206		0.034	0.172				
15	0.206	10	2.06	0.185		0.034	0.151				
16	0.185	10	1.85	0.167	0.195	0.034	0.133	9.500			
17	0.167	10	1.67	0.150		0.034	0.116				
18	0.150	10	1.5	0.135		0.034	0.101				
19	0.135	10	1.35	0.121	0.147	0.034	0.087	12.500			
20	0.121	10	1.21	0.109		0.034	0.075				
21	0.109	10	1.09	0.098		0.034	0.064				
22	0.098	10	0.98	0.088	0.115	0.034	0.054	15.500			
23	0.065	10	0.65	0.059	0.084	0.034	0.025	21.500			
24	0.059	10	0.59	0.053		0.034	0.019				
25	0.053	10	0.53	0.047		0.034	0.013				
26	0.047	10	0.47	0.043		0.034	0.009				
27	0.043	10	0.43	0.038		0.034	0.004				
28	0.038	10	0.38	0.035	0.060	0.034	0.000	10.000			
29	0.038	10	0.38	0.035		0.034	-0.010				
30	0.038	10	0.38	0.035		0.034	-0.010				
31	0.038	10	0.38	0.035	0.048	0.034	-0.010	12.750			
32	0.038	10	0.38	0.035		0.034	-0.010				
33	0.038	10	0.38	0.035		0.034	-0.010				
34	0.038	10	0.38	0.035		0.034	-0.010				
35	0.038	10	0.38	0.035	0.040	0.034	-0.010	15.000			

Production Run #12
Piece: 1A4C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809		0.034	0.775				
2	0.809	10	8.09	0.728	0.762	0.034	0.694	2.500			
3	0.728	10	7.28	0.656		0.034	0.622				
4	0.656	10	6.56	0.590	0.625	0.034	0.556	3.000			
5	0.590	10	5.9	0.531		0.034	0.497				
6	0.531	10	5.31	0.478	0.511	0.034	0.444	3.750			
7	0.478	10	4.78	0.430		0.034	0.396				
8	0.478	10	4.78	0.430	0.447	0.034	0.396	4.125			
9	0.430	10	4.3	0.387		0.034	0.353				Cross Rolled
10	0.387	10	3.87	0.348	0.380	0.034	0.314	5.000			
11	0.348	10	3.48	0.314		0.034	0.280				
12	0.314	10	3.14	0.282	0.310	0.034	0.248	6.000			
13	0.282	10	2.82	0.254		0.034	0.220				
14	0.254	10	2.54	0.229	0.258	0.034	0.195	7.250			
15	0.229	10	2.29	0.206		0.034	0.172				
16	0.206	10	2.06	0.185	0.213	0.034	0.151	8.750			
17	0.185	10	1.85	0.167		0.034	0.133				
18	0.167	10	1.67	0.150	0.175	0.034	0.116	10.500			
19	0.150	10	1.5	0.135		0.034	0.101				
20	0.135	10	1.35	0.121	0.144	0.034	0.087	12.500			
21	0.121	10	1.21	0.109		0.034	0.075				
22	0.109	10	1.09	0.098	0.123	0.034	0.064	15.000			
23	0.098	10	0.98	0.088		0.034	0.050				
24	0.088	10	0.88	0.080		0.034	0.040				
25	0.080	10	0.8	0.072		0.034	0.030				
26	0.065	10	0.65	0.059	0.080	0.034	0.020	20.000			Cut into 3 pieces
27	0.059	10	0.59	0.053		0.034	0.010				7" Long
28	0.038	10	0.38	0.035		0.034	0.000				
29	0.038	10	0.38	0.035		0.034	0.000				
30	0.038	10	0.38	0.035		0.034	0.000				
31	0.038	10	0.38	0.035		0.034	0.000				
32	0.038	10	0.38	0.035	0.040	0.034	0.000				

Production Run #13
Piece: 1A3B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809		0.034	0.775				
2	0.809	10	8.09	0.728	0.750	0.034	0.694	2.625			
3	0.728	10	7.28	0.656		0.034	0.622				
4	0.656	10	6.56	0.590	0.612	0.034	0.556	3.125			
5	0.590	10	5.9	0.531		0.034	0.497				
6	0.531	10	5.31	0.478	0.505	0.034	0.444	3.750			
7	0.478	10	4.78	0.430		0.034	0.396				
8	0.430	10	4.3	0.387	0.420	0.034	0.353	4.375			
9	0.387	10	3.87	0.348		0.034	0.314				Cross Rolled
10	0.348	10	3.48	0.314	0.346	0.034	0.280	5.000			
11	0.314	10	3.14	0.282		0.034	0.248				
12	0.282	10	2.82	0.254	0.287	0.034	0.220	6.125			
13	0.254	10	2.54	0.229		0.034	0.195				
14	0.229	10	2.29	0.206	0.283	0.034	0.172	7.250			
15	0.206	10	2.06	0.185		0.034	0.151				
16	0.185	10	1.85	0.167	0.197	0.034	0.133	8.875			
17	0.167	10	1.67	0.150		0.034	0.116				
18	0.150	10	1.5	0.135	0.160	0.034	0.101	10.500			
19	0.135	10	1.35	0.121		0.034	0.087				
20	0.121	10	1.21	0.109	0.130	0.034	0.075	13.000			
21	0.109	10	1.09	0.098		0.034	0.064				
22	0.098	10	0.98	0.088	0.101	0.034	0.055	16.250			
23	0.088	10	0.88	0.080		0.034	0.046				
24	0.080	10	0.8	0.072	0.075	0.034	0.038	21.500			
25	0.065	10	0.65	0.059		0.034	0.020				Cut into 3 pieces
26	0.059	10	0.59	0.053		0.034	0.010				7" Long
27	0.038	10	0.38	0.035	0.055	0.034	0.000	10.000			
28	0.038	10	0.38	0.035		0.034	-0.010				
29	0.038	10	0.38	0.035		0.034	-0.010				
30	0.038	10	0.38	0.035		0.034	-0.010				
31	0.038	10	0.38	0.035		0.034	-0.010				
32	0.038	10	0.38	0.035		0.034	-0.010				
33	0.038	10	0.38	0.035		0.034	-0.010				
34	0.038	10	0.38	0.035		0.034	-0.010				
35	0.038	10	0.38	0.035		0.034	-0.010				
36	0.038	10	0.38	0.035		0.034	-0.010				
37	0.038	10	0.38	0.035	0.040	0.034	-0.010	14.000			

Production Run #14

Piece: 1A2D

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.392	0.034	0.341	3.000			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.293	0.034	0.239	4.125			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199	0.225	0.034	0.165	5.250			
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161	0.172	0.034	0.127	7.000			

Production Run #15

Piece: 2A2B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.395	0.034	0.341	2.750			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.299	0.034	0.239	3.500			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199	0.220	0.034	0.165	4.750			
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161	0.171	0.034	0.127	6.125			

Production Run #16

Piece: 2A2C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.395	0.034	0.341	2.750			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.295	0.034	0.239	3.750			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199	0.220	0.034	0.165	5.000			
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161	0.170	0.034	0.127	6.500			

Production Run #17
Piece: 2A2D

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.390	0.034	0.341	2.750			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.295	0.034	0.239	3.750			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199	0.220	0.034	0.165	5.000			
10	0.199	10	1.99	0.179		0.034	0.145				

Production Run #18
Piece: 2A3B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.386	0.034	0.341	2.500			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.290	0.034	0.239	3.500			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179	0.172	0.034	0.145	5.500			

Production Run #19
Piece: 2A3C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.395	0.034	0.341	2.750			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.292	0.034	0.239	3.750			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199	0.216	0.034	0.165	5.000			
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161	0.171	0.034	0.127	6.250			

Production Run #20
Piece: 2A3D

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375	0.390	0.034	0.341	2.750			
4	0.375	10	3.75	0.337		0.034	0.303				
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273	0.292	0.034	0.239	3.750			
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221		0.034	0.187				
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161	0.172	0.034	0.127	6.125			

Production Run #21
Piece: 2A4B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.350	0.034	0.303	3.125			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273		0.034	0.239				
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.250	0.034	0.187	4.500			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161	0.172	0.034	0.127	6.250			

Production Run #22
Piece: 2A4C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.365	0.034	0.303	3.000			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273		0.034	0.239				
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.250	0.034	0.187	4.125			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161		0.034	0.127				
12	0.161	10	1.61	0.145	0.170	0.034	0.111	6.000			

Production Run #23
Piece: 2A4D

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.360	0.034	0.303	2.875			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273		0.034	0.239				
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.253	0.034	0.187	4.250			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161		0.034	0.127				
12	0.161	10	1.61	0.145	0.165	0.034	0.111	6.250			

Production Run #24
Piece: 2A5B

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.360	0.034	0.303	2.750			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273		0.034	0.239				
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.260	0.034	0.187	4.000			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161		0.034	0.127				
12	0.161	10	1.61	0.145	0.160	0.034	0.111	6.750			

Production Run #25
Piece: 2A5C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.370	0.034	0.303	2.875			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273		0.034	0.239				
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.255	0.034	0.187	4.125			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161		0.034	0.127				
12	0.161	10	1.61	0.145	0.172	0.034	0.111	6.000			

Production Run #26
Piece: 2A5D

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.500	7.5	3.75	0.463		0.034	0.429				
2	0.463	10	4.63	0.416		0.034	0.382				
3	0.416	10	4.16	0.375		0.034	0.341				
4	0.375	10	3.75	0.337	0.365	0.034	0.303	3.000			
5	0.337	10	3.37	0.303		0.034	0.269				
6	0.303	10	3.03	0.273		0.034	0.239				
7	0.273	10	2.73	0.246		0.034	0.212				
8	0.246	10	2.46	0.221	0.290	0.034	0.187	4.250			
9	0.221	10	2.21	0.199		0.034	0.165				
10	0.199	10	1.99	0.179		0.034	0.145				
11	0.179	10	1.79	0.161		0.034	0.127				
12	0.161	10	1.61	0.145	0.170	0.034	0.111	6.250			

Production Run #27
Piece: 1A3C

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
1	0.875	7.5	6.56	0.809		0.034	0.775				
2	0.809	10	8.09	0.728	0.765	0.034	0.694	2.500			
3	0.728	10	7.28	0.656		0.034	0.622				
4	0.656	10	6.56	0.590		0.034	0.556				
5	0.590	10	5.9	0.531	0.567	0.034	0.497	3.250			
6	0.531	10	5.31	0.478		0.034	0.444				
7	0.478	10	4.78	0.430		0.034	0.396				
8	0.478	10	4.78	0.430	0.450	0.034	0.396	4.125			
9	0.430	10	4.3	0.387		0.034	0.353				Cross Rolled
10	0.387	10	3.87	0.348		0.034	0.314				
11	0.348	10	3.48	0.314	0.347	0.034	0.280	5.250			
12	0.314	10	3.14	0.282		0.034	0.248				
13	0.282	10	2.82	0.254		0.034	0.220				
14	0.254	10	2.54	0.229	0.260	0.034	0.195	7.125			
15	0.229	10	2.29	0.206		0.034	0.172				
16	0.206	10	2.06	0.185		0.034	0.151				
17	0.185	10	1.85	0.167		0.034	0.133				
18	0.167	10	1.67	0.150	0.165	0.034	0.110	11.000			
19	0.150	10	1.5	0.135		0.034	0.101				
20	0.135	10	1.35	0.121		0.034	0.085				
21	0.121	10	1.21	0.109	0.126	0.034	0.070	14.000			
22	0.109	10	1.09	0.098		0.034	0.060				
23	0.098	10	0.98	0.088		0.034	0.050				
24	0.088	10	0.88	0.080		0.034	0.040				
25	0.080	10	0.8	0.072		0.034	0.030				
26	0.065	10	0.65	0.059	0.084	0.034	0.020	23.000			Cut into 2 pieces
27	0.059	10	0.59	0.053		0.034	0.010				8" Long & the third piece
27	0.059	10	0.59	0.053		0.034	0.010				was cut short and rolled to
27	0.059	10	0.59	0.053		0.034	0.010				0.030"
27	0.059	10	0.59	0.053		0.034	0.010				
27	0.059	10	0.59	0.053	0.052	0.034	0.010				
28	0.038	10	0.38	0.035		0.034	0.000				

Pass	Thickness, (in.)	Target reduction, (%)	Actual reduction, (%)	New thickness, (in.)	Actual thickness, (in.)	Screw loss	Screw	Actual length, (in.)	Time	Actual width, (in.)	Comments
29	0.038	10	0.38	0.035		0.034	0.000				
30	0.038	10	0.38	0.035		0.034	0.000				
31	0.038	10	0.38	0.035		0.034	0.000				
32	0.038	10	0.38	0.035		0.034	0.000				
28	0.038	10	0.38	0.035		0.034	0.000				
29	0.038	10	0.38	0.035		0.034	0.000				
30	0.038	10	0.38	0.035		0.034	0.000				
31	0.038	10	0.38	0.035		0.034	0.000				
32	0.038	10	0.38	0.035	0.040	0.034	0.000	15.250			

Appendix B—Tensile Strength Data

Sample ID		Roll temp, (°C)	Total reduction, (%)	Rolling speed, (m/min)	Post rolling heat treat temp, (°C)	Test temp, (°C)	UTS, (MPa)	UTS, (ksi)	0.2% offset yield strength, (MPa)	0.2% offset yield strength, (ksi)	Elongation, (%)
1a2b	L2	215	65	21.0	unknown	500	154	22.3	145	21.0	10.4
1a2b	L4	215	65	21.0	unknown	23	414	60.0	323	46.8	23.6
1a2b	T1	215	65	21.0	unknown	23	425	61.6	314	45.5	22.0
1a2b	T2	215	65	21.0	unknown	500	157	22.8	148	21.4	11.8
1a2c	L2	215	65	21.0	unknown	500	153	22.2	142	20.6	12.0
1a2c	L4	215	65	21.0	unknown	23	403	58.4	294	42.6	23.1
1a2c	T1	215	65	21.0	unknown	23	418	60.6	305	44.2	22.0
1a2c	T2	215	65	21.0	unknown	500	159	23.0	141	20.4	12.3
1a2d	L1	300	65	5.2	0	500	157	22.8	146	21.2	17.5
1a2d	L2	300	65	5.2	0	23	546	79.1	486	70.5	15.9
1a2d	L3	300	65	5.2	0	23	539	78.1	469	68.0	17.2
1a2d	T1	300	65	5.2	0	500	160	23.2	140	20.3	17.5
1a3b	L1	415	95	5.2	0	23	531	76.9	453	65.6	14.3
1a3b	L2	415	95	5.2	0	500	160	23.2	148	21.5	13.9
1a3b	L5	415	95	5.2	0	23	536	77.7	472	68.4	7.3
1a3b	T1	415	95	5.2	0	500	154	22.3	140	20.3	18.6
1a3b-450	L2	415	95	5.2	450	23	424	61.4	293	42.5	19.9
1a3b-450	L5	415	95	5.2	450	23	433	62.8	296	42.9	18.3
1a3b-450	T1	415	95	5.2	450	500	159	23.1	130	18.9	12.7
1a3b-450	T2	415	95	5.2	450	500	167	24.2	144	20.8	12.1
1a3c	L1	215	95	5.2	0	500	172	24.9	156	22.6	16.5
1a3c	L10	215	95	5.2	0	500	164	23.7	144	20.8	16.2
1a3c	L2	215	95	5.2	0	23	483	70.0	426	61.7	10.5
1a3c	T1	215	95	5.2	0	23	489	70.9	429	62.2	10.1
1a3c	T2	215	95	5.2	0	500	142	20.6	141	20.5	0.0
1a3c-450	L1	215	95	5.2	450	500	162	23.5	138	20.0	18.7
1a3c-450	L2	215	95	5.2	450	23	442	64.0	297	43.0	17.8
1a3c-450	T1	215	95	5.2	450	23	439	63.6	324	46.9	16.8
1a3c-450	T2	215	95	5.2	450	500	164	23.8	141	20.5	23.0
1a4b	L1	300	95	5.2	unknown	500	157	22.7	141	20.4	17.5
1a4b	L2	300	95	5.2	unknown	23	435	63.1	328	47.5	23.8
1a4b	L3	300	95	5.2	unknown	23	424	61.5	297	43.1	21.8
1a4b	T1	300	95	5.2	unknown	500	164	23.7	144	20.9	16.4
1a4c	L1	300	95	21.0	0	23	540	78.3	458	66.4	13.0
1a4c	L3	300	95	21.0	0	500	152	22.1	144	20.8	15.2
1a4c	T1	300	95	21.0	0	500	159	23.0	145	21.0	13.3
1a4c	T2	300	95	21.0	0	23	535	77.5	454	65.8	14.6
1a5b	L3	415	95	21.0	0	500	160	23.2	147	21.3	16.2
1a5b	L5	415	95	21.0	0	23	538	78.0	457	66.2	11.0
1a5b	L6	415	95	21.0	0	500	160	23.2	147	21.3	16.7
1a5b	T1	415	95	21.0	0	23	543	78.7	457	66.2	12.6
1a5c	L1	300	95	5.2	0	500	137	19.8	135	19.5	0.4
1a5c	L3	300	95	5.2	0	23	520	75.4	461	66.8	9.7
1a5c	L4	300	95	5.2	0	500	157	22.8	135	19.5	15.7
1a5c	L6	300	95	5.2	0	500	166	24.0	144	20.9	12.6
1a5c	T1	300	95	5.2	0	23	515	74.7	457	66.3	8.2
1a5c-350	L1	300	95	5.2	350	23	435	63.0	286	41.5	26.2
1a5c-350	L3	300	95	5.2	350	500	161	23.4	140	20.3	15.7
1a5c-350	L5	300	95	5.2	350	500	161	23.4	138	20.0	26.0
1a5c-350	T2	300	95	5.2	350	23	424	61.4	304	44.1	19.4

Sample ID		Roll temp, (°C)	Total reduction, (%)	Rolling speed, (m/min)	Post rolling heat treat temp, (°C)	Test temp, (°C)	UTS, (MPa)	UTS, (ksi)	0.2% offset yield strength, (MPa)	0.2% offset yield strength, (ksi)	Elongation, (%)
1a5c-450	L3	300	95	5.2	450	500	166	24.0	144	20.8	18.4
1a5c-450	L4	300	95	5.2	450	500	163	23.6	134	19.4	19.7
1a5c-450	T1	300	95	5.2	450	23	482	69.8	395	57.3	13.0
1a5c-450	T2	300	95	5.2	450	23	472	68.4	380	55.0	15.2
2a2b	L1	300	65	5.2	0	500	157	22.7	141	20.5	17.7
2a2b	L4	300	65	5.2	0	23	518	75.0	482	69.9	17.7
2a2b	T1	300	65	5.2	0	500	156	22.6	130	18.9	18.9
2a2b	T2	300	65	5.2	0	23	515	74.6	440	63.7	18.0
2a2c	L3	300	65	21.0	0	500	151	21.9	138	20.0	17.0
2a2c	L4	300	65	21.0	0	500	155	22.5	142	20.6	15.9
2a2c	L5	300	65	21.0	0	23	542	78.6	496	71.9	15.0
2a2c	T1	300	65	21.0	0	23	543	78.7	466	67.6	15.3
2a3b	L2	415	65	5.2	0	23	518	75.1	475	68.9	16.0
2a3b	L3	415	65	5.2	0	500	164	23.8	142	20.6	24.7
2a3b	T1	415	65	5.2	0	23	524	76.0	450	65.2	16.4
2a3b	T2	415	65	5.2	0	500	168	24.4	143	20.7	24.2
2a3d	L2	415	65	21.0	0	500	160	23.2	139	20.1	24.7
2a3d	L3	415	65	21.0	0	500	162	23.5	138	20.0	22.6
2a3d	L5	415	65	21.0	0	23	513	74.3	469	67.9	16.9
2a3d	T1	415	65	21.0	0	23	513	74.4	440	63.8	15.7
2a4c-450	L2	215	65	5.2	450	500	151	21.9	134	19.4	12.2
2a4c-450	L4	215	65	5.2	450	23	408	59.2	305	44.2	24.5
2a4c-450	T1	215	65	5.2	450	23	411	59.6	306	44.3	23.8
2a4c-450	T2	215	65	5.2	450	500	156	22.6	140	20.3	11.9
3a2b	L2	415	99	21.0	0	23	531	77.0	450	65.2	13.8
3a2b	L5	415	99	21.0	0	500	181	26.3	147	21.3	10.7
3a2b	T1	415	99	21.0	0	23	520	75.4	440	63.7	14.0
3a2b	T2	415	99	21.0	0	500	171	24.8	137	19.8	10.8
3a4b	L1	215	95	5.2	0	500	162	23.5	131	19.0	9.3
3a4b	L10	215	95	5.2	0	23	Bad Test				
3a4b	L2	215	95	5.2	0	23	518	75.0	468	67.8	5.8
3a4b	L9	215	95	5.2	0	500	160	23.2	133	19.3	12.4
3a4b	T1	215	95	5.2	0	23	504	73.1	443	64.2	12.8
3a4b	T2	215	95	5.2	0	500	154	22.3	121	17.5	11.1
3a4b-2	L2	215	95	5.2	0	500	166	24.0	138	20.0	17.1
3a4b-2	L4	215	95	5.2	0	23	444	64.4	332	48.1	18.7
3a4b-2	T1	215	95	5.2	0	23	460	66.7	335	48.6	15.8
3a4b-2	T2	215	95	5.2	0	500	163	23.6	139	20.2	18.1
3a4c	L2	215	95	21.0	0	500	164	23.8	141	20.4	13.5
3a4c	L4	215	95	21.0	0	23	501	72.6	417	60.5	14.5
3a4c	T1	215	95	21.0	0	23	498	72.2	418	60.6	15.0
3a4c	T2	215	95	21.0	0	500	157	22.8	122	17.7	13.6
3a5c	T4	215	65	5.2	0	23	560	81.1	469	67.9	12.9
3a5c	T5	215	65	5.2	0	500	169	24.5	147	21.3	12.5
3a5c	T6	215	65	5.2	0	23	576	83.5	499	72.3	11.8
3a5c	T8	215	65	5.2	0	500	160	23.2	154	22.3	12.1
3a5d	L2	215	65	5.2	0	500	159	23.1	137	19.9	11.0
3a5d	L4	215	65	5.2	0	23	567	82.2	509	73.7	12.7
3a5d	T1	215	65	5.2	0	23	573	83.1	498	72.2	12.6
3a5d	T2	215	65	5.2	0	500	162	23.5	144	20.8	11.4

Appendix C—Hardness Data

Sample ID	Rolling temperature, (°C)	Reduction, (%)	Speed, (m/min)	Heat treatment temperature, (°C)	Hardness, (HR_B)
3a5c	215	65	5.2	0	88.2
3a5d	215	65	5.2	0	88.2
1a3c	215	95	5.2	0	74.4
3a4b	215	95	5.2	0	76.9
1a2d	300	65	5.2	0	84.2
2a2b	300	65	5.2	0	83.1
2a2c	300	65	21.0	0	85.2
1a5c	300	95	5.2	0	77.9
1a4c	300	95	21.0	0	81.7
2a3b	415	65	5.2	0	82.1
2a3d	415	65	21.0	0	81.4
1a3b	415	95	5.2	0	79.1
1a5b	415	95	21.0	0	81.2
3a2b	415	99	21.0	0	80.1
3a2b-250	415	99	69	250	76.0
1a4b-350	300	95	5.2	350	62.3
1a5c-350	300	95	5.2	350	68.0
3a2b-350	415	99	21.0	350	75.2
2a4c-450	215	65	5.2	450	70.4
2a4d-450	215	65	5.2	450	69.9
2a5b-450	215	65	21.0	450	66.8
2a5c-450	215	65	21.0	450	70.5
1a3c-450	215	95	5.2	450	66.0
3a4c-450	215	95	21.0	450	70.4
2a5d-450	300	65	5.2	450	70.7
2a2d-450	300	65	21.0	450	70.0
1a4b-450	300	95	5.2	450	64.7
1a5c-450	300	95	5.2	450	75.1
1a4c-450	300	95	21.0	450	62.7
2a3c-450	415	65	5.2	450	69.3
2a4b-450	415	65	21.0	450	70.3
1a3b-450	415	95	5.2	450	64.3
1a5b-450	415	95	21.0	450	61.5
3a2b-450	415	99	21.0	450	76.9
1a3c L7	215	95	5.2	600	51.6
1a3c L8	215	95	5.2	600	58.3
3a4b L7	215	95	5.2	600	61.3
3a4b T4	215	95	5.2	600	57.6
3a4c L6	215	95	21.0	600	62.3
3a4c T4	215	95	21.0	600	60.4
1a5c L10	300	95	5.2	600	54.5
1a5c T3	300	95	5.2	600	52.4
1a4c L6	300	95	21.0	600	52.7
1a4c T3	300	95	21.0	600	47.5
1a3b L7	415	95	5.2	600	52.1
1a3b T4	415	95	5.2	600	54.1
1a5b L8	415	95	21.0	600	51.6
1a5b T5	415	95	21.0	600	50.3
3a2b L6	415	99	21.0	600	64.4
3a2b T10	415	99	21.0	600	65.6

Appendix D—Creep Data

Sample ID	Sample no.	Rolling temperature, (°C)	Reduction, (%)	Rolling speed, (m/min)	Creep test temperature, (°C)	Actual stress, (MPa)	Creep rate, (1/s)	Creep life, (h)	Total elongation, (%)
3a5c	T03	215	65	5.2	500	104.15	3.5E-06	7.1	17.1
3a5c	T2	215	65	5.2	650	44.08	2.28E-06	7.2	14.5
3a5d	L1	215	65	5.2	500	104.12	3.13E-06	7.3	13.8
3a5d	L3	215	65	5.2	650	44.28	7.87E-06	3.2	15.1
3a5d	L5	215	65	5.2	800	17.10	7.55E-07	23.8	11.6
1a2b	L1	215	65	21	500	104.12	9.25E-06	2.7	14.3
1a2b	L3	215	65	21	650	44.08	5.87E-06	3.0	12.9
1a2b	L5	215	65	21	800	17.04	9.09E-07	18.4	10.5
1a2c	L1	215	65	21	500	104.22	4.71E-06	5.4	14.5
1a2c	L3	215	65	21	650	44.13	3.31E-06	4.6	10.9
1a2c	L5	215	65	21	800	17.03	7.58E-07	21.3	9.7
1a3c	L3	215	95	5.2	500	104.85	1.35E-05	2.7	22.7
1a3c	L5	215	95	5.2	650	44.87	2.28E-05	1.5	17.2
1a3c	L4	215	95	5.2	800	17.47	2.36E-05	1.2	23.2
3a4b	L3	215	95	5.2	500	102.77	Bad Test		
3a4b	L5	215	95	5.2	650	44.46	6.11E-04	0.2	71.6
3a4b	L4	215	95	5.2	800	14.90	Bad Test		
3a4b-2	L1	215	95	5.2	500	105.09	1.69E-05	1.8	14.0
3a4b-2	L3	215	95	5.2	650	44.54	8.80E-05	0.4	23.2
3a4b-2	L5	215	95	5.2	800	17.04	1.72E-05	0.0	78.9
3a4c	L1	215	95	21	500	105.83	7.65E-04	0.1	38.8
3a4c	L3	215	95	21	650	44.58	4.57E-06	6.9	28.2
3a4c	L5	215	95	21	800	15.04	Bad Test		
1a2d	L4	300	65	5.2	500	104.23	3.67E-06	6.3	12.2
1a2d	L5	300	65	5.2	650	44.35	5.60E-05	0.5	29.3
1a2d	T2	300	65	5.2	800	16.61	9.87E-07	18.3	20.1
2a2b	L2	300	65	5.2	500	104.15	6.81E-06	4.5	17.9
2a2b	L3	300	65	5.2	650	43.71	4.66E-06	3.6	17.2
2a2b	L5	300	65	5.2	800	17.18	8.27E-06	2.6	23.6
2a2c	L1	300	65	21	500	104.17	Bad Test		
2a2c	L2	300	65	21	650	44.41	6.78E-05	0.4	23.5
2a2c	T2	300	65	21	800	17.16	6.92E-07	23.0	10.4
1a4b	T2	300	95	5.2	500	96.61	3.31E-05	1.0	21.0
1a4b	L5	300	95	5.2	650	42.38	2.18E-05	1.6	26.4
1a4b	L4	300	95	5.2	800	15.44	4.73E-06	6.6	38.3
1a5c	T2	300	95	5.2	500	102.88	2.17E-05	1.5	25.6
1a5c	L2	300	95	5.2	650	42.15	4.95E-06	3.7	10.8
1a5c	L5	300	95	5.2	800	14.99	6.23E-07	21.2	9.6
1a4c	L5	300	95	21	500	105.73	5.82E-04	0.1	36.5
1a4c	L2	300	95	21	650	44.84	6.20E-05	0.8	34.3
1a4c	L4	300	95	21	800	15.22	1.10E-05	3.7	34.5
2a3b	L1	415	65	5.2	500	104.06	1.66E-05	2.8	32.1
2a3b	L4	415	65	5.2	650	43.74	1.39E-06	9.6	17.4
2a3b	L5	415	65	5.2	800	16.56	1.51E-07	64.0	13.3
2a3d	L1	415	65	21	500	104.76	4.85E-05	0.9	29.9
2a3d	L4	415	65	21	650	43.74	1.66E-06	8.3	14.3
2a3d	T2	415	65	21	800	16.60	2.39E-07	43.2	14.2
1a3b	T2	415	95	5.2	500	102.97	2.86E-05	1.2	30.0
1a3b	L4	415	95	5.2	650	44.80	9.40E-05	0.4	28.4
1a3b	L3	415	95	5.2	800	16.92	Bad Test		
1a5b	L2	415	95	21	500	105.21	1.27E-05	2.1	13.3
1a5b	L4	415	95	21	650	44.45	1.04E-05	2.3	14.5

Sample ID	Sample no.	Rolling temperature, (°C)	Reduction, (%)	Rolling speed, (m/min)	Creep test temperature, (°C)	Actual stress, (MPa)	Creep rate, (1/s)	Creep life, (h)	Total elongation, (%)
1a5b	T2	415	95	21	800	17.14	Bad Test		
3a2b	L1	415	99	21	500	102.14	5.77E-05	0.6	14.5
3a2b	L3	415	99	21	650	42.36	7.77E-05	0.6	31.4
3a2b	L4	415	99	21	800	17.44	1.01E-04	0.6	29.7

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report is a section of the final report on the GRCop-84 task of the Constellation Program and incorporates the results obtained between October 2000 and September 2005, when the program ended. NASA Glenn Research Center (GRC) has developed a new copper alloy, GRCop-84 (Cu-8 at.% Cr-4 at.% Nb), for rocket engine main combustion chamber components that will improve rocket engine life and performance. This work examines the sensitivity of GRCop-84 mechanical properties to rolling parameters as a means to better define rolling parameters for commercial warm rolling. Experiment variables studied were total reduction, rolling temperature, rolling speed, and post rolling annealing heat treatment. The responses were tensile properties measured at 23 and 500 °C, hardness, and creep at three stress-temperature combinations. Understanding these relationships will better define boundaries for a robust commercial warm rolling process. The four processing parameters were varied within limits consistent with typical commercial production processes. Testing revealed that the rolling-related variables selected have a minimal influence on tensile, hardness, and creep properties over the range of values tested. Annealing had the expected result of lowering room temperature hardness and strength while increasing room temperature elongations with 600 °C (1112 °F) having the most effect. These results indicate that the process conditions to warm roll plate and sheet for these variables can range over wide levels without negatively impacting mechanical properties. Incorporating broader process ranges in future rolling campaigns should lower commercial rolling costs through increased productivity.

15. SUBJECT TERMS
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