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Office of Research,
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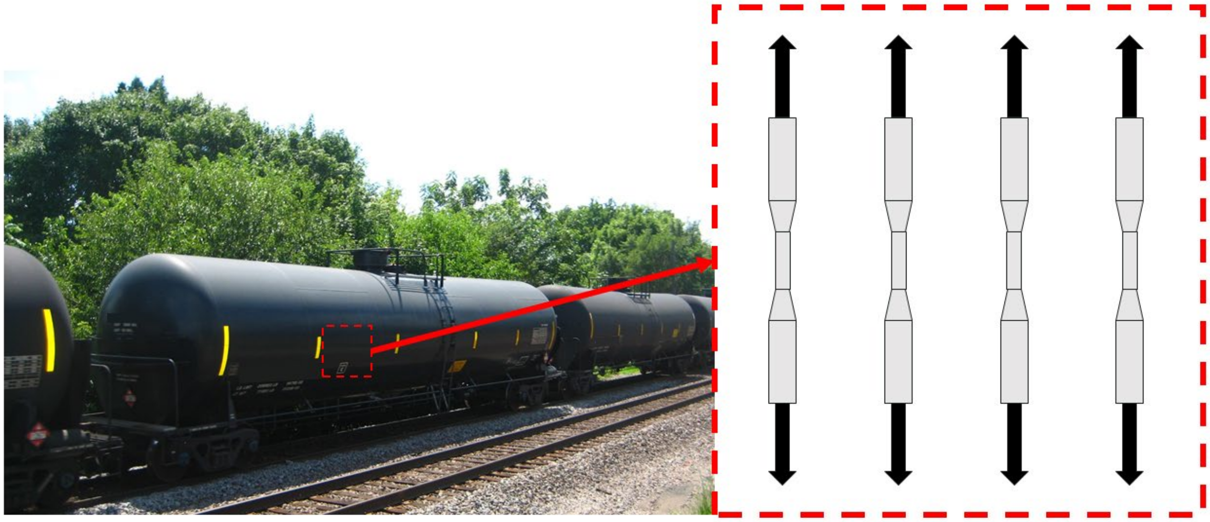
Washington, DC 20590

Mechanical Properties of TC-128B Steel during Multiple Stages of Tank Car Fabrication



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14. ABSTRACT

This report describes a testing program examining the effects of different stages of tank car fabrication on the mechanical properties of TC-128B steel. This work focused on two procedures: cold-working associated with rolling a flat plate of steel into the cylindrical tank shell and post-weld heat treatment (PWHT). The Volpe National Transportation Systems Center developed a plan and executed a contract for tensile tests on TC-128B steel samples. TC-128B was provided in four different conditions by two different tank car builders: an "as-received" flat plate, a flat plate put through PWHT, a cold-worked shell, and a cold-worked shell put through PWHT. By characterizing the material properties at different stages of fabrication, the effect of each manufacturing process on the material's behavior could be isolated. Cold-working did not have a consistent effect on strength or ductility, while PWHT increased ductility but reduced ultimate tensile strength.

15. SUBJECT TERMS

Steel, TC-128B, tank cars, fabrication, post-weld heat treatment, PWHT, transportation safety, fabrication, tensile testing, mechanical properties, material characterization,

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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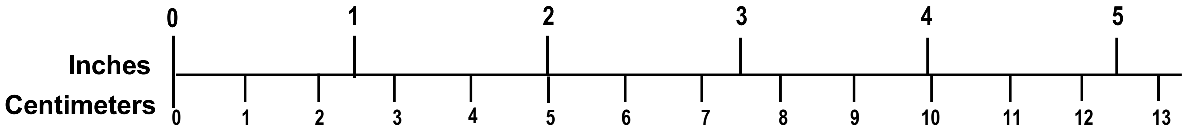
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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The tank car steel samples provided at various stages of fabrication tested in this research program were donated by two different manufacturers of railroad tank cars. The authors gratefully acknowledge the generous contributions of material, material test reports, and technical insight from these two manufacturers.

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Executive Summary

This report describes the results of a testing program examining the mechanical properties of TC-128B tank car steel at different stages of tank car fabrication. This research was intended to characterize the range of tensile properties of samples of TC-128B tank car steel and to examine if the processes used to manufacture tank cars had an observable and consistent effect on these properties. This work focused on two processes thought to affect the mechanical properties of TC-128B: cold-working associated with rolling a flat plate of steel into the cylindrical tank shell, and post-weld heat treatment (PWHT). Researchers at Element Materials Technology (Element) performed all sample tests from March 2020 to May 2020.

The specific material properties of interest were the yield strength, ultimate tensile strength, and elongation. By characterizing the material properties at different stages of fabrication, the effect of each manufacturing process on the material's behavior could be isolated. This project included only tensile testing and microstructural characterization. While some of the samples tested underwent PWHT, no welded samples were included in this study. This study did not consider any other grades or types of tank car steels. Researchers tested TC-128B samples in four different conditions: "as-received" flat plate, flat plate that was put through PWHT, cold-worked shell, and cold-worked shell that was put through PWHT. Two different tank car manufacturers provided material for this study in each of the four material states. Each manufacturer also provided the material test report (MTR) from the steel mill that fabricated each plate tested.

Researchers found that values for yield strength and ultimate tensile strength (UTS) reported on MTRs varied significantly from the properties measured from plates at different stages of fabrication, including the as-received condition, for some plates. There was no consistent trend in variation from MTR values observed in this study.

Researchers identified several clear and consistent relationships between mechanical properties and fabrication processes based on the results of the tests performed in this study. The results of this study indicated each material that had been cold-worked but did not undergo PWHT experienced a decrease in its yield strength and an increase in its UTS. This result was somewhat unexpected, as cold-working without PWHT was expected to increase the yield strength of a material. The results of this study also indicated that for both the flat plate (i.e., not cold-worked) and cold-worked TC-128B samples, PWHT resulted in an apparent decrease in each material's UTS and an apparent increase in each material's elongation at break. The data collected in this study permitted additional effects to be investigated (e.g., the relationship between PWHT and yield strength). However, no additional clear and consistent relationships were identified in the limited number of materials tested.

Note that Element researchers tested three examples of TC-128B material samples provided by two tank car manufacturers. A larger sample size of TC-128B material from additional tank car manufacturers might be appropriate to verify the initial findings of this report.

1. Introduction

The Federal Railroad Administration (FRA) has a long-standing research program aimed at improving the safety of hazardous material transportation via railroad tank cars. This report describes the results of a recent material characterization study of a tank car steel, TC-128B, conducted in support of this program.

1.1 Background

The U.S. Department of Transportation (USDOT) Volpe National Transportation Systems Center (Volpe) supports FRA's hazardous material and tank car research program. One portion of this program aims to analyze and improve the impact response and puncture resistance of railroad tank cars, with a focus on shell impacts. Within this program, multiple full-scale shell impact tests of various specification tank cars have been performed, with complementary finite element (FE) analyses conducted alongside these tests. Characterizing the material response is a critical factor in predicting the structural behavior of a tank car in an impact simulation. Based on experience gained through the full-scale testing program as well as observations made in other research programs, one area identified for further study is the influence of tank car manufacturing processes (e.g., forming, welding, and heat treatment) on the mechanical properties of the shell material in a completed car. There is specific interest in examining the influence (if any) that the changes in mechanical properties of the tank car steel may have on the shell impact puncture resistance of the completed car.

The question of whether fabrication processes affect the mechanical properties of the completed tank car has been raised in previous sources. An industry-sponsored study (Kirkpatrick & McKeighan, 2018) of material properties of various current and potential future steels for use in tank cars characterized materials both as flat plates and after being excised from tank cars during fabrication. The results for TC-128B excised from a tank car during fabrication (the shell cutout for the manway) was observed to have the lowest strengths (yield and ultimate) and highest ductility of the characterized materials. The report stated that "this material was subjected to a PWHT treatment [sic] since it had been curved into one of the tank car segments. It is unknown whether the slight difference in tensile properties for this material when compared to the other materials is a consequence of the PWHT or simply lot-to-lot variability" (Kirkpatrick & McKeighan, 2018). The authors raised the prospect that apparent differences in material properties could be caused by the use of a sample extracted from a partially formed car, but further study would be necessary to confirm this observation. However, in subsequent discussions, the tank car manufacturer that provided the shell cutout for the manway described in that study indicated that this statement was incorrect, as the manway cutout in that prior study did *not* undergo PWHT. As will be discussed subsequently in this report, a manway cutout would normally be discarded prior to the tank car undergoing PWHT.

Separately, the subject of fabrication effects on material properties was also raised during an FRA-sponsored impact test of a DOT117 railroad tank car. Prior to that test, the manufacturer of the tank car to be tested provided the Volpe modeling team with data from the material test reports (MTRs) for the TC-128B plates used to manufacture the tank car's shell. These properties were used to develop material inputs for the pre-test FE models. Following the test, material samples were excised from an undeformed area of the tank car and characterized through tensile testing. The post-test characterization revealed that the TC-128B in the completed car exhibited significantly lower yield strength and ultimate strength, but significantly increased ductility compared with the data provided in the MTR (Rakoczy, Carolan, Eshraghi, & Gorhum, 2019). This observation once again raised the possibility that the mechanical properties of TC-128B steel were changing as a result of fabrication.

In general, tensile and chemical analyses are performed on the steel plates and documented in MTRs prior to the plates being accepted by a tank car manufacturer. These records are typically maintained for the life of the tank car. Thus, there is a relatively large pool of data documenting the mechanical properties of TC-128B plates prior to the start of fabrication. Note that the individual tank car manufacturers may require the tensile testing performed by a steel mill to account for the planned post-weld heat treatment, in an attempt to characterize the "as-built" material properties of the tank car.

Testing of the mechanical properties of as-built tank cars, however, are performed relatively rarely, as this requires destroying the tank car to obtain the samples. In the FRA-sponsored tank car impact testing program, accurate material property data is a critical input to the FE models used to conduct pre- and post-test simulations, and used to extrapolate beyond the impact test conditions. Typically, tensile testing is only performed post-test because pre-test removal of coupons from the tank could affect the results of the test by compromising the tank car.

Other research programs (McKeighan, 2008) have also examined the mechanical properties of as-built tank cars. McKeighan found that the tank cars from which coupons were excised were cars being retired from the tank car fleet. This study included a wide range of tank car materials, vintages, and specification tank cars. Since it focused on characterizing the properties of tank cars retired from the fleet, characterizing the properties of tank car steels in their pre-fabrication condition was outside of its scope.

Outside of research, another typical reason for excising coupons from completed tank cars and performing tensile characterization is accident investigation. In a typical investigation of an incident involving hazmat-carrying tank cars, the National Transportation Safety Board (NTSB) will excise coupons from tank cars of interest (e.g., tank cars that released commodity, tank cars that sustained damage but resisted puncturing) and conduct tensile characterization, among other tests. This characterization is intended to confirm that the tank cars' materials of construction met the applicable requirements and to investigate whether the properties of the materials of construction contributed to the outcome of the incident. Typically, NTSB makes its tensile testing data publicly available through its docket system, but does not typically include MTRs from the as-received plates that made up the subject car. Thus, post-accident characterization can be thought of as a "snapshot" of the as-built car's properties, but not a complete picture of how those values compared to the "as-received" plates in the pre-fabrication condition.

The potential for fabrication processes to affect the mechanical properties of the completed tank car is of interest for several reasons. If careful study reveals that the material properties remain consistent at each stage of fabrication, this is confirmation that the MTR of the initial plate also describes the mechanical properties of the as-built tank car. If careful study of the mechanical properties reveal that the mechanical properties do change during fabrication, this change could be considered either a benefit or a detriment. For example, increased ductility in the as-built car can lead to improved puncture resistance, but increased ductility is often accompanied by decreased strength. If fabrication processes do lead to some desirable change in the mechanical properties, it may be of interest to learn which stage of fabrication led to that change and whether further desirable change can be realized. At the same time, if the MTR that the mill provides to the manufacturer of the tank car does not accurately represent the mechanical properties of the as-built tank car, this would be a disconnect that could lead to a vague conclusion as to whether the car complied with the material properties contained in the applicable material specification. Since an as-built car is most likely to be tested following an incident under investigation or as a part of a research program, it could be concluded that the as-built car did not comply with the material requirements if it was found to have an as-built yield strength, ultimate strength, or ductility that did not meet the specification requirements.

1.2 Objectives

This research was intended to characterize the range of tensile properties of TC-128B tank car steel as produced in plates and to determine if the processes used to manufacture tank cars had an observable and consistent effect on these properties. The specific material properties of interest are the yield strength, ultimate tensile strength, and elongation. Ideally, this study would have accounted for differences in fabrication processes arising from different material suppliers, different tank car manufacturers, and different tank car specifications (with corresponding shell thicknesses and tank diameters). The end objective was to produce a report documenting the material properties of interest after different stages of fabrication for each of the different samples of TC-128B provided by manufacturers. By characterizing the material properties at different stages of fabrication, the effect of each manufacturing process on the material's behaviour could be isolated. This report also documents any trends observed in the coupon results, and includes discussion as to whether there were any conclusions that could be drawn on the effects of manufacturing on the puncture resistance of the tank car shells.

1.3 Overall Approach

Volpe engaged in discussions with two different manufacturers of railroad tank cars used in service in the U.S. These manufacturers agreed to provide TC-128B tank car material for this testing program, taken from various stages of their typical fabrication processes. Much of this material was scrap or excess material associated with typical tank car fabrication processes. Volpe also contracted with a commercial testing laboratory (Element Materials Technology), which conducted tensile tests and microstructural characterization on the material samples provided by the two manufacturers and documented the results in test reports and photographs.

1.4 Scope

This report describes the results of the first stage of a testing program examining whether the different stages of tank car fabrication had an observable and consistent effect on the mechanical properties of TC-128B tank car steel. The work described in this report included only tensile testing and microstructural characterization. This report does not feature a detailed discussion of the specific heat treatment processes used by the individual manufacturers that provided material in the heat-treated condition for characterization within this program, as tank car heat treatment is prescribed by the tank car standard AAR M-1002 (Association of American Railroads, 2007). This report focuses on the effects of shell fabrication processes on the material properties and does not include any study of tank car head properties. While the samples used in this testing program underwent post-weld heat treatment (PWHT), no welded samples were included in this study.

1.5 Organization of the Report

Section 2 describes the existing requirements and standards used for railroad tank car design, describes general fabrication techniques used to manufacture tank cars, and discusses the development of the testing plan to obtain samples from different stages of tank car fabrication.

Section 3 presents the tensile and microstructure results from the TC-128B samples provided by Manufacturer A.

Section 4 presents the tensile and microstructure results from the TC-128B samples provided by Manufacturer B.

Section 5 contains the conclusions of this report. This section contains results from both Manufacturer A and Manufacturer B’s TC-128B samples organized by fabrication stage. This section also includes discussion of trends observed in the data across the different material conditions from both manufacturers.

Section 6 contains a list of references made in this report.

2. Fabrication and Test Plan

The intent of this study was to examine the mechanical properties of TC-128B material at different stages of fabrication, after the material has undergone various physical and thermal processes. A sampling and test plan was developed with input from both Manufacturers A and B to identify logical stages of fabrication where material could be obtained. Additionally, a test plan was developed to accommodate the material geometry that would be available at each stage of fabrication.

2.1 Existing Requirements and Standards

A DOT specification tank car must conform with the requirements of 49 CFR 179, "Specifications for Tank Cars," which incorporates AAR Standard M-1002 by reference (Association of American Railroads, 2007). AAR M-1002 contains detailed requirements for tank car design, fabrication, and maintenance. The fabrication processes discussed throughout this report have been simplified and generalized. AAR M-1002 also contains the specification for tank car steel TC-128B. The minimum mechanical properties for TC-128B are as shown in Table 1.

Table 1. Minimum Properties for TC-128B

Property	Value
Yield Strength	50,000 psi
Ultimate Tensile Strength	81,000 psi
Elongation at Failure	22% (2-inch gauge)
Elongation at Failure	16% (8-inch gauge)

Standard procedures for performing tensile tests of steel samples are found in ASTM E8 (ASTM International, 2013). This standard also contains geometric information on standardized coupons for use in tensile tests. Among the geometric limits provided in the standard are limits on the thickness of steel plate for which different coupon geometries can be used. Three coupon geometries given in ASTM E8 are applicable to plates of thickness typically encountered in tank car construction. These coupon geometries are a 2-inch gauge length cylindrical coupon, a 2-inch gauge length rectangular coupon, and an 8-inch gauge length rectangular coupon. The plate thickness limits from ASTM E8 are summarized in Table 2. Tensile test results for yield strength and ultimate tensile strength can be compared to one another if different gauge length coupons are used. However, elongation at break values from 2-inch gauge length coupons cannot be directly compared with elongation at break values from 8-inch gauge length coupons. Note that the specification for TC-128B (Table 1) contains different minimum values for elongation depending on whether a 2-inch or 8-inch gauge length coupon was tested.

Table 2. Plate Thickness Limits from ASTM E8

Gauge Length	Coupon Shape	Plate Thickness Limits
2 inches	Cylindrical	Coupon diameter = 0.5 inch, plate t ≥ 0.5 inch
2 inches	Rectangular – Sheet Type	t ≤ 0.75 inch
8 inches	Rectangular – Plate Type	0.188 inch ≤ t

The plate thickness limits presented in the table above were considered when determining what coupon shape(s) to prescribe for tensile testing in this study. As the 8-inch gauge length coupons require a larger specimen, these coupons would require a larger piece of excised tank car to have been available. Ideally, the same test coupon would have been specified for the samples taken at different fabrication stages as had been used in the values reported on the MTR for that plate's heat of TC-128B. However, that was not always possible, given the dimensions of the material cutouts provided from the fabrication processes, as will be discussed subsequently in this report.

2.2 Stages of Fabrication

Focusing on the tank itself, a typical DOT specification tank car is made up of several cylindrical rings forming the shell and an ellipsoidal head on each end. This study focused on the effects of fabrication processes on the mechanical properties of the tank shell and did not include any material from tank heads. However, the tank head is mentioned in this section for completeness. The shell rings are typically formed by cold-rolling the flat plates into cylindrical rings. Each ring has a longitudinal weld, and adjacent rings are welded together circumferentially. In a separate process, the tank heads may be cold-formed or hot-formed, typically by stamping. The tank head is welded to the tank shell via a circumferential weld. Typically, cutouts for openings (e.g., the manway, inlet and outlet valves, piping, etc.) in the tank shell are made after the shell plates have been rolled and welded. Additionally, the nozzles are welded into the tank shell after the cutouts have been made. After welding, the entire tank goes through a PWHT process in accordance with AAR M-1002. A simplified version of the fabrication processes is shown in Figure 1.

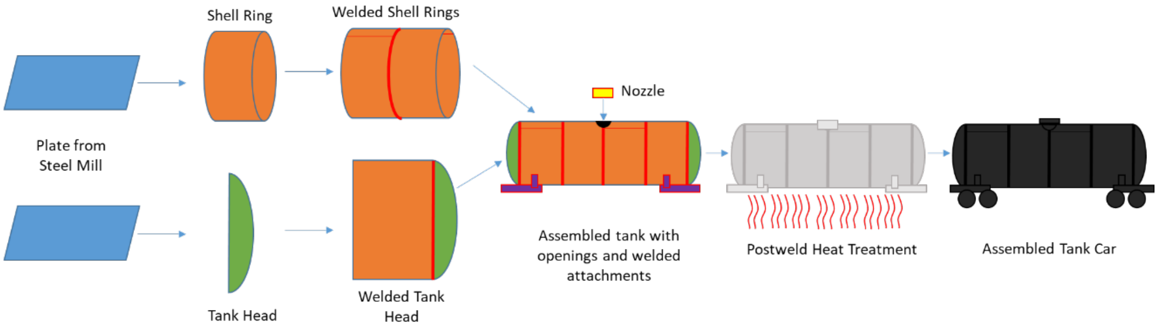


Figure 1. Simplified Tank Car Fabrication Process, Focused on Tank Itself

Several stages in the simplified tank car fabrication process were identified where the material properties could be potentially affected by the process. The process of rolling the tank's shell at room temperature puts the tank shell through a cold-working process. Cold-working is a process by which a metallic material is strained beyond its elastic limit, inducing some permanent deformation but also increasing its yield strength during subsequent loadings. Because the material has been initially loaded beyond its elastic limit, the ductility of the material decreases. This process is also referred to as strain-hardening; by inducing plastic strain in the material, the strength is increased but at the cost of ductility (Callister, Jr., 2003). Thus, it was desirable to obtain a sample of material after the ring rolling process to examine whether cold-rolling had an appreciable effect on the TC-128B's strength and ductility.

The magnitude of the increase in strength and decrease in ductility caused by cold-working is related to the amount of plastic strain induced in the material undergoing deformation. In the case of rolling a flat plate into a cylindrical ring, the amount of cold work to be done will depend on the thickness of the plate being rolled, the diameter of the cylinder being rolled, and the plastic portion of that plate's TC-128B stress-strain response. A thicker plate will undergo more work than a thin plate, for a fixed-diameter cylinder. A smaller diameter will require more work than a larger diameter for a fixed plate thickness. For typical tank car plate thicknesses (< 1 inch) and tank diameters (> 100 inches), the amount of cold-working the TC-128B plate undergoes during cold-rolling is expected to be relatively small. The effect of this cold-working on the shell plate's mechanical properties would also be expected to be small. In the case of rolling a circular ring, the inner fibers of the plate will experience compression and the outer fibers of the plate will experience tension. As the stress varies through the thickness of the plate, there is some depth within the plate where the residual stress must be zero. Further, by cutting samples out of the tank shell for testing, the residual stresses within the sample will redistribute as the sample is no longer constrained by the adjacent material in the tank's shell.

After the welding of the tank itself and any attachments or appurtenances to the tank have been completed, the entire tank goes through a PWHT process. The requirements for PWHT are more fully-described in AAR M-1002, but an important point is that the duration of the PWHT increases with the thickness of the plate. Note that for plate of less than 1-inch thickness, AAR M-1002 prescribes a minimum 1 hour of holding time for PWHT. AAR M-1002 also limits TC-128B plate to a maximum thickness of 1 inch. Typical tank car shell thicknesses are under 1 inch, with some exceptions. Due to the 1-inch limit on TC-128B plate thickness imposed by AAR M-1002, thicker tank car shells must be made from an approved steel other than TC-128B.

The purpose of the PWHT is to reduce residual internal stresses that may have developed through the tank car as a result of the welding processes, as high residual stresses can have a deleterious effect if left unrelieved. PWHT does not entirely relieve the material's internal stresses, but can significantly reduce their magnitude. The purpose of this study was not to examine the efficacy at PWHT at reducing internal stresses for TC-128B tank cars. Rather, PWHT has been identified as a stage in fabrication that could have an effect on both the mechanical properties and on the microstructure of the TC-128B in the as-built tank car. While PWHT is, by its very name, applied after welding, this study used TC-128B plates that had not been welded. This allowed the effects of PWHT on the parent TC-128B's mechanical properties to be assessed independent of any effects local to the welds.

2.3 Test Plan

The goal of this study was to examine how the material properties of TC-128B varied during the fabrication process from the as-received flat plate to the as-built tank car. Examining the incremental changes in material behavior after undergoing various fabrication processes would allow any changes between as-received and as-built to hopefully be associated with one or more of the mechanical and thermal processes that the plate had gone through. One major challenge associated with this goal was the obvious inability to excise a coupon from a brand new as-built tank car to allow its material properties to be examined. Reasonable analogues for the material condition of the as-built tank car had to be explored using available tank car materials that had undergone similar mechanical and thermal processes as the complete tank car.

Four material conditions were identified as targets for tensile testing in this study. Three of these material conditions occur during typical fabrication of tank cars: as-received plate, plate after being rolled into a cylinder, and plate after being rolled into a cylinder and subjected to PWHT. While there are additional fabrication steps following PWHT of the tank car, such as painting, these additional fabrication stages were not expected to have any effects on the material properties of the tank's steel. Thus, the mechanical properties of TC-128B plate that has been cold-worked into a cylinder and put through a PWHT should represent the mechanical properties of the as-built tank car. The fourth material condition included in this study, as-received plate put through the same PWHT as the rest of the tank, was added as a means of separating any effects due to PWHT alone, and due to both cold-working and then PWHT.

Once the material conditions of interest were identified, the availability of material at each stage of fabrication had to be examined. As-received plate did not present any challenges because plates are typically cut down to the exact size needed for a specific tank car design, or manufacturers order excess plate to conduct their own characterizations on the material. Because the openings in the tank's shell are typically cut out after the tank's shell rings have been cold-rolled, there was ample scrap material in the cold-rolled condition. The manway opening is typically the largest opening in the tank's shell, thus manway blanks were used for this study. Typically, there is not material in the cold-worked and PWHT condition removed from the tank car during normal fabrication. For this study, the manway blanks removed from the cold-rolled shell were divided into two categories: half were left as-is, and half were subsequently put through the same PWHT as the rest of the car from which they had been removed. In this way, the manway blank that had undergone PWHT was a stand-in for the material conditions in the actual tank car. Finally, a portion of the as-received plate was also subjected to the same PWHT as the rest of the car fabricated from that plate. This stage of fabrication is not typical, but was included in this study to understand the effects of the PWHT on a plate that had undergone cold-working prior to PWHT, and a plate that had undergone PWHT. The fabrication stages and coupon sources used in this study are shown schematically in Figure 2. Note that while all coupons cut from a particular sample of TC-128B originated from the same heat, the coupons were all cut from different locations on the available plates.

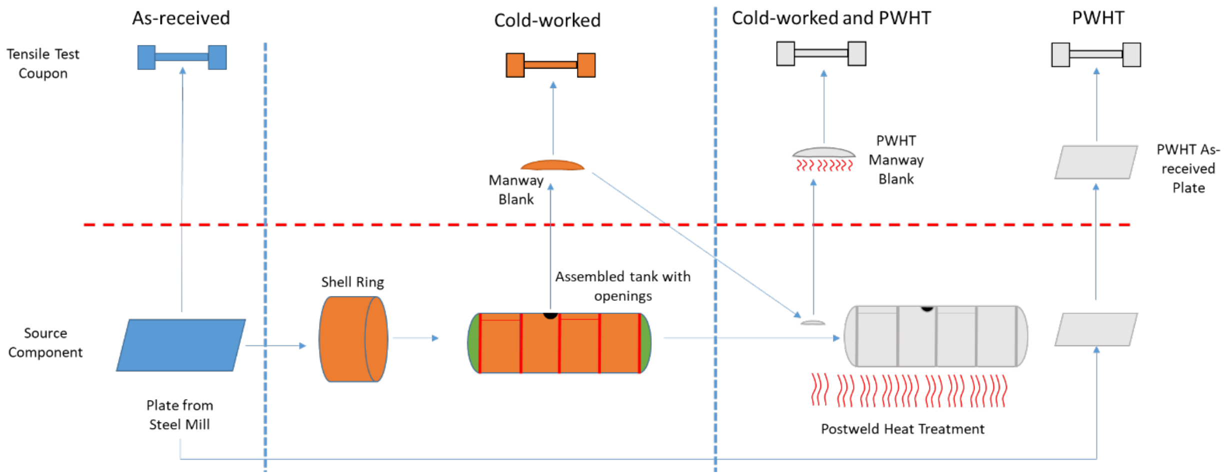


Figure 2. Schematic of Coupon Sources and Fabrication Stages

All test coupons were excised with the long direction of the coupon parallel to the long direction of the tank. The rolling direction of the steel plates making up the shell corresponds to the hoop direction of the formed cylinder. This means that all coupons were pulled in tension in the transverse-to-rolling direction. The coupon orientation is illustrated schematically in Figure 3, showing coupon orientation for samples obtained from the manway cutout.

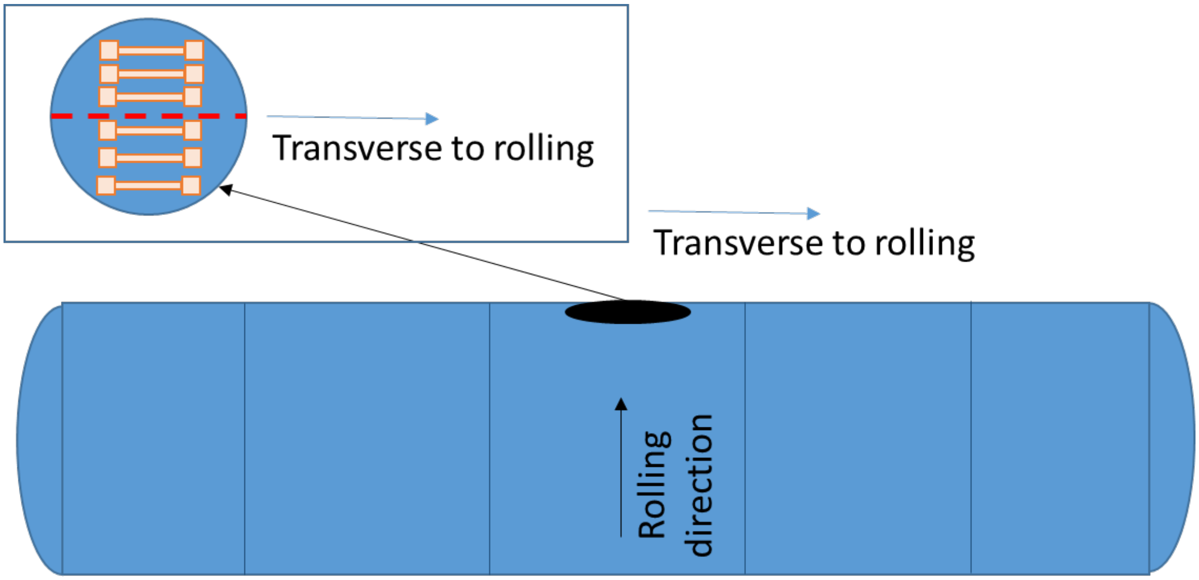


Figure 3. Schematic Illustration of Coupon Orientation on Tank

For each combination of material, coupon geometry, and stage of fabrication, three repeat tensile tests were performed. The results presented in this report include the measurements from each individual specimen as well as the average of the three measurements for yield strength, ultimate tensile strength, and elongation at break.

2.3.1 Samples from Manufacturer A

Manufacturer A provided samples in the four material states as summarized in Table 3. The plate had a nominal thickness of approximately 0.57 inch. Manufacturer A also provided the MTR for the heat that contained Material A1. From the MTR, material A1 was TC-128B in the normalized condition. According to Manufacturer A, the cold-worked samples were rolled into a shell ring having an outer diameter (OD) of approximately 111 inches.

Table 3. Summary of Sample Geometry and Coupons for Material A1

Material Identifier	Nominal Thickness (inch)	Sample Geometry	Fabrication Stage	Desired Coupon Geometry from ASTM E8
A1	0.57	Flat strip, approximately 1 inch x 26 inches	As-received plate	Sheet-type (2-inch gauge)
		Flat strip, approximately 1 inch x 26 inches	Heat-treated	Sheet-type (2-inch gauge)
		Half-circle, approximately 22-inch diameter	Cold-worked	Sheet-type (2-inch gauge)
		Half-circle, approximately 22-inch diameter	Cold-worked and Heat-treated	Sheet-type (2-inch gauge)

The MTR for Material A1 used 8-inch gauge length rectangular (plate-type) coupons for the tensile tests performed by the steel manufacturer. Ideally, the same coupon geometry would have been used for the coupons to be cut from the samples at different stages of fabrication. For Material A1, the flat plates provided the least amount of material to be cut into coupons. The dimensions of the flat plates did not allow for the 8-inch gauge length coupons to be used. Thus, a 2-inch gauge length coupon was used. While the yield and ultimate strengths measured in 2-inch and 8-inch gauge length coupons can be compared to one another, the elongation at break cannot be compared between specimens using a different gauge length. The samples provided by Manufacturer A in four conditions are shown in Figure 4. The arrows that appear on several samples indicate the transverse-to-rolling direction.

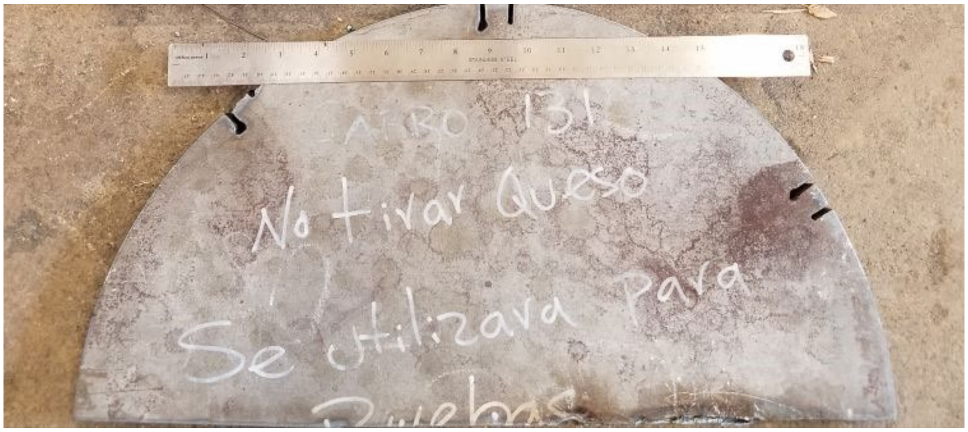
As-received Plate	
Heat-treated	
Cold-worked	
Cold-worked and Heat-treated	

Figure 4. Samples of Material A1 in Four Conditions

2.3.2 Samples from Manufacturer B

Manufacturer B provided two different sets of samples from two different heats of TC-128B having different thicknesses and rolled diameters. Manufacturer B provided samples in the four material states, as summarized in Table 4 for Material B1 and Material B2. Plate B1 had a nominal thickness of approximately 0.78 inch. Plate B2 had a nominal thickness of approximately 0.44 inch. Manufacturer B also provided the MTRs for the heats that contained

Materials B1 and B2. From the MTRs, both Materials B1 and B2 were TC-128B in the normalized condition.

Table 4. Summary of Sample Geometry and Coupons for Materials B1 and B2

Material Identifier	Nominal Thickness (inches)	Sample Geometry	Fabrication Stage	Desired Coupon Geometry from ASTM E8
B1	0.78	10-inch x 20-inch flat plate	As-received plate	Plate-type (8-inch gauge)
				Round-type (2-inch gauge)
		10-inch x 20-inch flat plate	Heat-treated	Plate-type (8-inch gauge)
				Round-type (2-inch gauge)
		2 half-circles, approximately 20-inch diameter	Cold-worked	Plate-type (8-inch gauge)
				Round-type (2-inch gauge)
		2 half-circles, approximately 20-inch diameter	Cold-worked and Heat-treated	Plate-type (8-inch gauge)
				Round-type (2-inch gauge)
B2	0.44	Three 10-inch x 20-inch flat plates	As-received plate	Sheet-type (2-inch gauge)
		Three 10-inch x 20-inch flat plates	Heat-treated	Sheet-type (2-inch gauge)
		2-foot x 4-foot ring section	Cold-worked	Sheet-type (2-inch gauge)
		2-foot x 4-foot ring section	Cold-worked and Heat-treated	Sheet-type (2-inch gauge)

The four samples of Material B1 were substantially similar in origin to the four samples of Material A1, with the cold-worked samples of each being obtained from the portion of tank shell removed to create the manway opening. However, the flat plates of material B1 were substantially larger than material A1. This allowed for samples of 8-inch gauge length to be cut from the material B1 samples at each material condition. Because of its thickness, material B1 exceeded the maximum thickness for 2-inch gauge length rectangular coupons given in ASTM E8. However, material B1 was suitable for cylindrical coupons of 2-inch gauge length. These coupons were included to allow for a comparison of results obtained using both 8-inch and 2-inch gauge lengths at each material condition, as a means of assessing whether the coupon geometry had a substantial effect on the strength results. Recall that the elongation at break results cannot be compared between tensile coupons of different gauge lengths.

Manufacturer B provided the MTR for material B1, which documented results from an 8-inch gauge length coupon. Thus, the results of the 8-inch coupon tests performed in this study on material B1 could be directly compared to the values provided on the MTR. The samples of Material B1 provided by Manufacturer B in four conditions are shown in Figure 5. The arrows that appear on several samples indicate the transverse-to-rolling direction.

As-received Plate	
Heat-treated	
Cold-worked	
Cold-worked and Heat-treated	

Figure 5. Samples of Material B1 in Four Conditions

Material B2 was rejected by Manufacturer B for use in a tank car shell due to the overall dimensions of the plate in the non-thickness directions not meeting Manufacturer B's requirements. However, based on the MTR this material met the strength and ductility requirements of specification TC-128B. Thus this scrap material was included in this study even though it was not going to be used to fabricate a tank car. The flat plate samples of material B2 were the same geometry as provided for material B1. The cold-worked samples for material B2 were flat plates rolled to an arc of a diameter typical of the type of tank car the plates would have been used to fabricate. While there was a sufficient amount of material B2 to fabricate and test 8-inch gauge length coupons, Manufacturer B also provided the MTR for material B2. The tests documented on the MTR used a 2-inch gauge length coupon. Thus, the results of the 2-inch coupon tests performed in this study on material B2 could be directly compared to the values provided on the MTR. The samples of Material B2 provided by Manufacturer B in four conditions are shown in Figure 6. The arrows on several samples indicate the transverse-to-rolling direction.

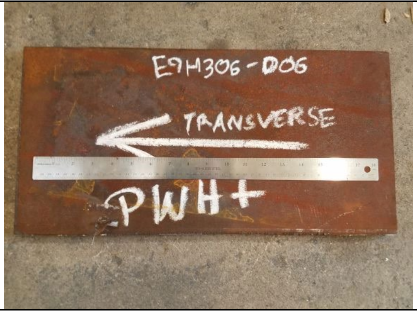
As-received Plate	
Heat-treated	
Cold-worked	
Cold-worked and Heat-treated	

Figure 6. Samples of Material B2 in Four Conditions

3. Results – TC-128B from Manufacturer A

This section presents tensile testing results obtained from Material A1's MTR, tensile testing results from tests conducted on samples at each stage of fabrication, microstructure analysis from samples at each stage of fabrication, and chemistry analyses obtained from Material A1's MTR.

3.1 Material A1

The tensile testing results from Material A1 are presented in this section in four ways: individual and average values of yield strength, ultimate tensile strength, and elongation as-is; individual and average values normalized against the corresponding values from Material A1's MTR; individual and average values normalized against the corresponding values from the "as-received" flat plate of Material A1; and individual and average values normalized against the corresponding minimum values from the TC-128B specification.

3.1.1 Tensile Test Results

The tensile test results measured in this project for Material A1 are presented alongside the values from Material A1's MTR in Table 5.

Table 5. Material A1 – Summary of Tensile Test Results

		From MTR	Flat Plate	Flat Plate, PWHT	Rolled into Ring	Rolled into Ring, PWHT
Yield Strength (psi)	Coupon 1	-	66,000	64,000	64,000	61,500
	Coupon 2	-	64,000	65,500	64,000	62,500
	Coupon 3	-	65,500	64,500	63,500	63,500
	Average	*69,100*	*65,167*	*64,667*	*63,833*	*62,500*
Ultimate Tensile Strength (psi)	Coupon 1	-	84,000	81,500	84,500	81,000
	Coupon 2	-	81,500	83,000	84,500	81,500
	Coupon 3	-	83,000	83,000	84,000	81,500
	Average	*90,600*	*82,833*	*82,500*	*84,333*	*81,333*
Elongation in 2" (%)	Coupon 1	-	33	36	35	35
	Coupon 2	-	33	36	35	34
	Coupon 3	-	34	37	33	35
	Average	-	*33*	*36*	*34*	*35*
Elongation in 8" (%)	Coupon 1	-	-	-	-	-
	Coupon 2	-	-	-	-	-
	Coupon 3	-	-	-	-	-
	Average	*22.8*	-	-	-	-

The yield strength of the individual coupons of Material A1 and the average value at each stage of fabrication are shown in Figure 7. This figure also includes the value of yield strength reported on Material A1's MTR and the minimum value of yield strength required by the TC-128B specification. The yield strength of Material A1 exceeded the required minimum in each material condition tested.

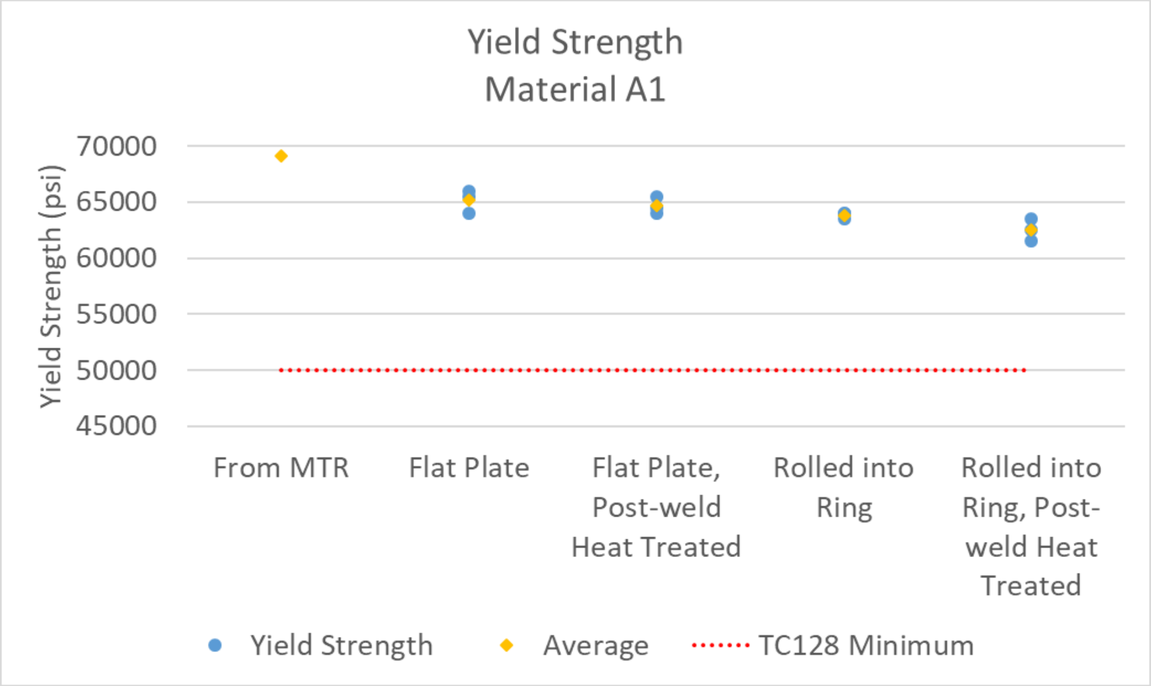


Figure 7. Material A1 – Yield Strength at Each Material Condition

Material A1's yield strength at the various stages of fabrication was consistently lower than the yield strength reported on the MTR, regardless of the stage of fabrication of the tested coupons. Focusing on the samples taken from the four stages of fabrication, the yield strength scatter was relatively narrow. Values ranged from 61,500 to 66,000 psi.

The ultimate tensile strength of the individual coupons of Material A1 and the average value at each stage of fabrication are shown in Figure 8. This figure also includes the value of ultimate tensile strength reported on Material A1's MTR and the minimum and maximum values of ultimate tensile strength required by the TC-128B specification. The ultimate tensile strength of Material A1 was within the required limits in each material condition tested.

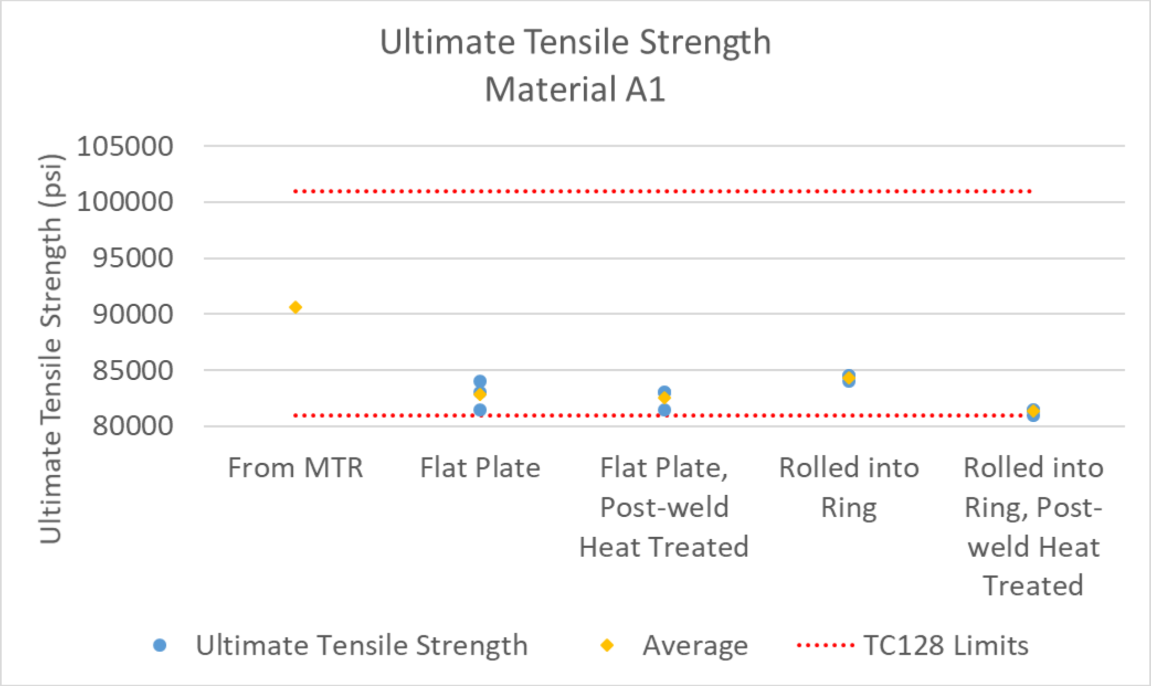


Figure 8. Material A1 – Ultimate Tensile Strength at Each Material Condition

Material A1's UTS was significantly below the value reported on the MTR at each stage of fabrication, but never fell below the range of acceptable values for TC-128B. Focusing on the four stages of fabrication, material A1's UTS remained fairly consistent – between 81,000 and 84,500 psi – for all stages of fabrication. The average value of the UTS in the final condition (rolled into ring, PWHT) fell within the scatter of UTS measurements from the flat plate. The average value of the UTS in the final condition (i.e., rolled into ring, PWHT) was approximately 10.2 percent lower than the UTS reported on the MTR.

The elongation in 2 inches of the individual coupons of Material A1 and the average value at each stage of fabrication are shown in Figure 9. This figure does not include a value of elongation in 2 inches reported on Material A1's MTR, as the MTR used an 8-inch gauge length coupon. Due to the geometry of the flat plate samples provided for this study, an 8 inch gauge length coupon could not be used for tensile testing of Material A1. The minimum value of elongation in 2 inches required by the TC-128B specification is also shown on this figure. The elongation in 2 inches of Material A1 exceeded the required minimum at each material condition tested.

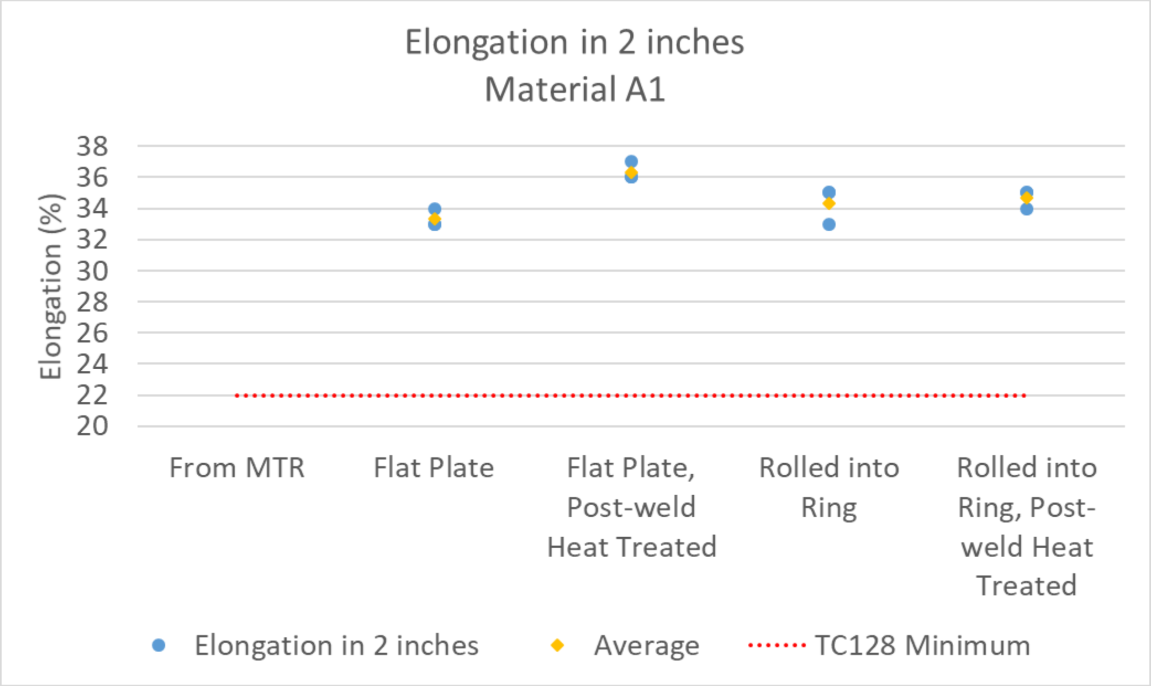


Figure 9. Material A1 – Elongation in 2 inches at Each Material Condition

Material A1's elongation in 2 inches was consistently higher for samples in the PWHT condition than samples in the same cold-worked condition (i.e., flat plate or rolled into ring) without PWHT. The range of elongation measurements were relatively narrow, ranging from 33 to 37 percent.

3.1.2 Tensile Test Results Normalized to MTR Values

The results for yield strength and ultimate tensile strength for Material A1 were normalized by dividing the individual and average values by the corresponding property value from Material A1's MTR. Normalizing the results allows for a quick comparison of how the measured properties at each stage of fabrication compare with the value reported on the MTR.

A plot of Material A1's yield strength at each stage of fabrication normalized against the yield strength reported on Material A1's MTR is shown in Figure 10. From this figure it is apparent that the values for yield strength measured during this testing program were all below the value reported on the MTR. The values measured in this testing program varied by, at most, approximately 11 percent below the MTR value (after cold-rolling the ring and going through PWHT).

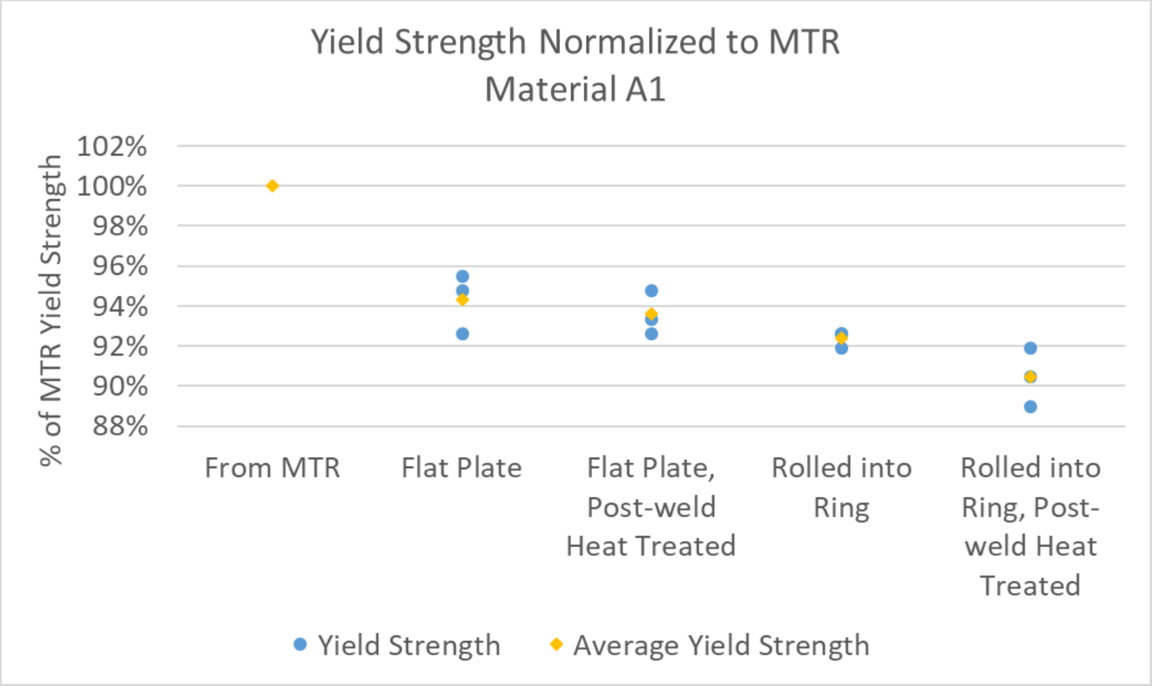


Figure 10. Material A1 – Yield Strength at Each Material Condition Normalized to MTR Yield Strength

A plot of Material A1's ultimate tensile strength at each stage of fabrication normalized against the ultimate tensile strength reported on Material A1's MTR is shown in Figure 11. From this figure it is apparent that the values for ultimate tensile strength measured during this testing program are all lower than the ultimate tensile strength values reported on Material A1's MTR. The largest decrease in ultimate tensile strength was measured in the coupons that had been both cold-rolled and PWHT. These coupons exhibited an ultimate tensile strength that was approximately 11 percent lower than the ultimate tensile strength reported on the MTR.

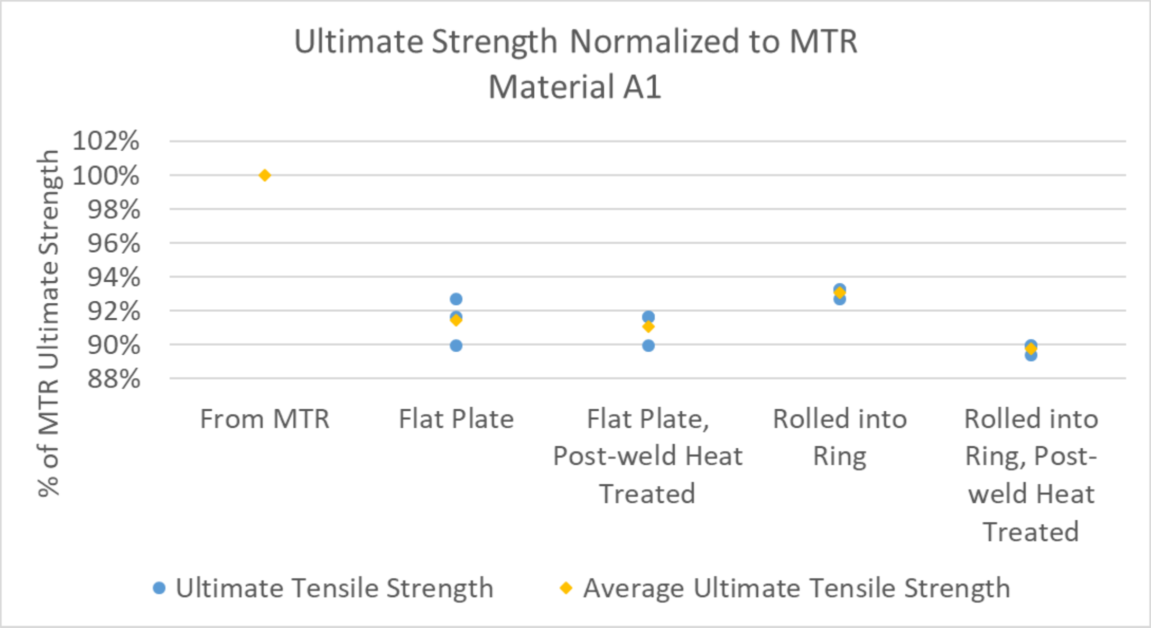


Figure 11. Material A1 – Ultimate Tensile Strength at Each Material Condition Normalized to MTR Ultimate Tensile Strength

Material A1's elongation in 2 inches at each stage of fabrication was not normalized against the value reported on the MTR because the MTR used an 8-inch gauge length coupon.

3.1.3 Tensile Test Results Normalized to Flat Plate Results

The results for yield strength, ultimate tensile strength and elongation in 2 inches for Material A1 were normalized by dividing the individual and average values by the corresponding average property value from Material A1 in the "as-received" flat plate condition. This normalization was done to provide a quick and straightforward comparison of how the mechanical properties of Material A1 changed at each stage of fabrication compared to the as-received flat plate. Note that the results reported on the MTR are included in each figure in this section for completeness.

A plot of Material A1's yield strength at each stage of fabrication normalized against the average yield strength measured for the as-received flat plate is shown in Figure 12. From this figure it is apparent that the values for yield strength measured during this testing program varied from < 1 percent above the as-received plate value (after cold-rolling the ring) to approximately 6 percent lower than the as-received plate value when in the cold-rolled and PWHT condition.

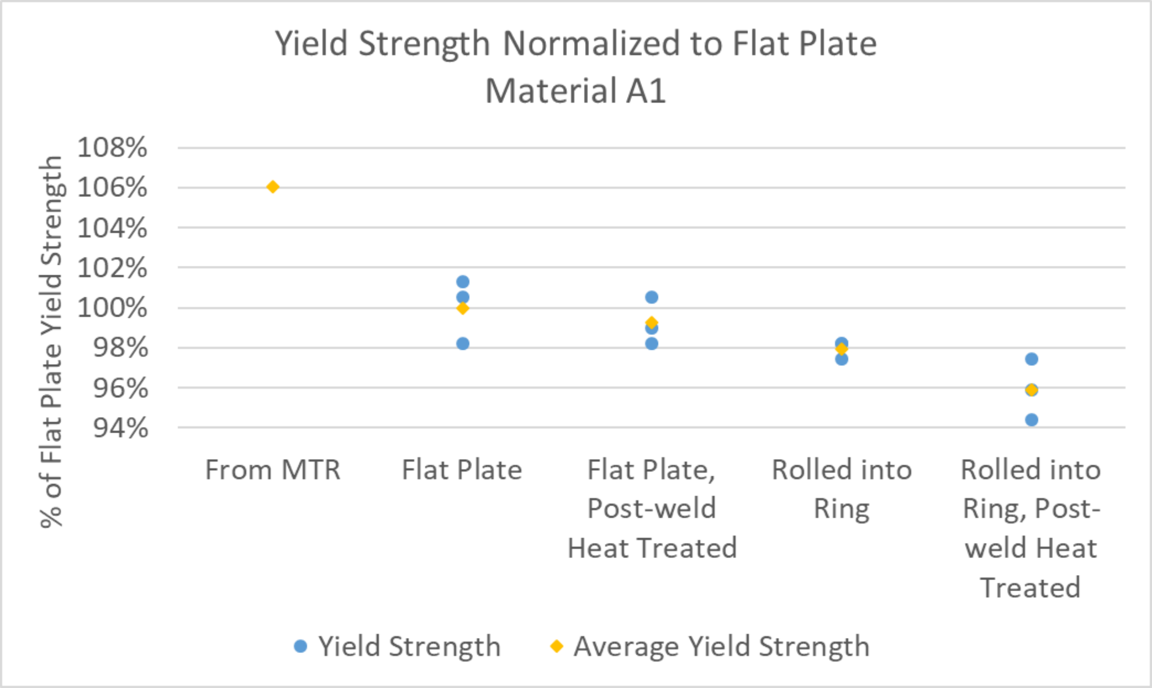


Figure 12. Material A1 – Yield Strength at Each Material Condition Normalized to Average Flat Plate Yield Strength

Cold-rolling of the flat plate into a ring would be expected to increase the yield strength of the material, as this is a form of strain-hardening. However, the yield strength decreased by, on average, 2 percent in the cold-rolled ring compared to the as-received flat plate. PWHT, whether on a flat plate or on a cold-rolled ring, resulted in more scattered yield strength results than for the rolled ring that did not undergo PWHT. While the average yield strength of the PWHT flat plate was slightly below the average yield strength of the as-received flat plate, the yield strengths of the PWHT rolled ring coupons exhibited an average yield strength approximately 4 percent lower than the average yield strength of the as-received flat plate. Note that the cold-rolled and PWHT coupons exhibited the largest spread of results of the tested coupons.

A plot of Material A1's ultimate tensile strength at each stage of fabrication normalized against the average ultimate tensile strength measured for the as-received flat plate is shown in Figure 13. From this figure it is apparent that the values for ultimate tensile strength measured during this testing program varied from 2 percent below the as-received plate value (after heat treatment, regardless of whether first cold-rolled) to approximately 2 percent higher than the as-received plate value when in the cold-rolled condition.

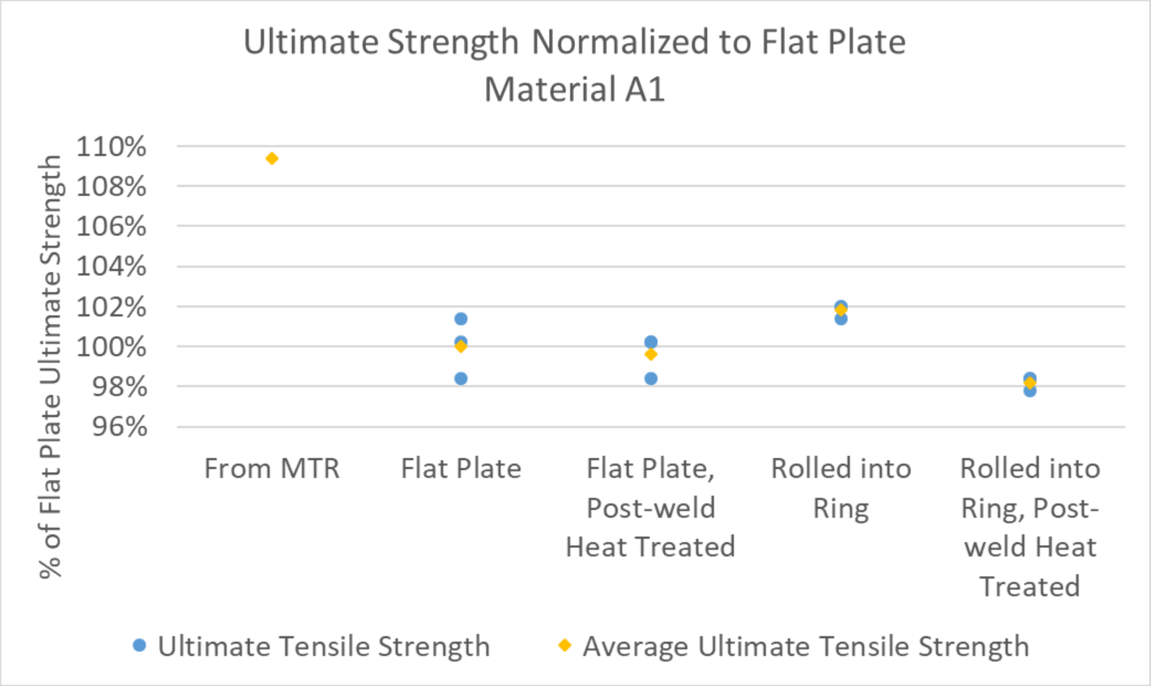


Figure 13. Material A1 – Ultimate Tensile Strength at Each Material Condition Normalized to Average Flat Plate Ultimate Tensile Strength

Cold-rolling the flat plate resulted in a slight increase in the ultimate tensile strength of the material, which was as expected. PWHT resulted in a decrease in the ultimate tensile strength of Material A1, regardless of whether the sample had been cold-rolled or not. Note that there was a considerable spread in the ultimate tensile strength results for the three flat plate coupons.

A plot of Material A1's elongation in 2 inches at each stage of fabrication normalized against the average elongation in 2 inches measured for the as-received flat plate is shown in Figure 14. From this figure it is apparent that the values for elongation in 2 inches measured during this testing program varied from approximately 1 percent below the average as-received plate value (after being cold-rolled) to approximately 11 percent higher than the average as-received plate value when in the PWHT condition. Note that as the MTR reported elongation in an 8-inch gauge length coupon, no data from the MTR are included in this plot.

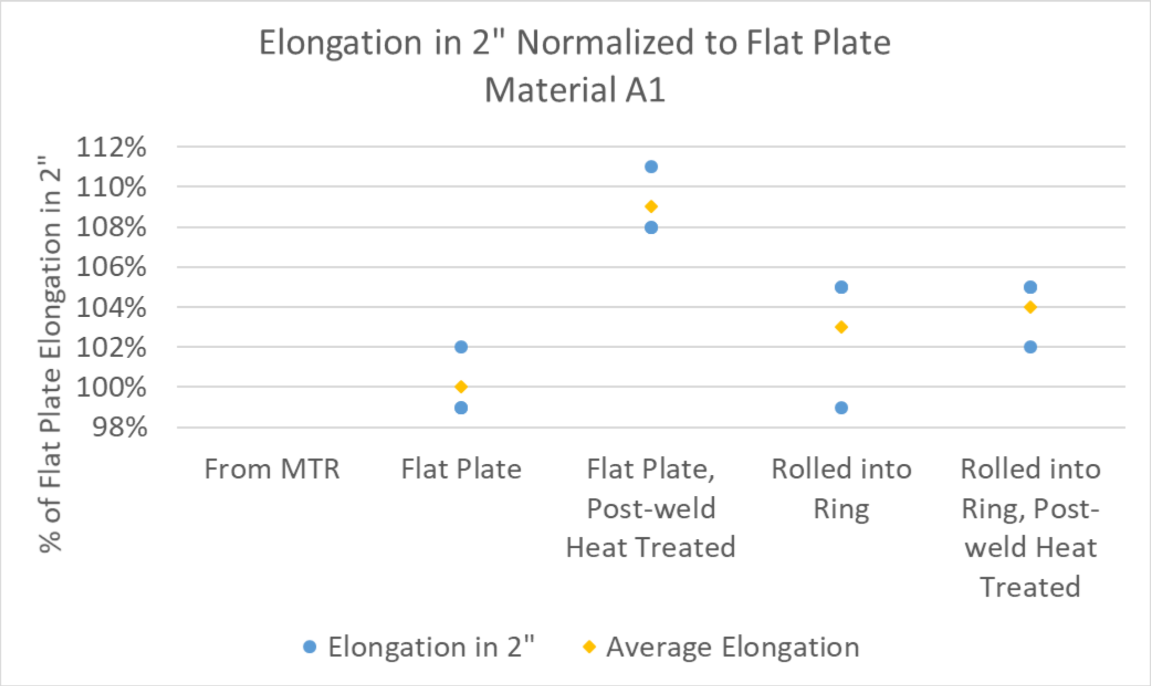


Figure 14. Material A1 – Elongation in 2 inches at Each Material Condition Normalized to Average Flat Plate Elongation in 2 inches

This result for elongation at different stages of fabrication exhibited some unexpected outcomes. Cold-rolling of the tank's ring is a form of cold-working, which is associated with a decrease in ductility compared to the as-received plate. However, the elongation in 2 inches reported from the coupons taken after cold-rolling exhibited an average value 3 percent higher than the as-received flat plate. Note that the material in this condition also exhibited the largest spread of elongation in 2-inch results, ranging from 5 percent above the flat plate elongation to roughly 1 percent below the flat plate elongation. From these results, heat treatment on either a flat plate of Material A1 or a cold-rolled ring segment of Material A1 resulted in a ductility that exceeded the ductility of the as-received flat plate. The increase in ductility after PWHT of Material A1 does appear to be greater in the PWHT flat plate compared to the plate that had been both cold-rolled and gone through PWHT.

3.1.4 Tensile Test Results Normalized to Minimum Specification Values

The results for yield strength, ultimate tensile strength, and elongation in 2 inches for Material A1 were normalized by dividing the individual and average values by the corresponding property value from the TC-128B specification minimum material properties. Normalizing the results allows for a quick comparison of how the measured properties at each stage of fabrication compared with the minimum values required. These results are plotted in Figure 15 through Figure 17. Each property exceeded the minimum requirement for TC-128B in each sample and at each stage of fabrication.

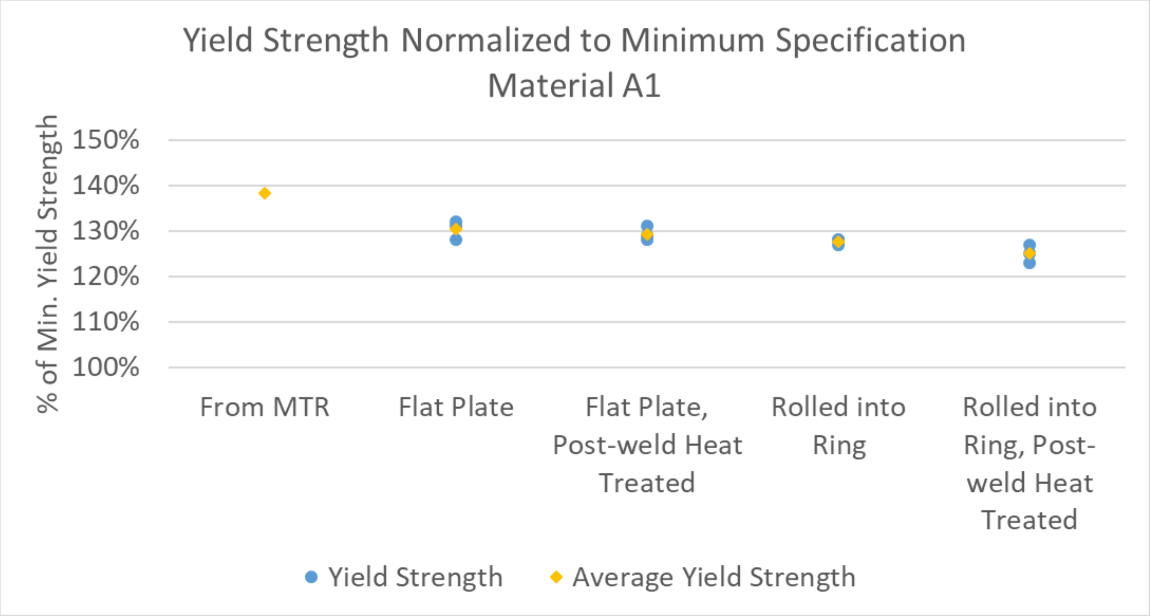


Figure 15. Material A1 – Yield Strength at Each Material Condition Normalized to Minimum Yield Strength in TC-128B Specification

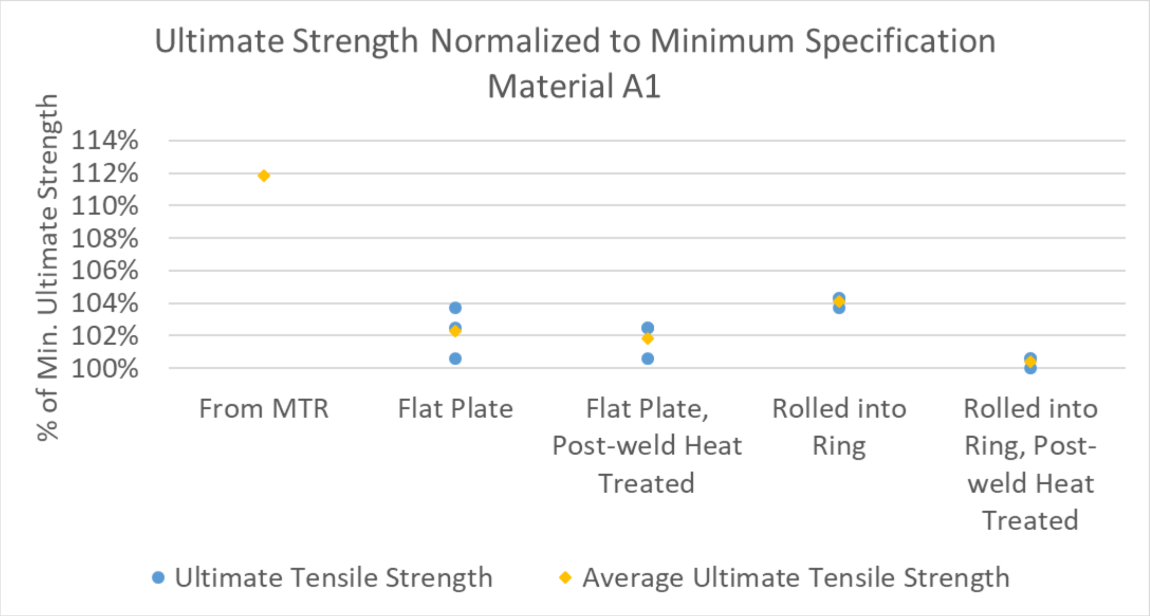


Figure 16. Material A1 – Ultimate Tensile Strength at Each Material Condition Normalized to Minimum Ultimate Tensile Strength in TC-128B Specification

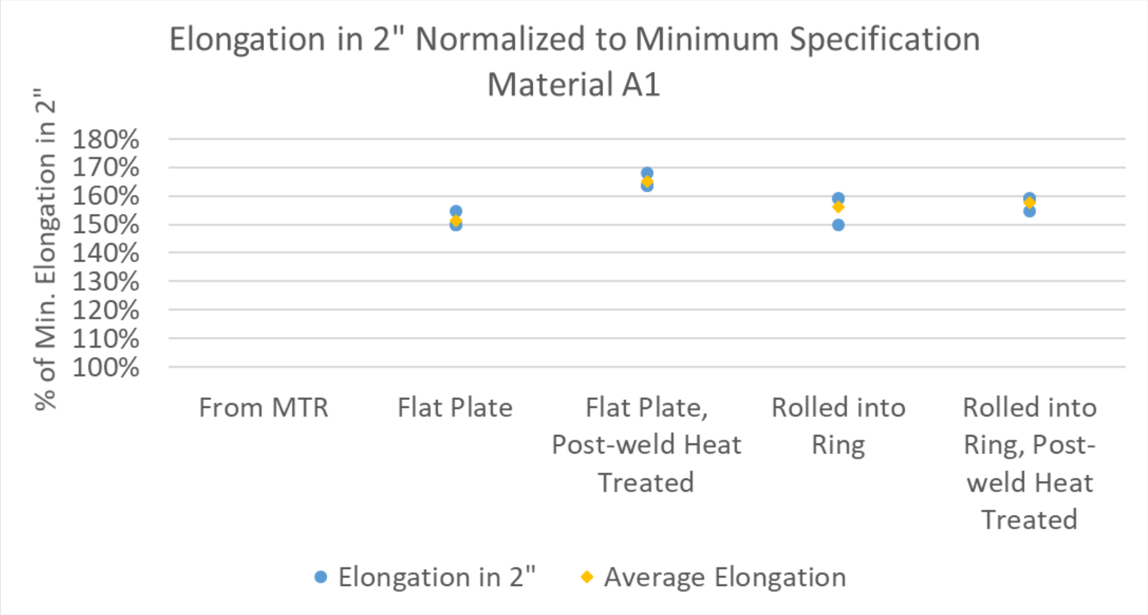


Figure 17. Material A1 – Elongation at Each Material Condition Normalized to Minimum Elongation in TC-128B Specification

3.1.5 *Microstructure Evaluation*

Figure 18 contains photomicrographs of the microstructure at the mid-thickness of Material A1 samples during each stage of fabrication. Below each image is a description of the material condition observed by the lab making the microstructural examination.

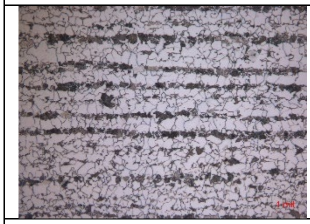
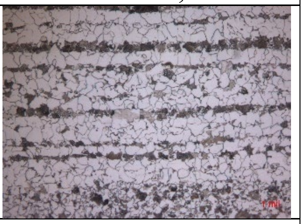
Flat Plate	Cold Worked	Flat Plate, PWHT	Cold Worked, PWHT
			
Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).

Figure 18. Material A1 – Photomicrographs Showing Typical Microstructure at Mid-thickness, 500x Magnification, Nital Etch

Figure 19 contains photomicrographs of the microstructure at the centerline of Material A1 samples during each stage of fabrication. Below each image is a description of the material condition observed by the lab that conducted the microstructural examination.

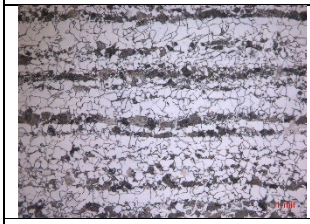
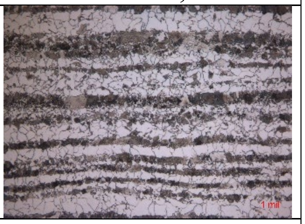
Flat Plate	Cold Worked	Flat Plate, PWHT	Cold Worked, PWHT
			
Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown). Segregation is minor, with the centerline showing slightly wider pearlite bands than the bulk of the material.	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown). There is a greater volume fraction of pearlite at the centerline relative to the bulk of the sample.	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown). Centerline segregation was not observed in this sample.	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown). There is a greater volume fraction of pearlite at the centerline relative to the bulk of the sample.

Figure 19. Material A1 – Photomicrographs Showing Typical Microstructure at Centerline, 500x Magnification, Nital Etch

3.1.6 Chemical Composition

The MTR provided by Manufacturer A for Material A1 included an analysis of the chemical composition of the plate. The chemistry data is shown in Table 6, alongside the chemistry limits for both product and ladle analysis required by M-1002 (Association of American Railroads, 2007). The chemistry of Material A1 was within the limits required by M-1002 for the elements reported.

Table 6. Chemical Composition of Material A1

Element	Material A1	M-1002 Requirement Heat Analysis	M-1002 Requirement Product Analysis
Carbon (C)	0.21	≤ 0.24	≤ 0.26
Manganese (Mn)	1.4	1.00 – 1.65	1.00 – 1.70
Phosphorous (P)	0.01	≤ 0.025	≤ 0.025
Sulfur (S)	0.001	≤ 0.015	≤ 0.015
Silicon (Si)	0.21	0.15 – 0.40	0.13 – 0.45
Copper (Cu)	0.21	0.35	0.35
Nickel (Ni)	0.08	No limit	No limit
Chromium (Cr)	0.11	No limit	No limit
Molybdenum (Mo)	0.02	No limit	No limit
Vanadium (V)	0.036	≤ 0.08	≤ 0.084
Niobium (Nb)	0.002	Per ASTM A20	Per ASTM A20
Titanium (Ti)	0.002	≤ 0.02	≤ 0.02
Nitrogen (N)	0.0043	≤ 0.01	≤ 0.012
Calcium (Ca)	0.0027	Not listed	Not listed
Boron (B)	0.0002	≤ 0.0005	≤ 0.0005
Tin (Sn)	0.009	≤ 0.02	≤ 0.02
C_{eq}[1]	0.5	≤ 0.53	≤ 0.55
P_{cm}[2]	0.31	Not listed	Not listed
Aluminum (Al) (total)	Not listed	0.015 – 0.060	0.015 – 0.060
Al (soluble)	0.03	≥ 0.015	≥ 0.015
CuSn	0.000	Not listed	Not listed
Cu + Ni + Cr + Mo*	0.42	≤ 0.65	≤ 0.65
Ti/N *	0.47	≤ 4.0	≤ 4.0

*Not listed on MTR. Calculated from values on MTR.

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[1] $C_{eq}=C+(Mn/6)+((Cr+Mo+V)/5)+((Cu+Ni)/15)$ (Association of American Railroads, 2007)

[2] $P_{cm}=C+(SI/30)+(Mn/20)+(Cu/20)+(Ni/60)+(Cr/20)+(Mo/15)+(V/10)+5B$ (U.S. Department of the Navy, Carderock Division, Naval Surface Warfare Center, 2000)

4. Results – TC-128B from Manufacturer B

Manufacturer B provided two different materials for this study, each at the four different stages of fabrication. Material B1 had a nominal thickness of 0.78 inch, and Material B2 had a nominal thickness of 0.44 inch. For both Materials B1 and B2, the MTRs state that the tensile test results were obtained after first subjecting the plates to stress relief, per AAR M-1002. This process should theoretically better represent the mechanical properties that will occur in the fully-fabricated tank car.

4.1 Material B1

The tensile testing results from Material B1 are presented in this section in three ways: individual and average values of yield strength, ultimate tensile strength, and elongation as-is; individual and average values normalized against the corresponding values from Material B1's MTR; and individual and average values normalized against the corresponding values of the "as-received" flat plate of Material B1. The MTR provided for material B1 included measured values from two coupons taken from the same heat. Individual and average values were then normalized against the corresponding minimum values from the TC-128B specification.

4.1.1 Tensile Test Results

The tensile test results measured for Material B1 using 2-inch gauge length cylindrical coupons are presented alongside the values from Material B1's MTR in Table 7. The tensile test results measured for Material B1 using an 8-inch gauge length rectangular coupon are shown in Table 8**.**

Table 7. Material B1 – Summary of Tensile Test Results (2-inch gauge length)

		From MTR[3]	**Flat Plate**	**Flat Plate, PWHT**	**Rolled into Ring**	**Rolled into Ring, PWHT**
Yield Strength (psi)	Coupon 1	57,000	66,500	62,000	62,500	65,500
	Coupon 2	58,000	67,000	63,000	62,500	64,500
	Coupon 3	-	64,500	61,000	64,000	62,500
	Average	*57,500*	*66,000*	*62,000*	*63,000*	*64,167*
Ultimate Tensile Strength (psi)	Coupon 1	82,000	92,500	81,500	93,500	83,500
	Coupon 2	82,000	93,500	83,500	93,500	83,500
	Coupon 3	-	93,500	83,000	93,500	82,500
	Average	*82,000*	*93,167*	*82,667*	*93,500*	*83,167*
Elongation in 2 inch (%)	Coupon 1	-	26	31	24	30
	Coupon 2	-	25	30	25	30
	Coupon 3	-	24	29	27	30
	Average	*-*	*25*	*30*	*25*	*30*
Elongation in 8 inch (%)	*Coupon 1*	*28*	-	-	-	-
	Coupon 2	*25*	-	-	-	-
	Coupon 3	-	-	-	-	-
	Average	*26.5*	*-*	*-*	*-*	*-*

---

[3] MTR reported results using an 8-inch gauge length coupon.

Table 8. Material B1 – Summary of Tensile Test Results (8-inch gauge length)

		From MTR	**Flat Plate**	**Flat Plate, PWHT**	**Rolled into Ring**	**Rolled into Ring, PWHT**
Yield Strength (psi)	Coupon 1	57,000	63,000	57,500	60,500	61,500
	Coupon 2	58,000	63,000	57,500	60,500	60,500
	Coupon 3	-	62,500	58,000	60,500	59,500
	Average	*57,500*	*62,833*	*57,667*	*60,500*	*60,500*
Ultimate Tensile Strength (psi)	Coupon 1	82,000	91,000	80,000	92,000	86,,500
	Coupon 2	82,000	91,000	81,000	92,000	84500
	Coupon 3	-	91,000	79,000	91,500	83,000
	Average	*82,000*	*91,000*	*80,000*	*91,833*	*84,667*
Elongation in 8 inch (%)	Coupon 1	28	23	26	22	26
	Coupon 2	25	25	26	24	26
	Coupon 3	-	23	25	26	24
	Average	*26.5*	*23.7*	*25.7*	*24.0*	*25.3*

The yield strengths of the individual coupons of Material B1 and the average value at each stage of fabrication are shown in Figure 20 for measurements made using 2-inch cylindrical coupons, and in Figure 21 for measurements made using 8-inch rectangular coupons. These figures also include the values of yield strength reported on Material B1's MTR and the minimum value of yield strength required by the TC-128B specification. The yield strength of Material B1 exceeded the required minimum in each material condition tested.

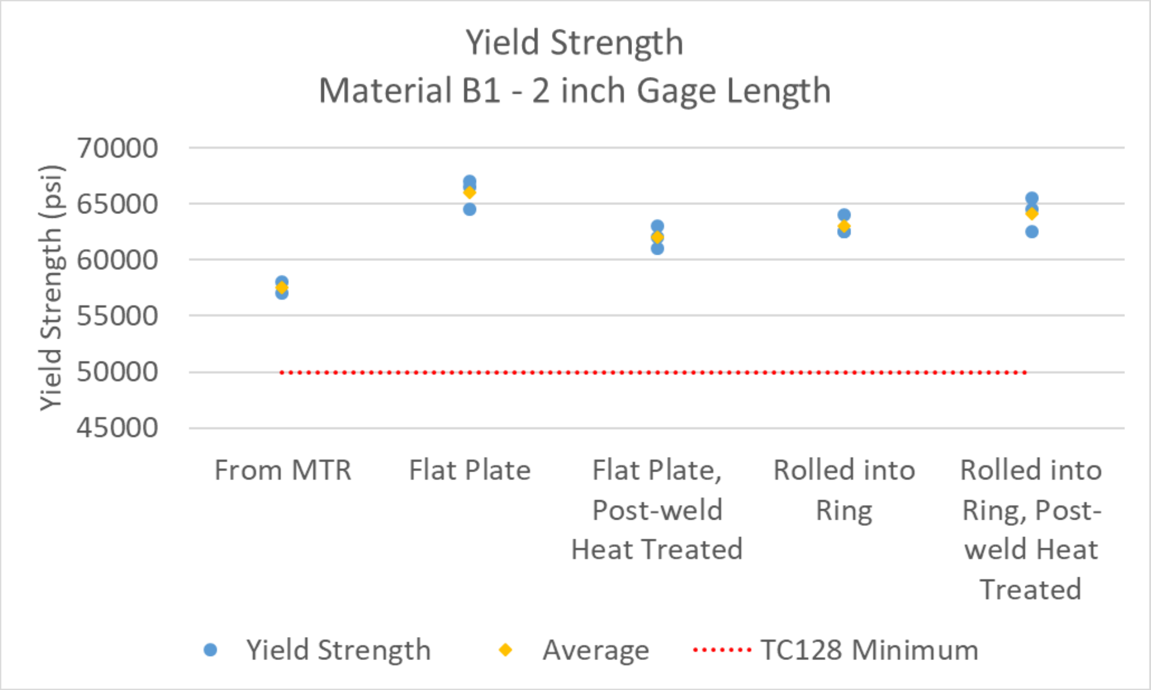


Figure 20. Material B1 – Yield Strength at Each Material Condition (2-inch gauge length)

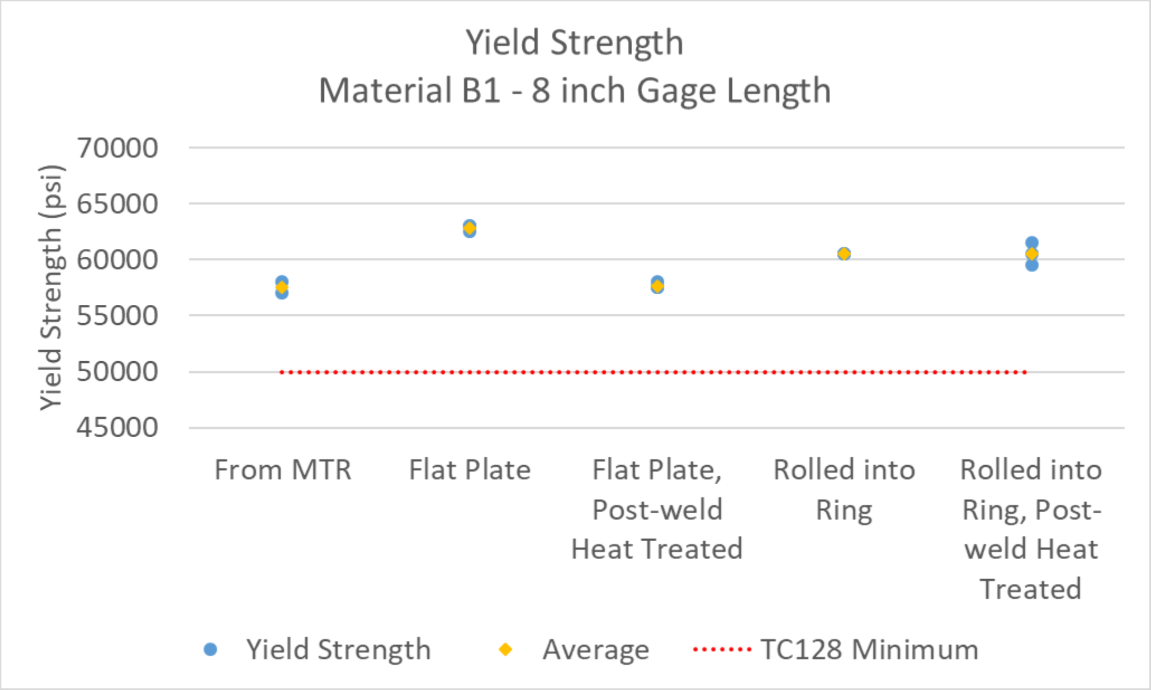


Figure 21. Material B1 – Yield Strength at Each Material Condition (8-inch gauge length)

Values for Material B1's yield strength at each material condition were slightly higher using the 2-inch gauge length coupons than when using the 8-inch gauge length coupons. The 2-inch gauge length coupons exhibited slightly larger variation for a given material condition than the 8-inch gauge length coupons. Regardless of the coupon size tested, Material B1 did not exhibit a consistent change in yield strength when comparing samples in the PWHT condition to samples in the non-PWHT condition, for a given cold-working condition (i.e., flat plate or rolled into ring). The coupons taken from the flat plate exhibited a slightly lower yield strength after PWHT. The coupons taken from the rolled ring exhibited no change (8-inch) or a slight increase (2-inch) in yield strength after PWHT.

The ultimate tensile strengths of the individual coupons of Material B1 and the average value at each stage of fabrication are shown in Figure 22 for coupons having a 2-inch gauge length. The ultimate tensile strengths of the individual coupons of Material B1 and the average value at each stage of fabrication are shown in Figure 23 for coupons having an 8-inch gauge length. These figures also include the values of ultimate tensile strength reported on Material B1's MTR and the minimum and maximum values of ultimate tensile strength required by the TC-128B specification. The ultimate tensile strength of Material B1 was within the required limits in each material condition tested, except for two 8-inch gauge length coupons in the PWHT condition, which were slightly below the minimum value. Note that a flat plate in the PWHT condition is not a condition typically encountered during tank car shell fabrication.

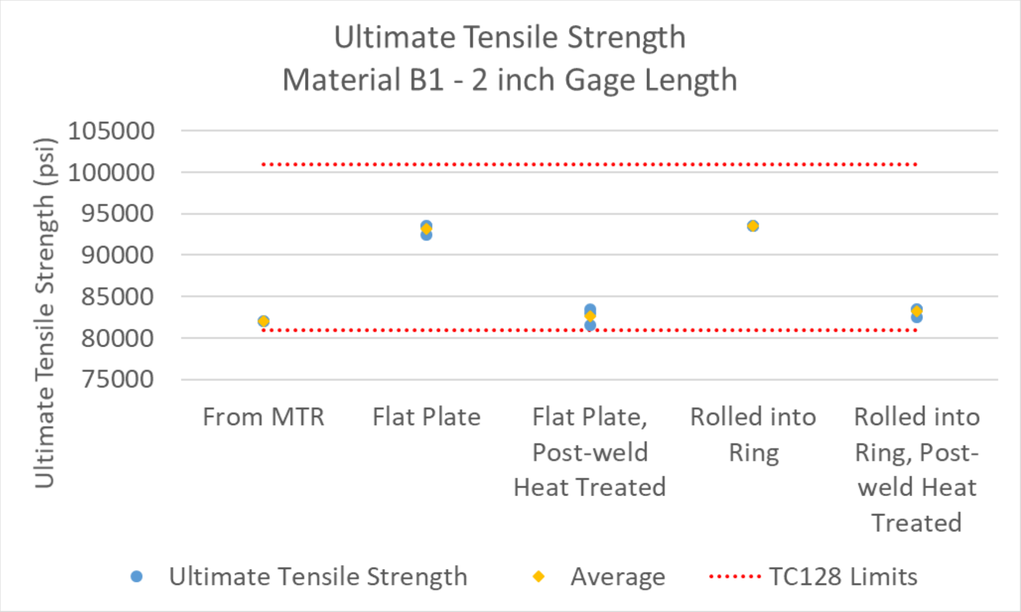


Figure 22. Material B1 – Ultimate Tensile Strength at Each Material Condition (2-inch gauge length)

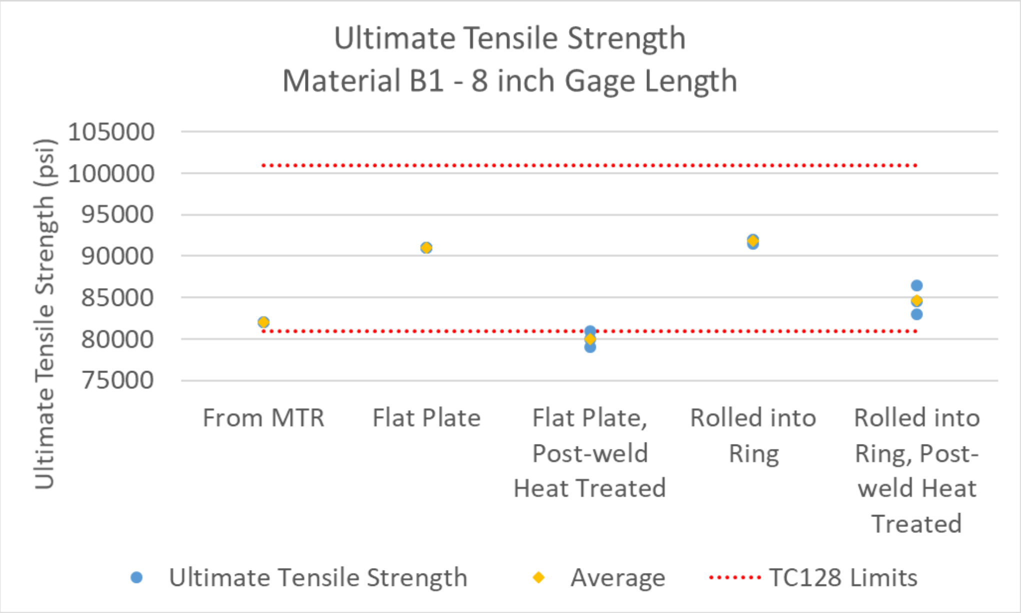


Figure 23. Material B1 – Ultimate Tensile Strength at Each Material Condition (8-inch gauge length)

Values for Material B1's UTS strength at each material condition were slightly higher using the 2-inch gauge length coupons than when using the 8-inch gauge length coupons. Material B1's UTS was consistent with the value reported on the MTR for all samples tested in the PWHT condition. Material B1 showed a lower apparent UTS in the PWHT condition than in the non-PWHT condition for each cold-worked condition (i.e., flat plate or rolled into ring). Material B1 displayed a range of UTS values between 79,000 psi and 93,500 psi depending on the stage of fabrication when the samples were tested. The final condition of the material had a UTS within 3.5 percent with the UTS recorded by the mill on the MTR. Note that the values of UTS that fell below the minimum requirement of TC-128B were for the flat plate after PWHT, a condition not typically encountered during tank car fabrication.

The elongation of the individual coupons of Material B1 and the average value at each stage of fabrication are shown in Figure 24 for measurements on 2-inch cylindrical coupons and Figure 25 for measurements on 8-inch rectangular coupons. Both figures also include the minimum value of elongation in by the TC-128B specification for the appropriate gauge length. The elongation of Material B1 exceeded the required minimum at each material condition that was tested. As the MTR reported elongation in two 8-inch coupons, no MTR results are shown for 2-inch gauge length.

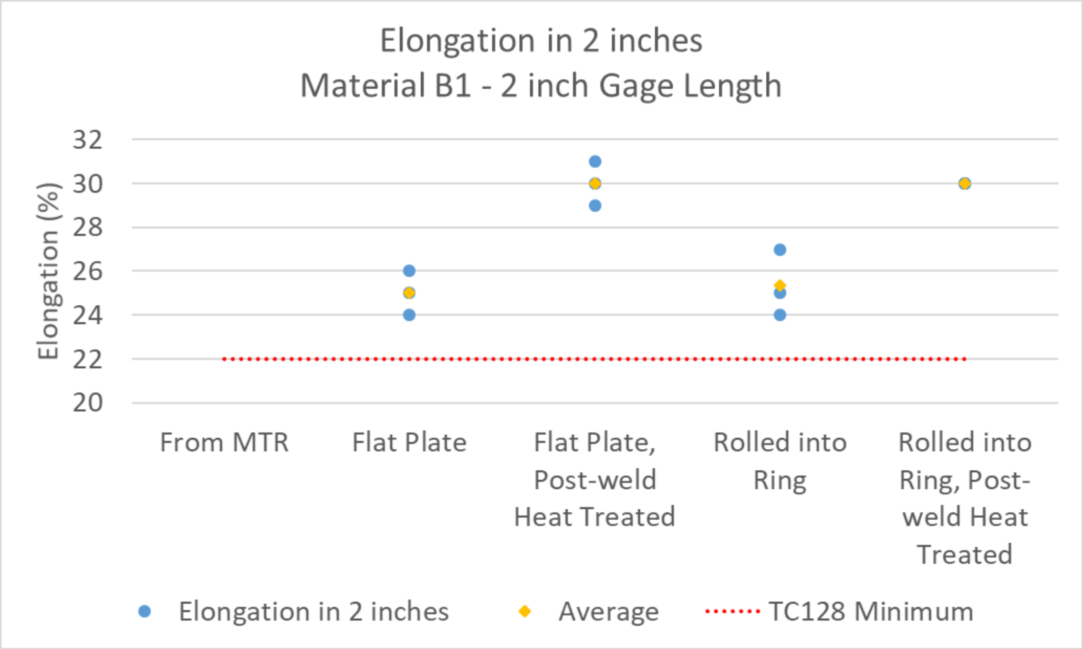


Figure 24. Material B1 – Elongation in 2 inches at Each Material Condition

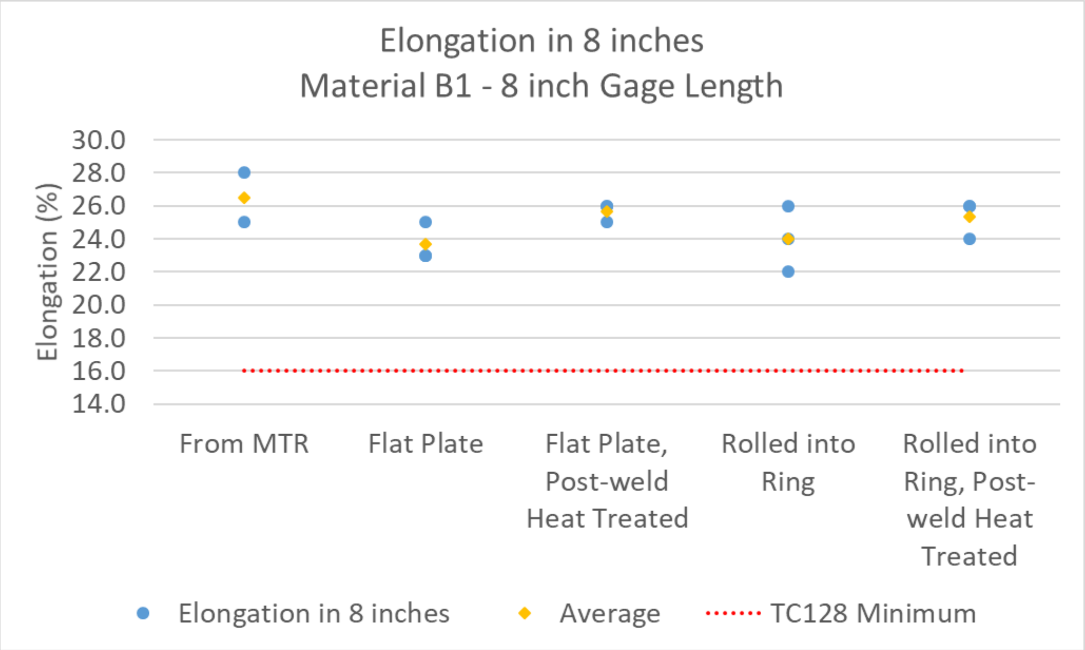


Figure 25. Material B1 – Elongation in 8 inches at Each Material Condition

Material B1's elongation in 2 inches was consistently higher in PWHT samples than in the samples that did not undergo PWHT. The elongation in 2 inches exhibited a range of values from 24 percent to 31 percent. Material B1's elongation in 8 inches was also generally higher in PWHT samples than in the samples that did not undergo PWHT. The samples taken from plate that was rolled into a ring but not given a PWHT exhibited the largest spread in elongation data. The elongation in 8 inches exhibited a range of values from 22 percent to 26 percent.

4.1.2 Tensile Test Results Normalized to MTR Values

The results for yield strength, ultimate tensile strength, and elongation in 8 inches for Material B1 were normalized by dividing the individual and average values by the corresponding average property value from Material B1's MTR. This presentation of results allows for a quick comparison of how the measured properties at each stage of fabrication compare with the value reported on the MTR.

A plot of Material B1's yield strength at each stage of fabrication normalized against the average yield strength reported on Material B1's MTR is shown in Figure 26 for all measurements made using 2-inch gauge length coupons. From this figure it is apparent that the values for yield strength measured during this testing program exceeded the value from the MTR for all material conditions examined.

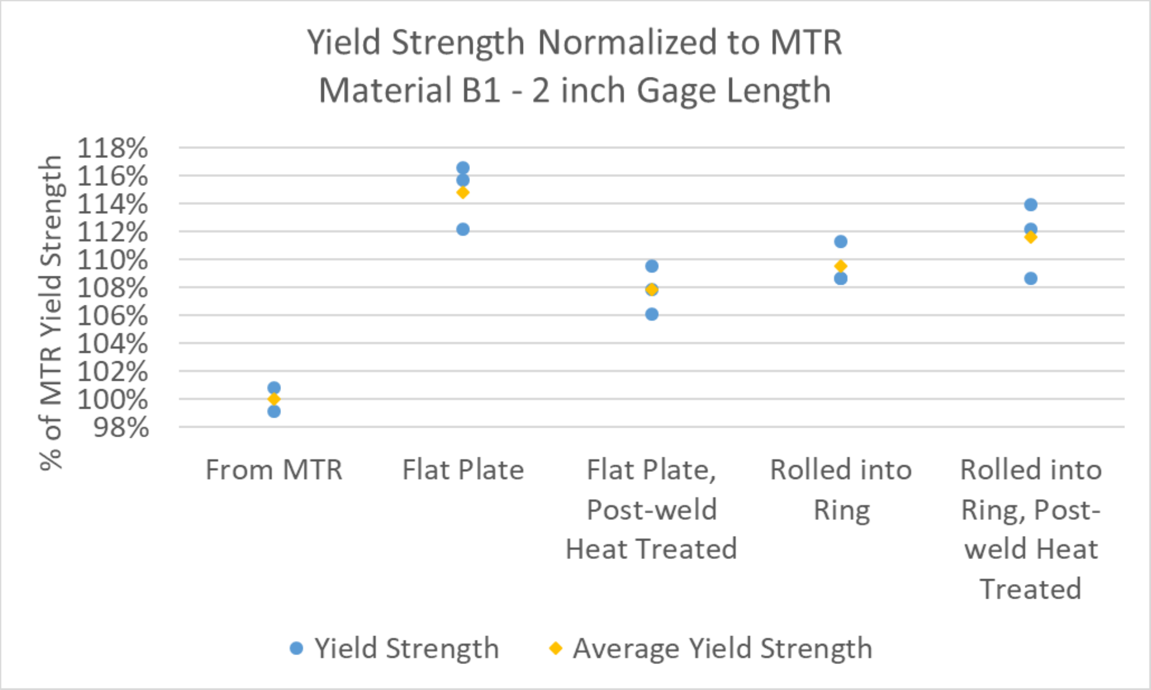


Figure 26. Material B1 – Yield Strength at Each Material Condition Normalized to MTR Yield Strength (2-inch gauge length)

A plot of Material B1's yield strength at each stage of fabrication normalized against the average yield strength reported on Material B1's MTR is shown in Figure 27 for all measurements made using 8-inch gauge length coupons. Consistent with the previous figure, it is apparent that the values for yield strength measured during this testing program exceeded the value from the MTR for all material conditions examined. While the general trend observed in yield strength normalized against MTR average yield strength was consistent for the 2-inch gauge length and the 8-inch gauge length coupons of Material B1, the apparent increase in yield strength over the MTR value was consistently higher when 2-inch cylindrical coupons were used. This difference was observed at each material condition for Material B1.

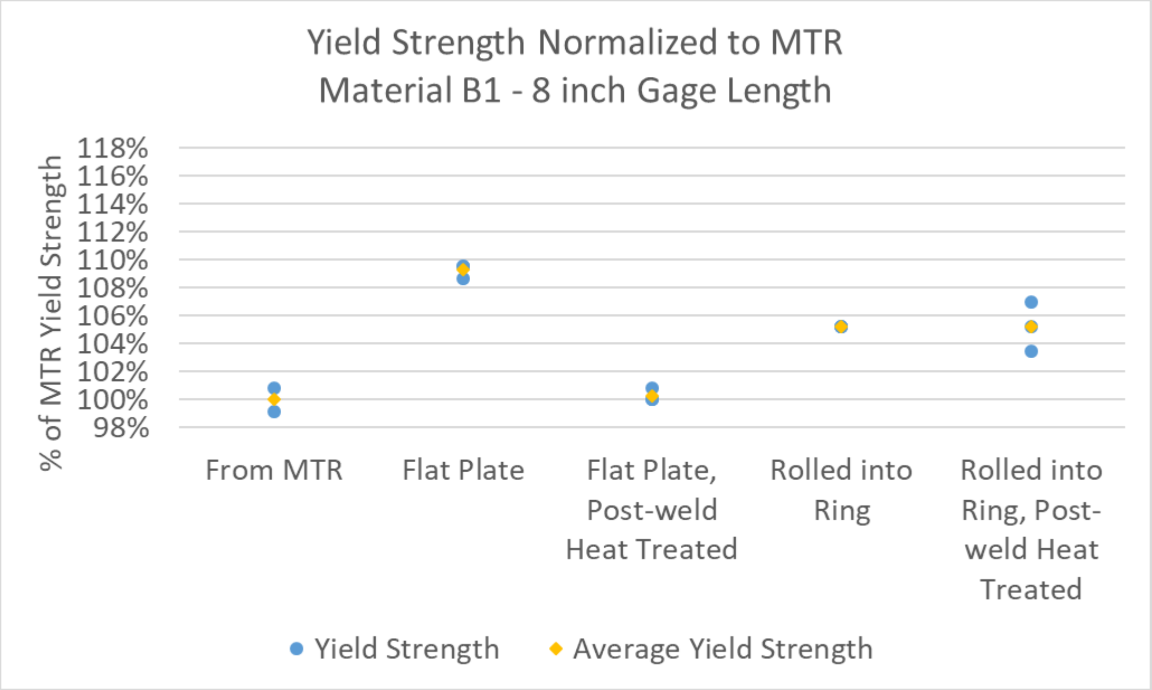


Figure 27. Material B1 – Yield Strength at Each Material Condition Normalized to MTR Yield Strength (8-inch gauge length)

A plot of Material B1's ultimate tensile strength at each stage of fabrication normalized against the average ultimate tensile strength reported on Material B1's MTR is shown in Figure 28 for all measurement made using 2-inch gauge length coupons, and in Figure 29 for 8-inch coupons. From these figures it is apparent that the values for ultimate tensile strength were 1–14 percent higher than the ultimate tensile strength values reported on Material B1's MTR, with the exception of coupons taken from a flat plate that had gone through PWHT. Similar to the MTR-normalized yield strength behavior, the overall trend in ultimate tensile strength was the same for both the 2-inch and 8-inch gauge length coupon, but the values reported from the 2-inch cylindrical coupon tended to be higher.

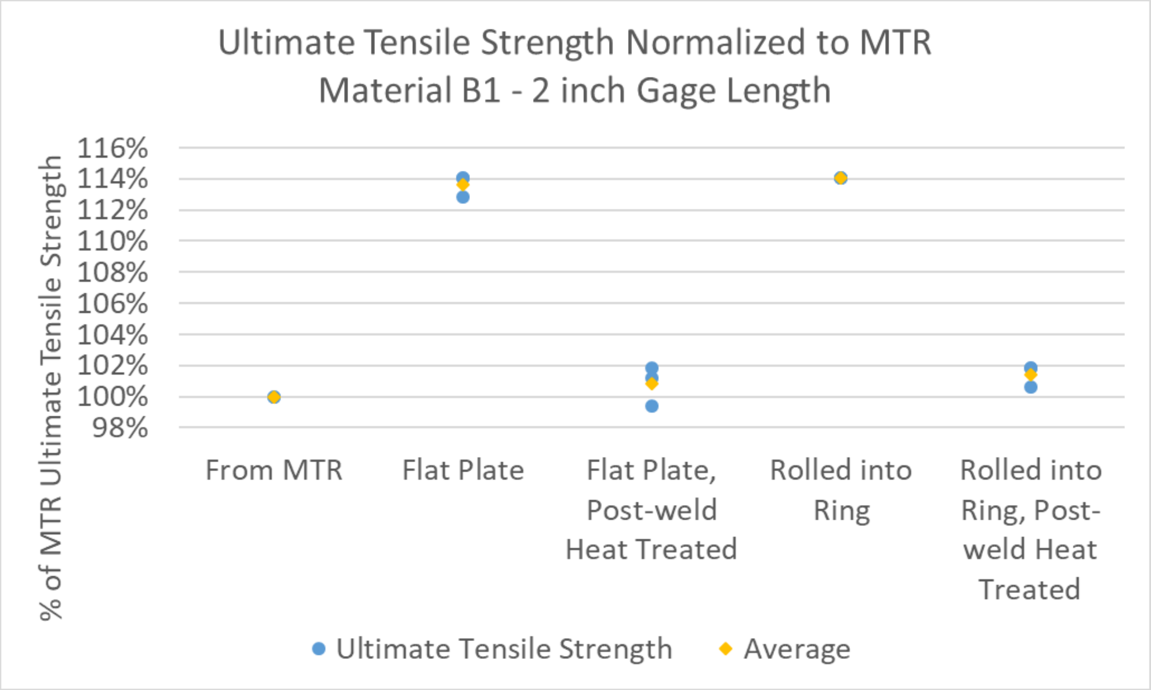


Figure 28. Material B1 – Ultimate Tensile Strength at Each Material Condition Normalized to MTR Ultimate Tensile Strength (2-inch gauge length)

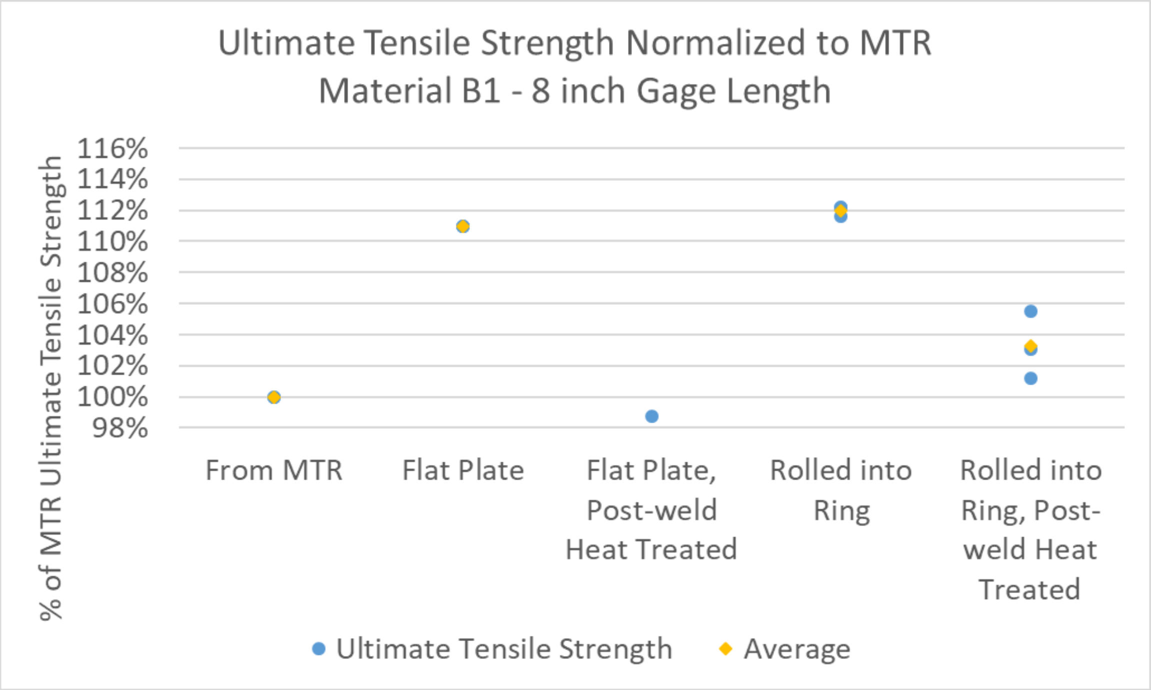


Figure 29. Material B1 – Ultimate Tensile Strength at Each Material Condition Normalized to MTR Ultimate Tensile Strength (8-inch gauge length)

Material B1's MTR reported elongation in 8 inches, thus was it not possible to normalize the elongation in 2 inches against the MTR results. A plot of Material B1's elongation in 8 inches at each stage of fabrication normalized against the average elongation in 8 inches reported on

Material B1's MTR is shown in Figure 30. From this figure it is apparent that the values for elongation in 8 inches measured during this testing program were lower than the average value obtained from the MTR data for all material conditions examined. Note that the MTR reported two values with a considerable spread in reported values.

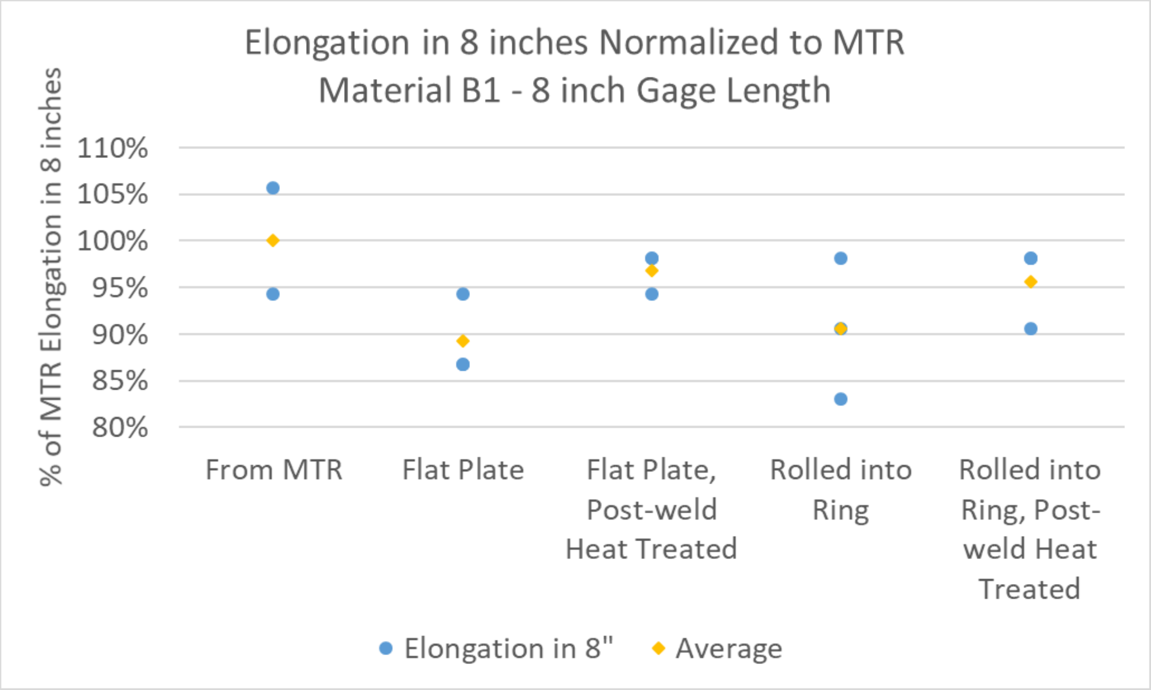


Figure 30. Material B1 – Elongation in 8 inches at Each Material Condition Normalized to MTR Elongation in 8 inches

4.1.3 Tensile Test Results Normalized to Flat Plate Results

The results for yield strength, ultimate tensile strength, and elongation in 8 inches for Material B1 were normalized by dividing the individual and average values by the corresponding average property value from Material B1 in the "as-received" flat plate condition. This normalization was conducted to provide a quick and straightforward comparison of how the mechanical properties of Material B1 changed at each stage of fabrication as compared to the as-received flat plate. Note that the results reported on the MTR are included in each figure in this section for completeness.

A plot of Material B1's yield strength at each stage of fabrication normalized against the average yield strength of the as-received flat plate is shown in Figure 31 for all measurements made using 2-inch gauge length coupons. From this figure it is apparent that the values for yield strength measured during this testing program decreased compared to the average value from the as-received flat plate for all subsequent material conditions examined.

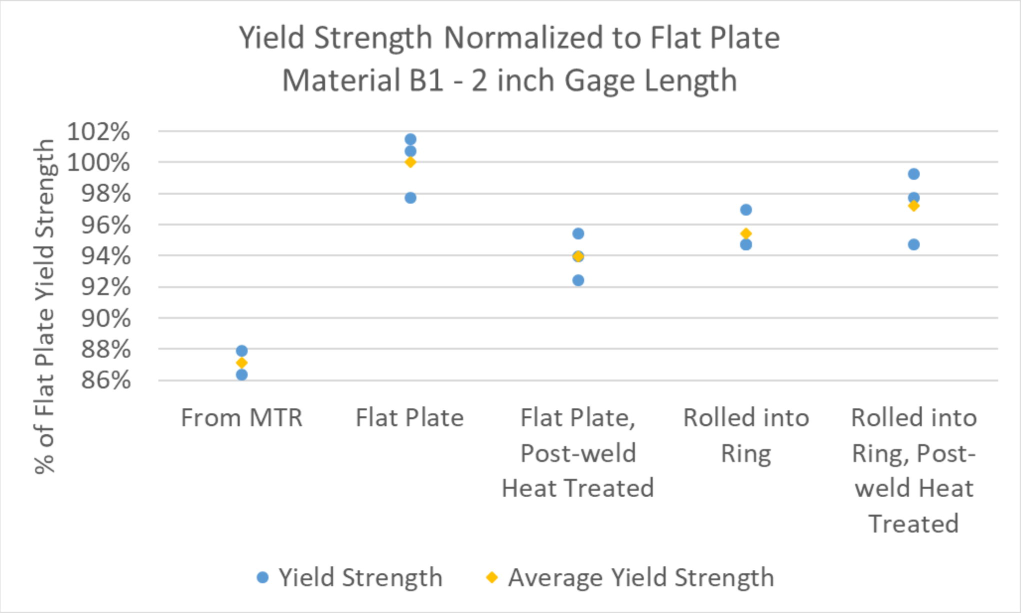


Figure 31. Material B1 – Yield Strength at Each Material Condition Normalized to Average Flat Plate Yield Strength (2-inch gauge length)

A plot of Material B1's yield strength at each stage of fabrication normalized against the average yield strength of the as-received flat plate is shown in Figure 32 for all measurements made using 8-inch gauge length coupons. From this figure it is apparent that the values for yield strength measured during this testing program decreased compared to the average value from the as-received flat plate for all subsequent material conditions examined. This result is consistent with the results for Material B1 using a 2-inch gauge length coupon.

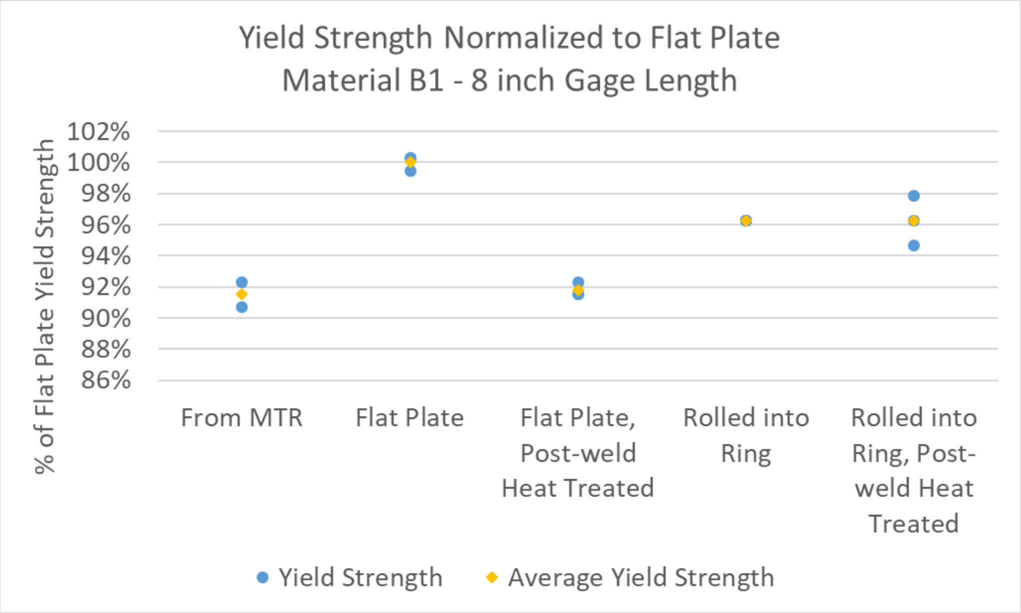


Figure 32. Material B1 – Yield Strength at Each Material Condition Normalized to Average Flat Plate Yield Strength (8-inch gauge length)

The effects of fabrication processes on Material B1's yield strength are somewhat inconsistent. Cold-rolling of the flat plate into a ring would be expected to increase the yield strength of the material, as this is a form of strain-hardening. However, the yield strength decreased by, on average, 4–5 percent in the cold-rolled ring compared to the as-received flat plate. The cold-rolled and PWHT results exhibit a smaller apparent decrease in yield strength compared to the PWHT flat plate.

A plot of Material B1's ultimate tensile strength at each stage of fabrication normalized against the average ultimate tensile strength measured for the as-received flat plate is shown in Figure 33 for all 2-inch gauge length coupon results. From this figure it is apparent that the values for ultimate tensile strength measured during this testing program varied from about 12 percent below the as-received plate value (after heat treatment, regardless of whether first cold-rolled) to approximately 1 percent higher than the as-received plate value when in the cold-rolled condition.

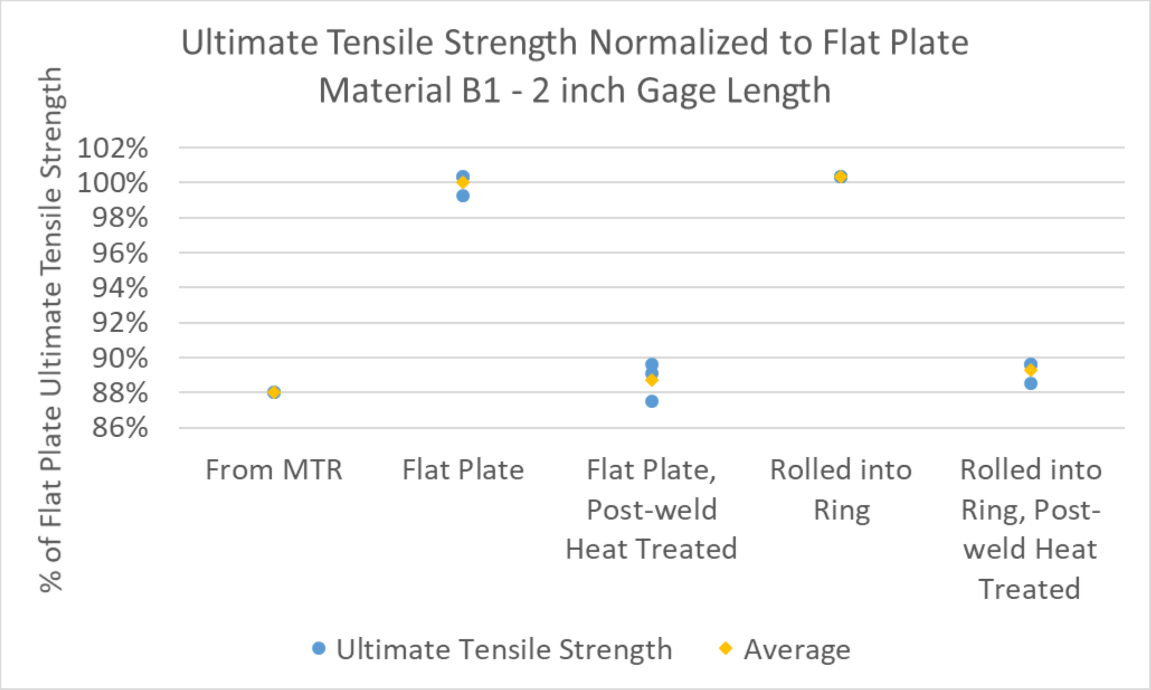


Figure 33. Material B1 – Ultimate Tensile Strength at Each Material Condition Normalized to Average Flat Plate Ultimate Tensile Strength (2-inch gauge length)

A plot of Material B1's ultimate tensile strength at each stage of fabrication normalized against the average ultimate tensile strength measured for the as-received flat plate is shown in Figure 34 for all 8-inch gauge length coupon results. From this figure it is apparent that the same general trend in properties as was observed in the 2-inch gauge length coupon results was also seen in the 8-inch gauge length coupon results, as expected.

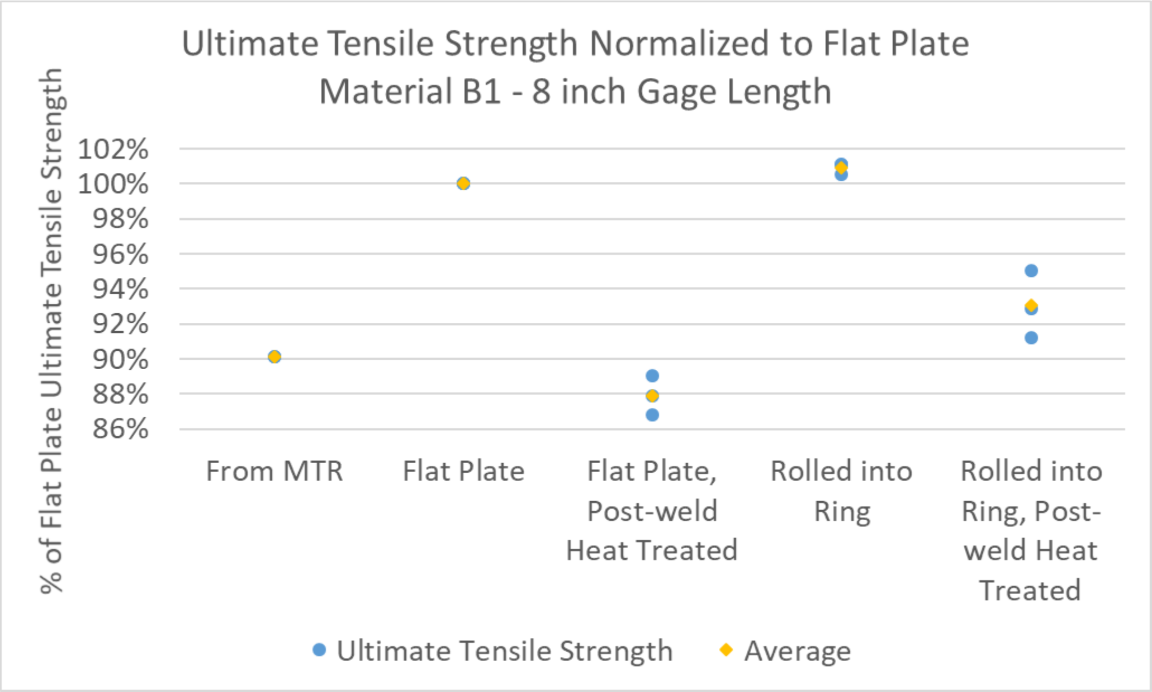


Figure 34. Material B1 – Ultimate Tensile Strength at Each Material Condition Normalized to Average Flat Plate Ultimate Tensile Strength (8-inch gauge length)

The effects of fabrication processes on the ultimate tensile strength of Material B1 were generally as expected. Cold-rolling the flat plate resulted in a slight increase in the ultimate tensile strength of the material. PWHT resulted in a decrease in the ultimate tensile strength of Material B1, regardless of whether or not the sample had been cold-rolled. The apparent decrease in Material B1's ultimate tensile strength was larger for the flat plate that had undergone PWHT compared to the cold-rolled ring that had undergone PWHT.

A plot of Material B1's elongation in 2 inches at each stage of fabrication normalized against the average elongation in 2 inches measured for the as-received flat plate is shown in Figure 35. Recall that Material B1's MTR reported an elongation in 8 inches, and thus no results from the MTR are included in this figure. From this figure it is apparent that the average values for elongation in 2 inches measured during this testing program varied from approximately the as-received plate value (after being cold-rolled) to approximately 20 percent higher than the as-received plate value when in the PWHT condition, whether or not first undergoing cold-rolling.

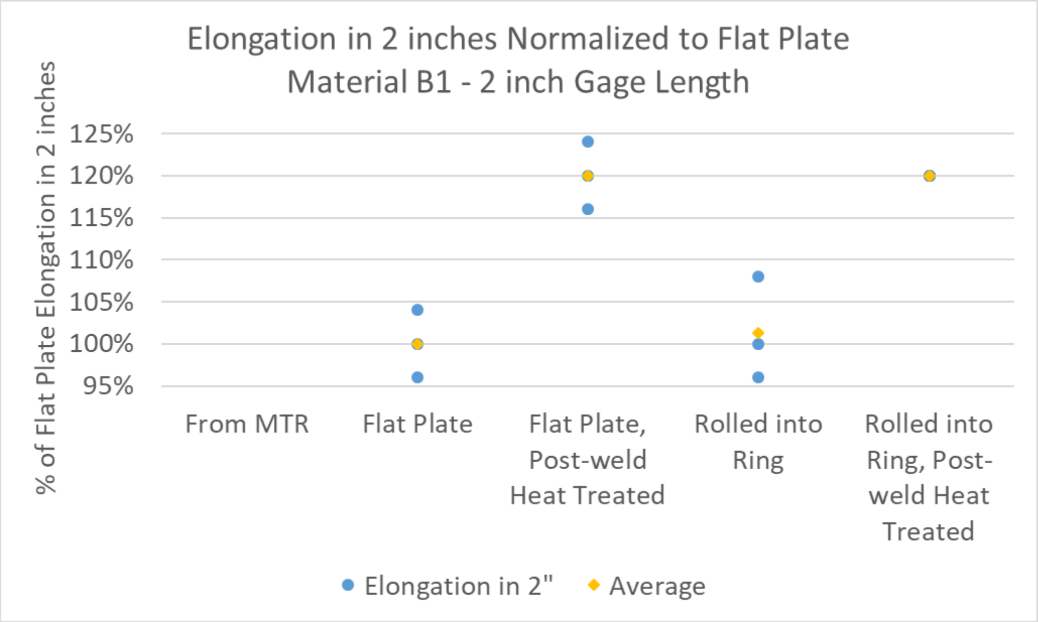


Figure 35. Material B1 – Elongation in 2 inches at Each Material Condition Normalized to Average Flat Plate Elongation in 2 inches

A plot of Material B1's elongation in 8 inches at each stage of fabrication normalized against the average elongation in 8 inches measured for the as-received flat plate is shown in Figure 36. From this figure, the general behavior of elongation in each material condition was similar to the measurements made using 2-inch gauge length coupons, but the magnitudes of apparent change were smaller when an 8-inch gauge length coupon was used.

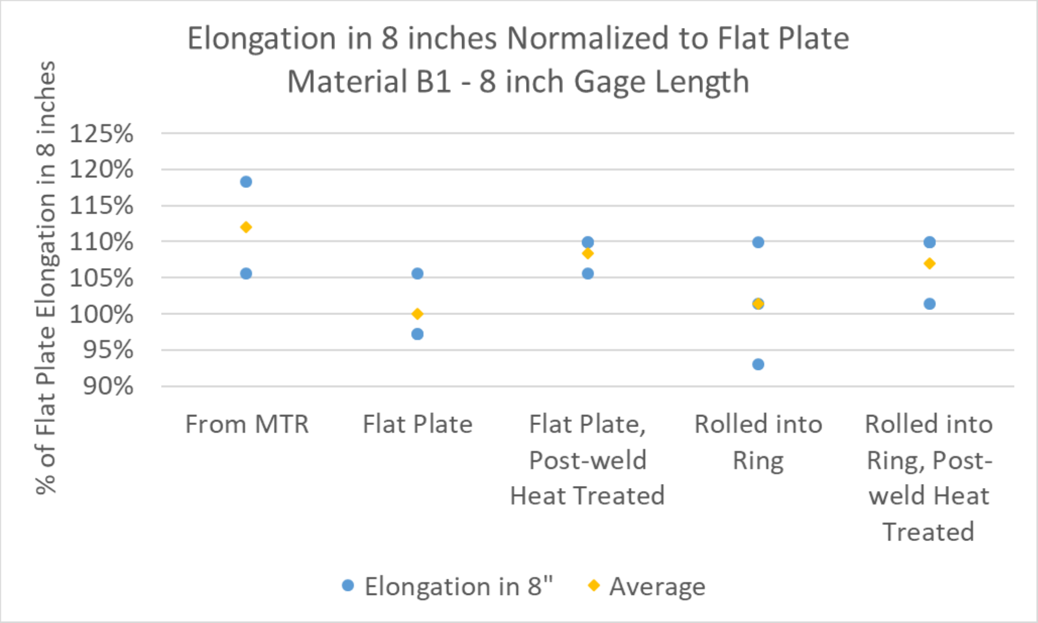


Figure 36. Material B1 – Elongation in 8 inches at Each Material Condition Normalized to Average Flat Plate Elongation in 8 inches

The results for elongation of Material B1 at different stages of fabrication was as expected. Cold-rolling of the tank's ring is a form of cold-working, associated with a decrease in ductility compared to the as-received plate. In the case of Material B1, that decrease was either small or non-existent. From these results, heat treatment on either a flat plate of Material B1 or a cold-rolled ring segment of Material B1 resulted in a ductility that exceeded the ductility of the as-received flat plate.

4.1.4 Tensile Test Results Normalized to Minimum Specification Values

The results for yield strength, ultimate tensile strength, and elongation in 8 inches for Material B1 were normalized by dividing the individual and average values by the corresponding property value from the TC-128B specification minimum material properties. This presentation of results allows for a quick comparison of how the measured properties at each stage of fabrication compare with the minimum values required. The results are presented in Figure 37 through Figure 42. These figures show that the minimum properties were exceeded by nearly every coupon of Material B1 at every stage of fabrication. The exceptions were for the ultimate tensile strength of several 8-inch coupons in the flat plate, post-weld, heat-treated condition, which were slightly below the minimum. This material condition is not typically encountered during tank fabrication.

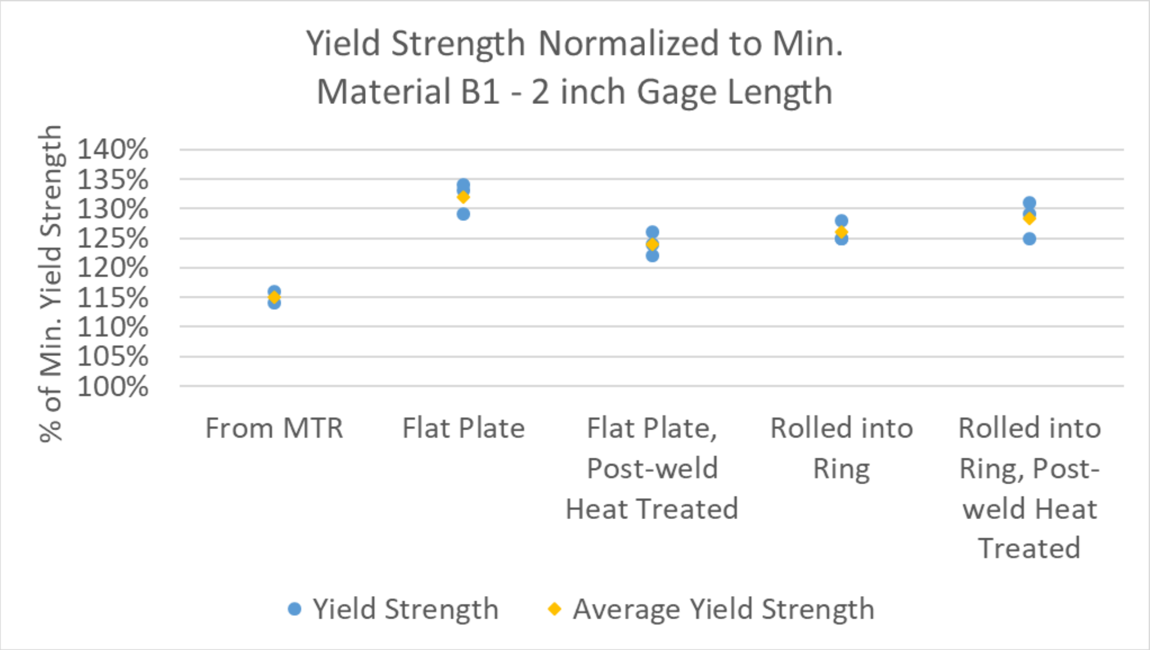


Figure 37. Material B1 – Yield Strength at Each Material Condition Normalized to Minimum Yield Strength in TC 128B Specification (2-inch gauge length)

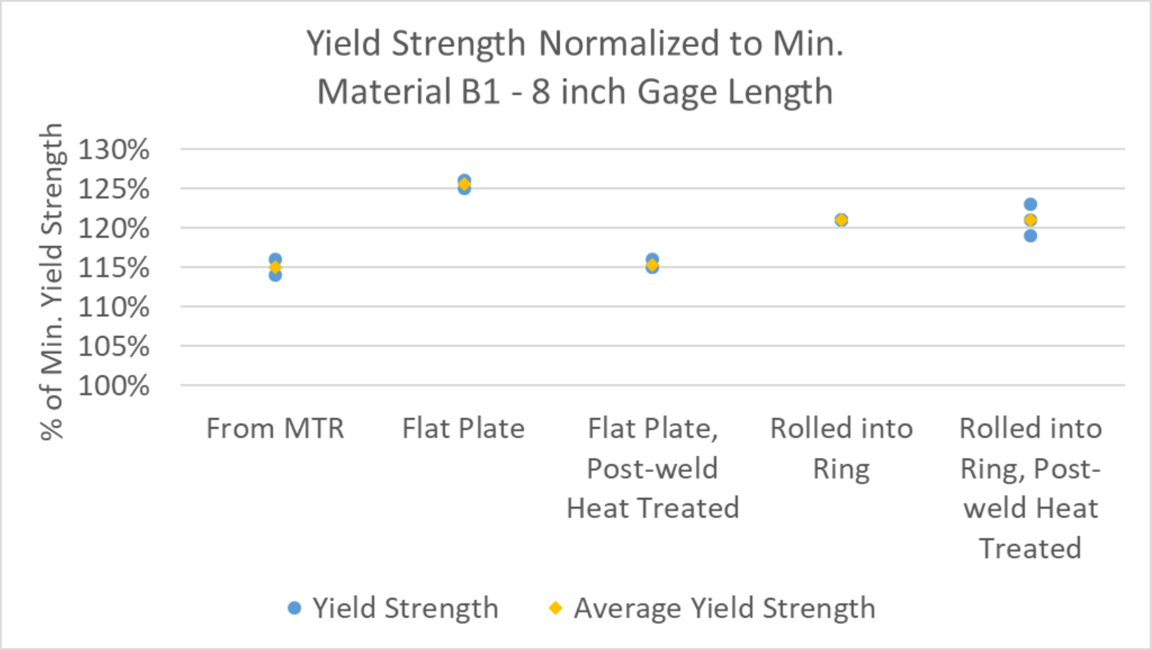


Figure 38. Material B1 – Yield Strength at Each Material Condition Normalized to Minimum Yield Strength in TC 128B Specification (8-inch gauge length)

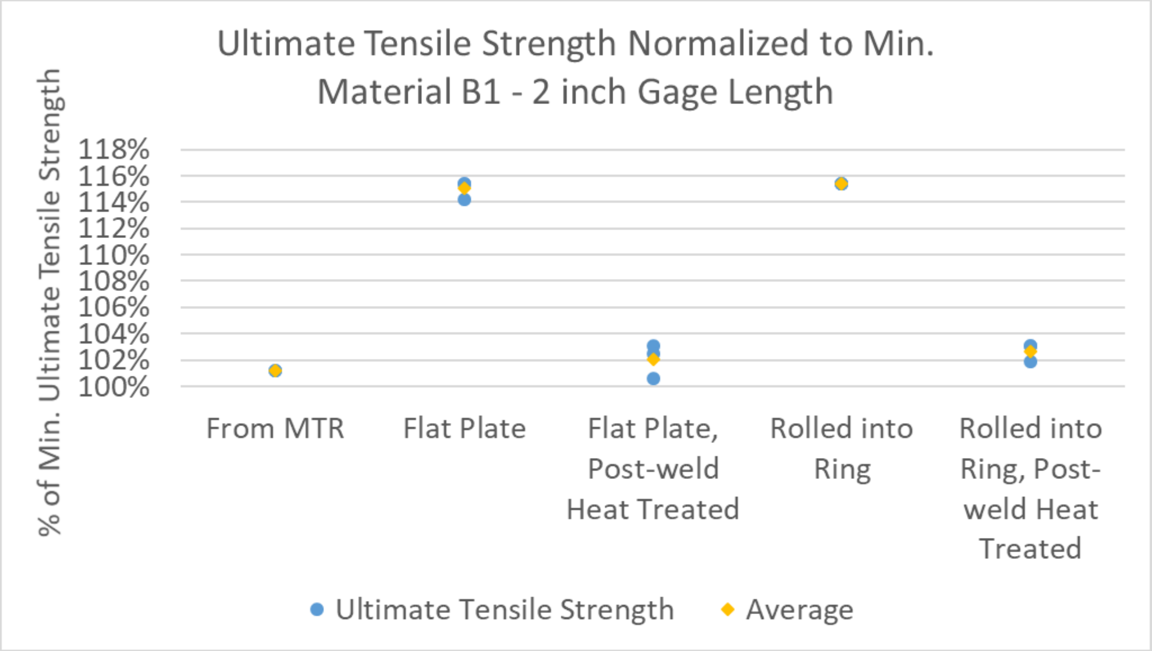


Figure 39. Material B1 – Ultimate Tensile Strength at Each Material Condition Normalized to Minimum Ultimate Tensile Strength in TC 128B Specification (2-inch gauge length)

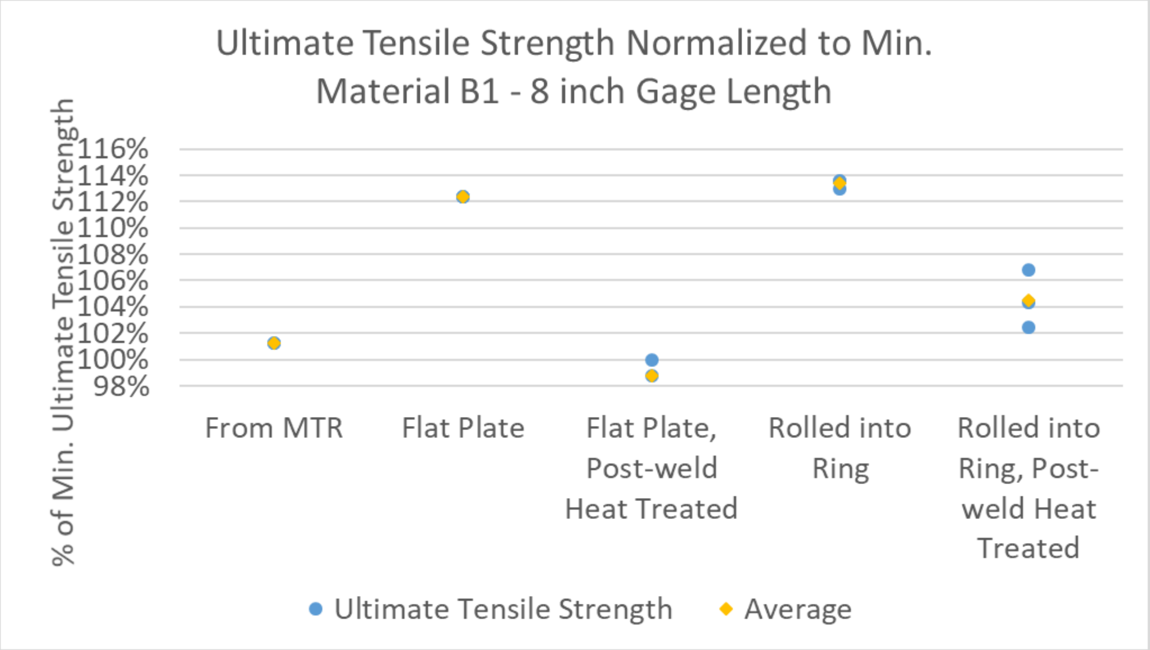


Figure 40. Material B1 – Ultimate Tensile Strength at Each Material Condition Normalized to Minimum Ultimate Tensile Strength in TC 128B Specification (8-inch gauge length)

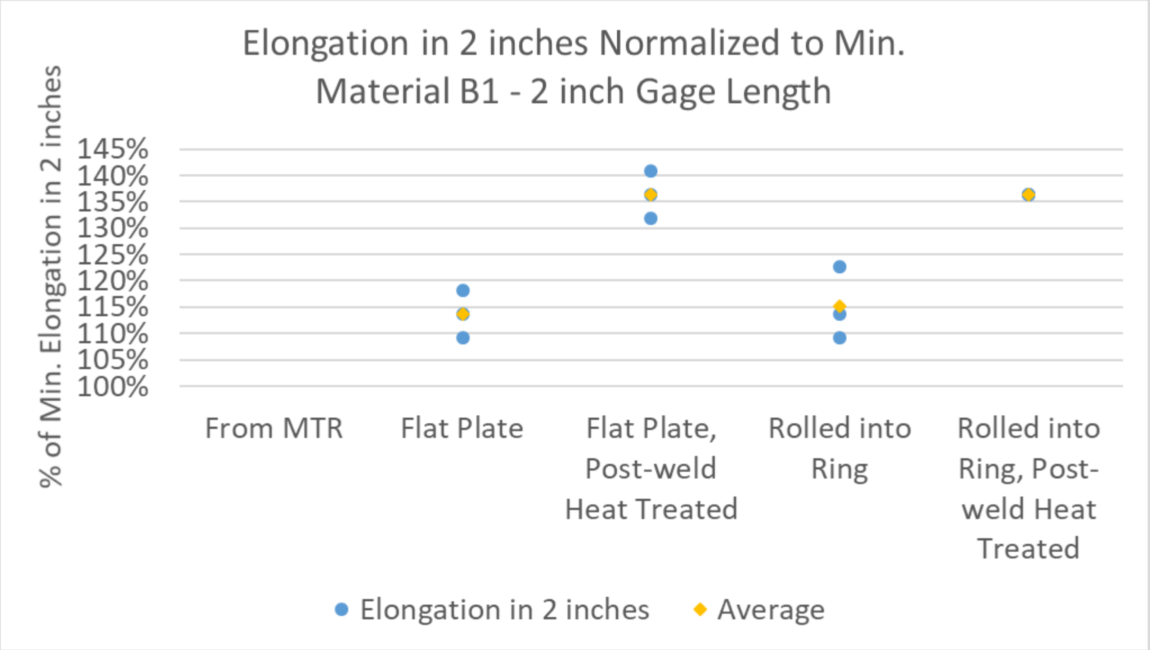


Figure 41. Material B1 – Elongation at Each Material Condition Normalized to Minimum Elongation in TC 128B Specification (2-inch gauge length)

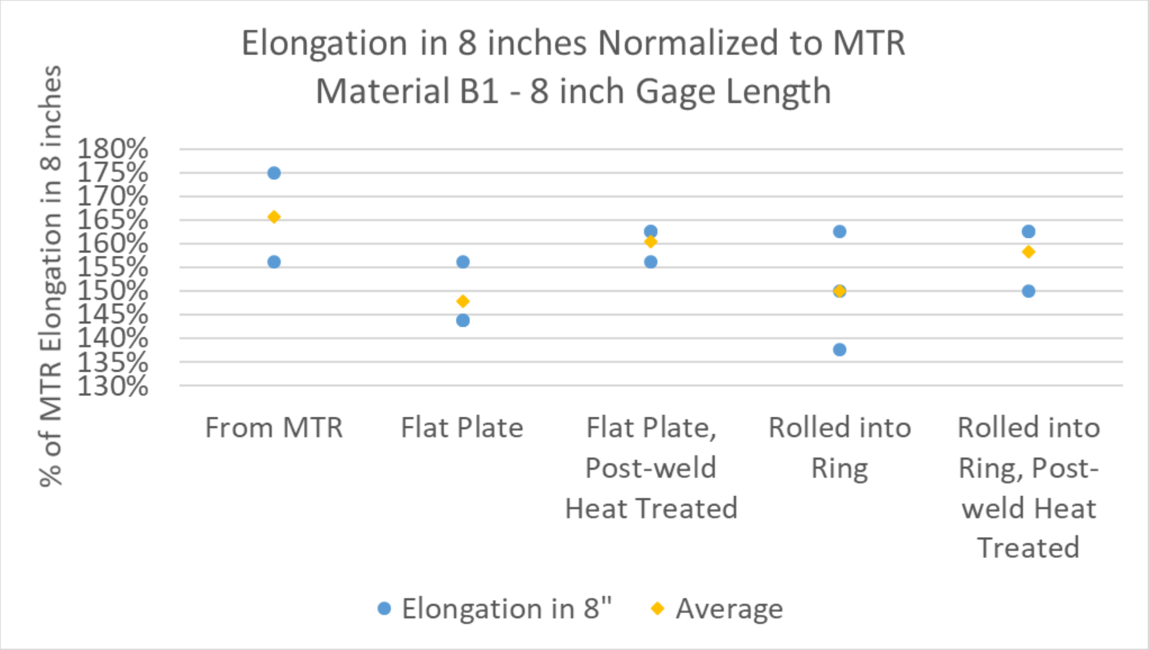


Figure 42. Material B1 – Elongation at Each Material Condition Normalized to Minimum Elongation in TC 128B Specification (8-inch gauge length)

4.1.5 Microstructure Evaluation

Figure 43 contains photomicrographs of the microstructure at the mid-thickness of Material B1 samples during each stage of fabrication. Below each image is a description of the material condition observed by the lab making the microstructural examination.

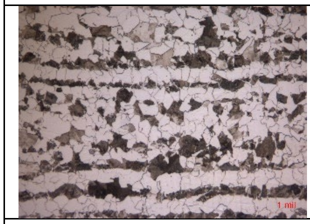
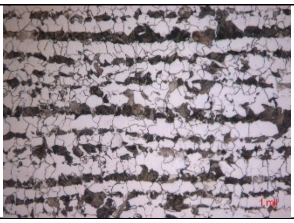
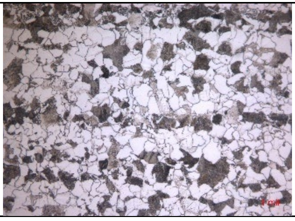
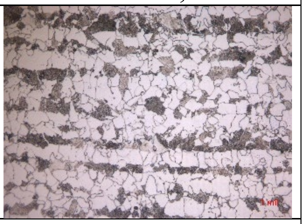
Flat Plate	Cold Worked	Flat Plate, PWHT	Cold Worked, PWHT
			
Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).

Figure 43. Material B1 – Photomicrographs Showing Typical Microstructure at Mid-thickness, 500x Magnification, Nital Etch

Figure 44 contains photomicrographs of the microstructure at the centerline of Material 1 samples during each stage of fabrication. Below each image is a description of the material condition observed by the lab making the microstructural examination.

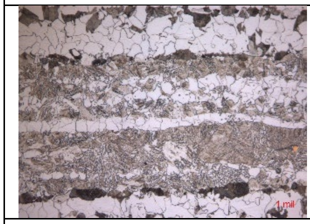
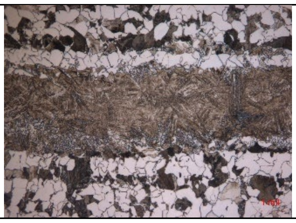
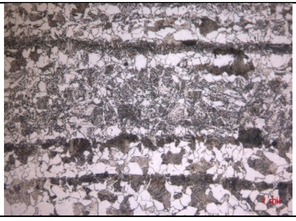
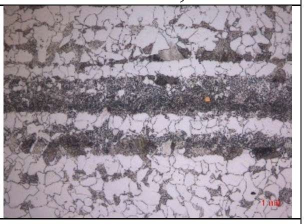
Flat Plate	Cold Worked	Flat Plate, PWHT	Cold Worked, PWHT
			
Microstructure consists of longitudinal bands of martensite (light brown) in addition to the equiaxed ferrite grains (white) and longitudinal pearlite bands (dark brown). Martensite is considerably harder and more brittle than ferrite or pearlite.	Microstructure consists of longitudinal bands of martensite (light brown) in addition to the equiaxed ferrite grains (white) and longitudinal pearlite bands (dark brown). Cold working had no noticeable effects on the martensite.	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown). The heat treatment has dissolved the martensite resulting in what should be a considerably softer, more ductile microstructure.	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown). The heat treatment has dissolved the martensite resulting in what should be a considerably softer, more ductile microstructure.

Figure 44. Material B1 – Photomicrographs Showing Typical Microstructure at Centerline, 500x Magnification, Nital Etch

4.1.6 Chemical Composition

The MTR provided by Manufacturer B for Material B1 included analysis of the chemical composition of the plate. The chemistry data is shown in Table 9, alongside the chemistry limits for both product and ladle analysis required by M-1002 (Association of American Railroads, 2007). The chemistry of Material B1 was within the limits required by M-1002 for the elements reported.

Table 9. Chemical Composition of Material B1

Element	Material B1	M-1002 Requirement Heat Analysis	M-1002 Requirement Product Analysis
C	0.21	≤ 0.24	≤ 0.26
Mn	1.42	1.00 – 1.65	1.00 – 1.70
P	0.009	≤ 0.025	≤ 0.025
S	< 0.001	≤ 0.015	≤ 0.015
Si	0.33	0.15 – 0.40	0.13 – 0.45
Cu	0.21	0.35	0.35
Ni	0.11	No limit	No limit
Cr	0.2	No limit	No limit
Mo	0.02	No limit	No limit
V	0.044	≤ 0.08	≤ 0.084
Nb	Not reported	Per ASTM A20	Per ASTM A20
Ti	0.002	≤ 0.02	≤ 0.02
N	0.0052	≤ 0.01	≤ 0.012
B	0.0004	≤ 0.0005	≤ 0.0005
Sn	0.008	≤ 0.02	≤ 0.02
C_{eq}	0.52	≤ 0.53	≤ 0.55
Al (total)	0.024	0.015 – 0.060	0.015 – 0.060
Al (soluble)	0.023	≥ 0.015	≥ 0.015
Cu + Ni + Cr + Mo*	0.54	≤ 0.65	≤ 0.65
Ti/N *	0.38	≤ 4.0	≤ 4.0

*Not listed on MTR. Calculated from values on MTR.

4.2 Material B2

The tensile testing results from Material B2 are presented in this section in four ways: individual and average values of yield strength, ultimate tensile strength, and elongation as-is; individual and average values normalized against the corresponding values from Material B2's MTR; individual and average values normalized against the corresponding values the "as-received" flat plate of Material B2; and individual and average values were normalized against the corresponding minimum values from the TC-128B specification.

4.2.1 Tensile Test Results

The tensile test results measured in this project for Material B2 are presented alongside the values from Material B2's MTR in Table 10.

Table 10. Material B2 – Summary of Tensile Test Results

		From MTR	Flat Plate	Flat Plate, PWHT	Rolled into Ring	Rolled into Ring, PWHT
Yield Strength (psi)	Coupon 1	-	68,500	68,500	64,500	71,500
	Coupon 2	-	68,500	71,500	65,500	71,000
	Coupon 3	-	68,500	71,500	64,000	68,000
	Average	*66,000*	*68,500*	*70,500*	*64,667*	*70,167*
Ultimate Tensile Strength (psi)	Coupon 1	-	94,500	91,000	95,500	91,000
	Coupon 2	-	94,500	91,500	95,500	91,500
	Coupon 3	-	95,000	92,000	96,000	91,000
	Average	*89,000*	*94,667*	*91,500*	*95,667*	*91,167*
Elongation in 2" (%)	Coupon 1	-	28	29	26	30
	Coupon 2	-	27	30	26	29
	Coupon 3	-	28	29	27	29
	Average	*36*	*28*	*29*	*26*	*29*

The yield strength of the individual coupons of Material B2 and the average value at each stage of fabrication are shown in Figure 45. This figure also includes the value of yield strength reported on Material B2's MTR and the minimum value of yield strength required by the TC-128B specification. The yield strength of Material B2 exceeded the required minimum in each material condition tested.

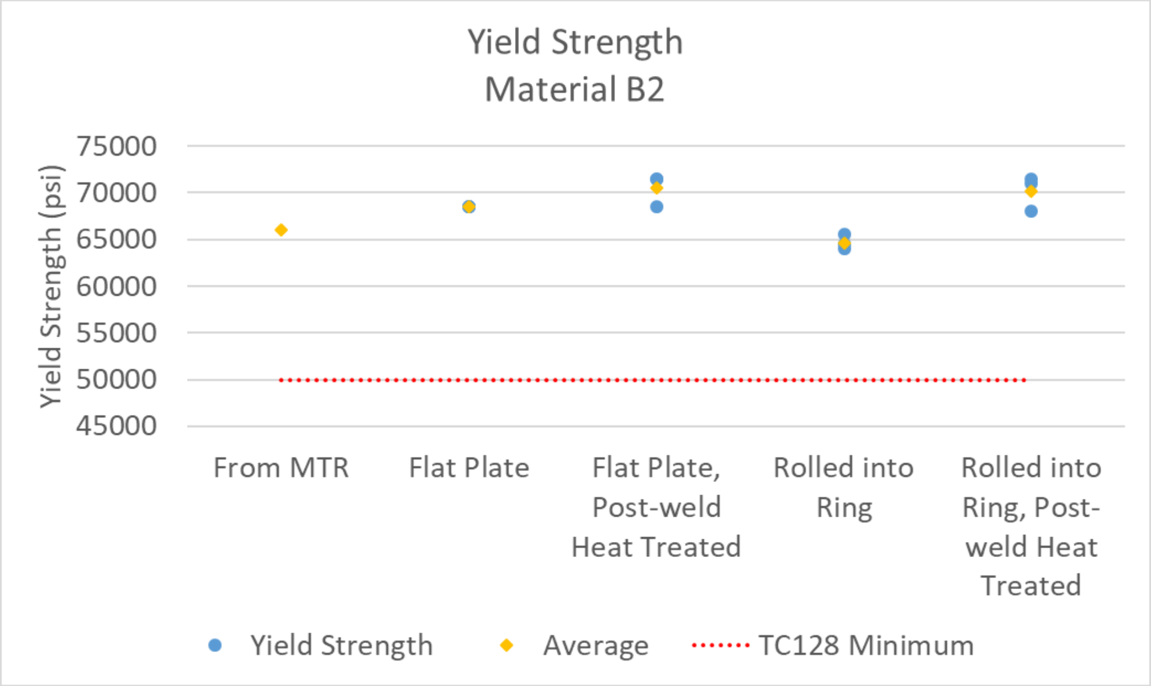


Figure 45. Material B2 – Yield Strength at Each Material Condition

Material B2's yield strength at the various stages of fabrication was higher than the yield strength reported on the MTR for coupons from three of the four stages of fabrication The yield strength measured from the coupons taken from the rolled ring without PWHT were slightly lower than the value reported on the MTR. Focusing on the samples taken from the four stages of fabrication, the yield strength scatter was relatively narrow; values ranged from 64,000 to 71,500 psi. Material B2 exhibited a slightly higher yield strength for coupons tested in the PWHT condition compared to coupons in the same cold-working condition that did not undergo PWHT.

The ultimate tensile strength of the individual coupons of Material B2 and the average value at each stage of fabrication are shown in Figure 46. This figure also includes the value of ultimate tensile strength reported on Material B2's MTR and the minimum and maximum values of ultimate tensile strength required by the TC-128B specification. The ultimate tensile strength of Material B2 was within the required limits in each material condition that was tested.

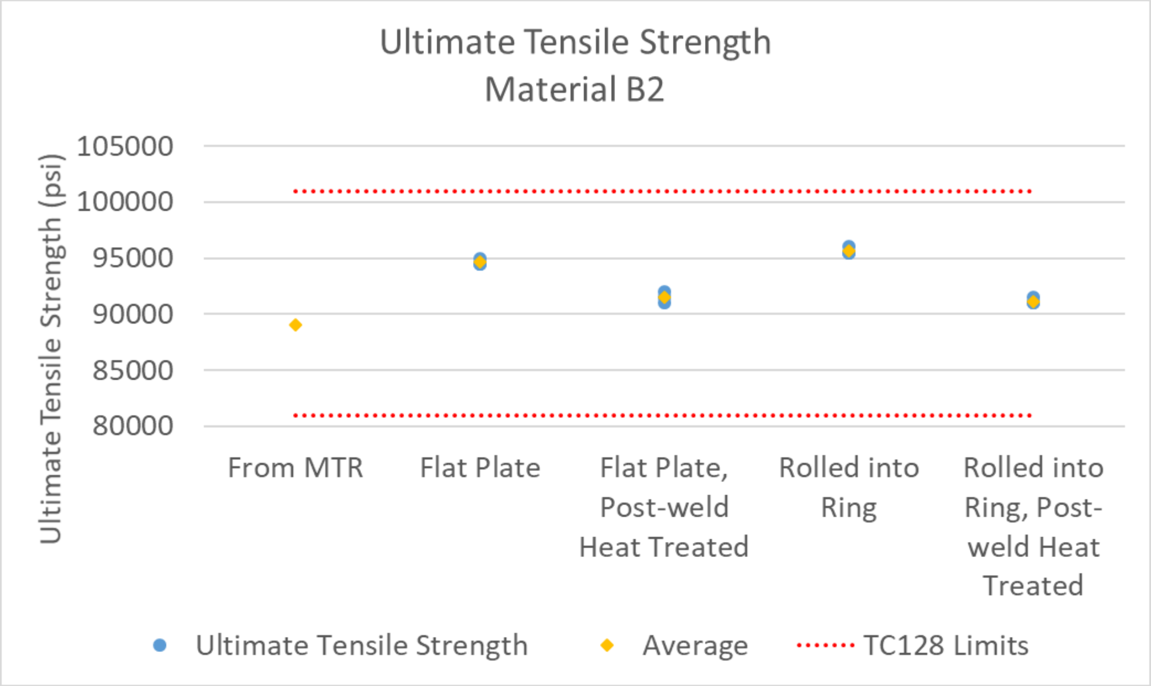


Figure 46. Material B2 – Ultimate Tensile Strength at Each Material Condition

Material B2's UTS was higher than the value reported on the MTR for all samples tested, regardless of the material condition. Material B2 showed a lower apparent UTS in the PWHT condition than in the non-PWHT condition for each cold-worked condition (i.e., flat plate or rolled into ring). Material B2 displayed a range of UTS values between 91,000 psi and 96,000 psi depending on the stage of fabrication when the samples were tested. The final condition of the material (rolled into ring, PWHT) had a UTS within 2.5 percent with the UTS recorded by the mill on the MTR. No values of UTS were measured that were outside of the range of acceptable values for TC-128B.

The elongation in 2 inches of the individual coupons of Material B2, and the average value at each stage of fabrication are shown in Figure 47. This figure also includes the value of elongation in 2 inches reported on Material B2's MTR and the minimum value of elongation in 2 inches required by the TC-128B specification. The elongation in 2 inches of Material B2 exceeded the required minimum at each material condition tested.

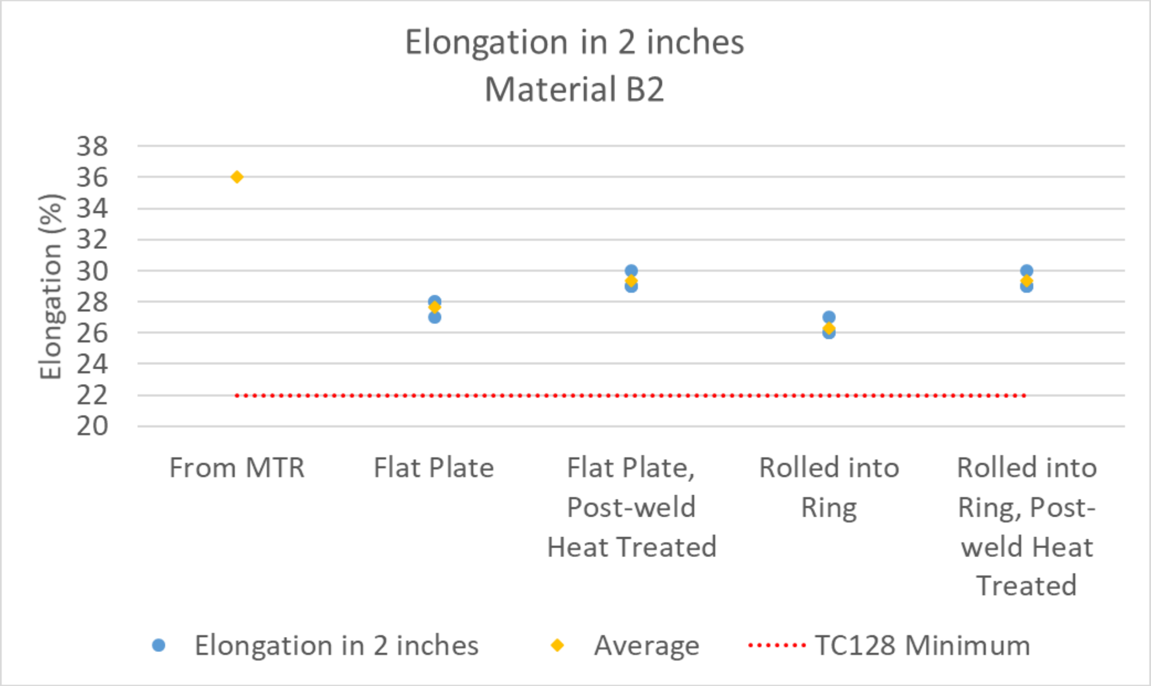


Figure 47. Material B2 – Elongation in 2 inches at Each Material Condition

The value for Material B2's elongation in 2 inches listed on the MTR was higher than the elongation in 2 inches measured at any stage of fabrication. Material B2's elongation in 2 inches exceeded the minimum requirement for TC-128B at each stage of fabrication. Material B2's elongation in 2 inches was consistently higher for samples in the PWHT condition than samples in the same cold-worked condition (i.e., flat plate or rolled into ring) without PWHT. The range of elongation measurements were relatively narrow, ranging from 26 to 30 percent.

4.2.2 Tensile Test Results Normalized to MTR Values

The results for yield strength, ultimate tensile strength, and elongation in 2 inches for Material B2 were normalized by dividing the individual and average values by the corresponding property value from Material B2's MTR. This presentation of results allows for a quick comparison of how the measured properties at each stage of fabrication compare with the value reported on the MTR.

A plot of Material B2's yield strength at each stage of fabrication normalized against the yield strength reported on Material B2's MTR is shown in Figure 48. From Figure 48 it is apparent that the values for yield strength measured during this testing program varied from 2 percent below the MTR value (after cold-rolling the ring) to as much as 8 percent higher than the value reported on the MTR when in the PWHT condition. Note that when Material B2 was in the PWHT condition, regardless of whether it had also undergone cold-rolling, the measured values of yield strength exhibited the largest spread compared to the other material conditions examined.

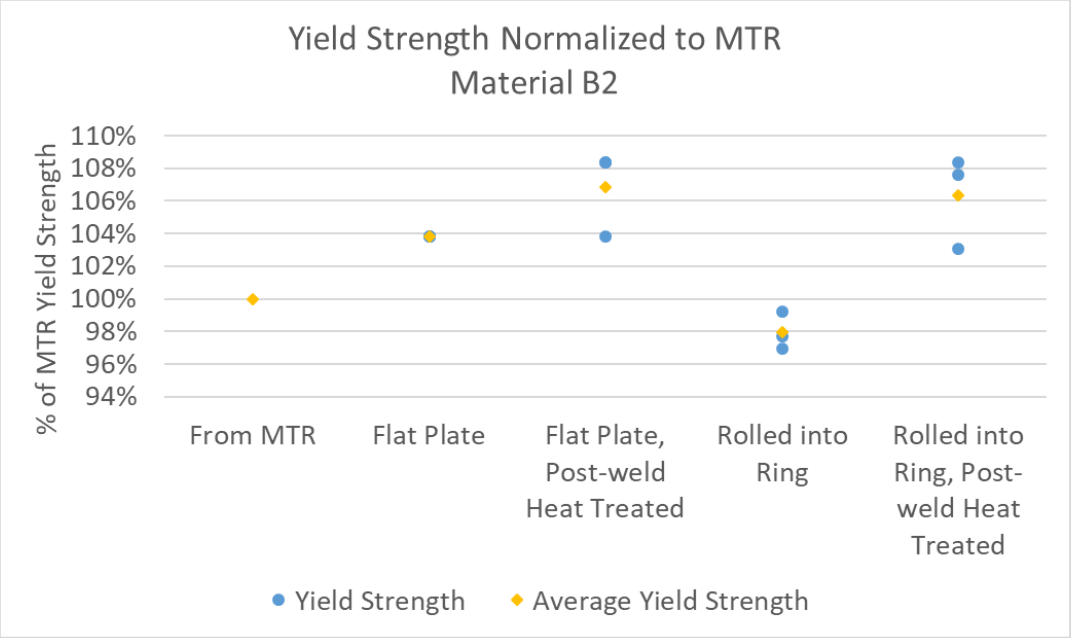


Figure 48. Material B2 – Yield Strength at Each Material Condition Normalized to MTR Yield Strength

A plot of Material B2's ultimate tensile strength at each stage of fabrication normalized against the ultimate tensile strength reported on Material B2's MTR is shown in Figure 49. From Figure 49 it is apparent that the values for ultimate tensile strength measured during this testing program were 2–8 percent higher than the ultimate tensile strength values reported on Material B2's MTR.

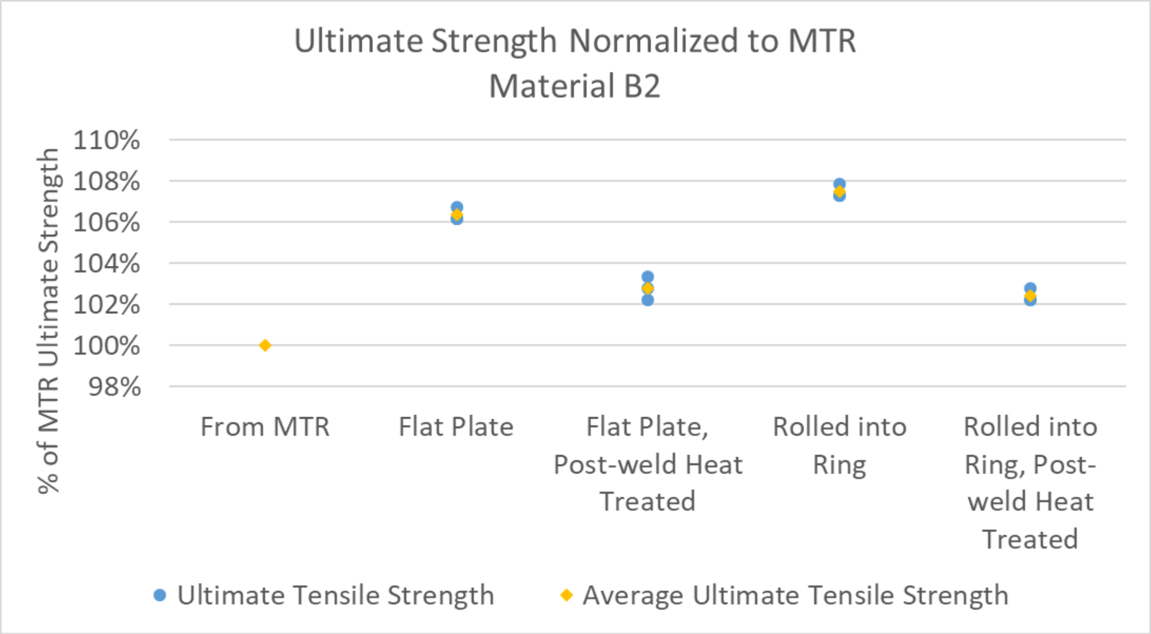


Figure 49. Material B2 – Ultimate Tensile Strength at Each Material Condition Normalized to MTR Ultimate Tensile Strength

A plot of Material B2's elongation in 2 inches at each stage of fabrication normalized against the elongation in 2 inches reported on Material B2's MTR is shown in Figure 50. From Figure 50 it is apparent that the values for elongation in 2 inches measured during this testing program were substantially lower than the value for elongation in 2 inches reported on Material B2's MTR.

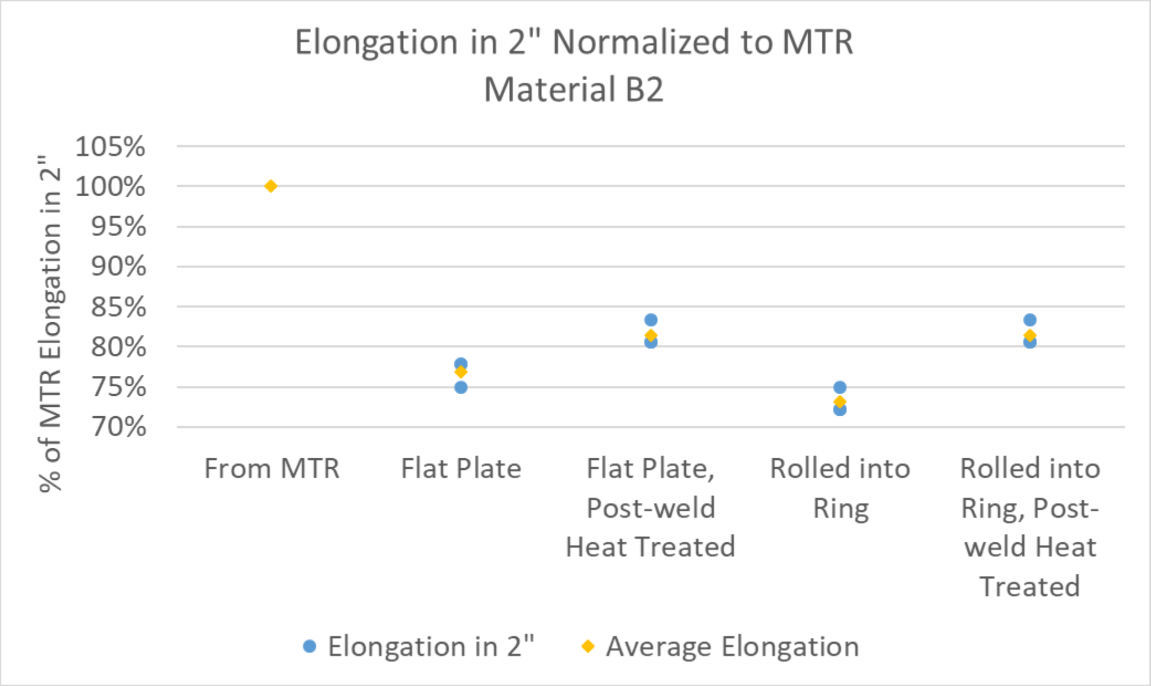


Figure 50. Material B2 – Elongation in 2 inches at Each Material Condition Normalized to MTR Elongation in 2 inches

4.2.3 Tensile Test Results Normalized to Flat Plate Results

The results for yield strength, ultimate tensile strength, and elongation in 2 inches for Material B2 were normalized by dividing the individual and average values by the corresponding average property value from Material B2 in the "as-received" flat plate condition. This normalization was conducted to provide a quick and straightforward comparison of how the mechanical properties of Material B2 changed at each stage of fabrication compared to the as-received flat plate. Note that the results reported on the MTR are included in each figure in this section for completeness.

A plot of Material B2's yield strength at each stage of fabrication normalized against the average yield strength measured for the as-received flat plate is shown in Figure 51. From this figure it is apparent that the values for yield strength measured during this testing program varied from 6 percent below the as-received plate value (after cold-rolling the ring) to as much as 5 percent higher than the as-received plate value when in the PWHT condition. Note that when Material B2 was in the PWHT condition, regardless of whether it had also undergone cold-rolling, the measured values of yield strength exhibited the largest spread compared to the other material conditions examined.

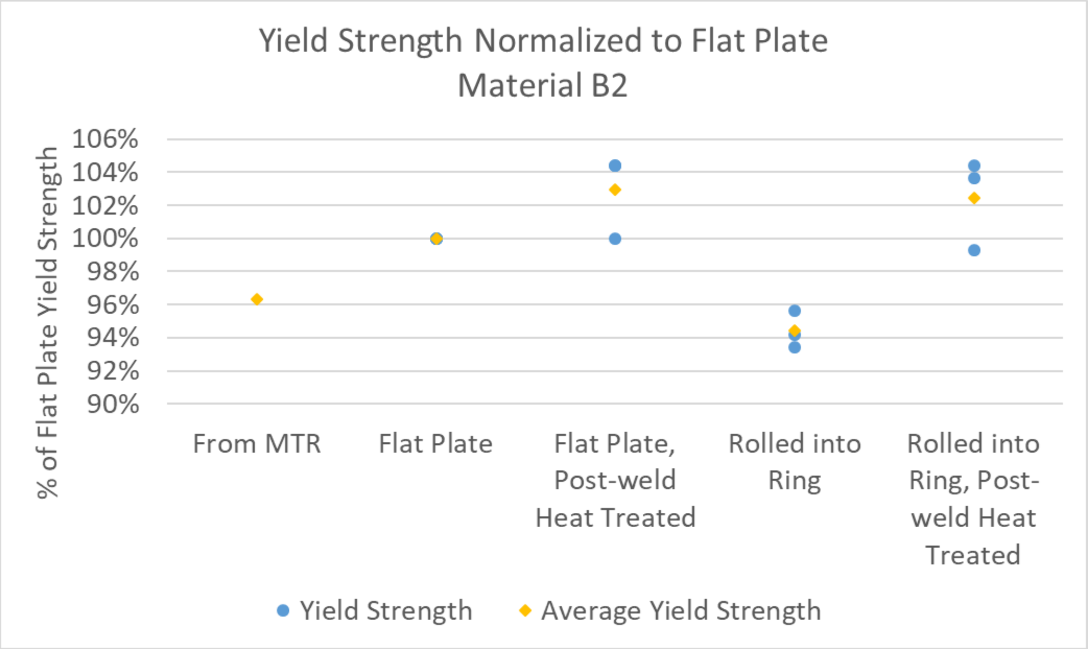


Figure 51. Material B2 – Yield Strength at Each Material Condition Normalized to Average Flat Plate Yield Strength

The effects of fabrication processes on Material B2's yield strength were somewhat inconsistent. Cold-rolling of the flat plate into a ring was expected to increase the yield strength of the material, as this is a form of strain-hardening. However, the yield strength decreased by, on average, 6 percent in the cold-rolled ring compared to the as-received flat plate. PWHT, whether on a flat plate or on a cold-rolled ring, resulted in more scattered yield strength results. While the average yield strength of both the PWHT flat plate and PWHT rolled ring were slightly higher than the average yield strength of the as-received plate, the scatter in PWHT yield strengths included values that show no increase and one result that shows a slight decrease in yield strength.

A plot of Material B2's ultimate strength at each stage of fabrication normalized against the average yield strength measured for the as-received flat plate is shown in Figure 52. From this figure it is apparent that the values for ultimate tensile strength measured during this testing program varied from 4 percent below the as-received plate value (after heat treatment, regardless of whether first cold-rolled) to approximately 1 percent higher than the as-received plate value when in the cold-rolled condition.

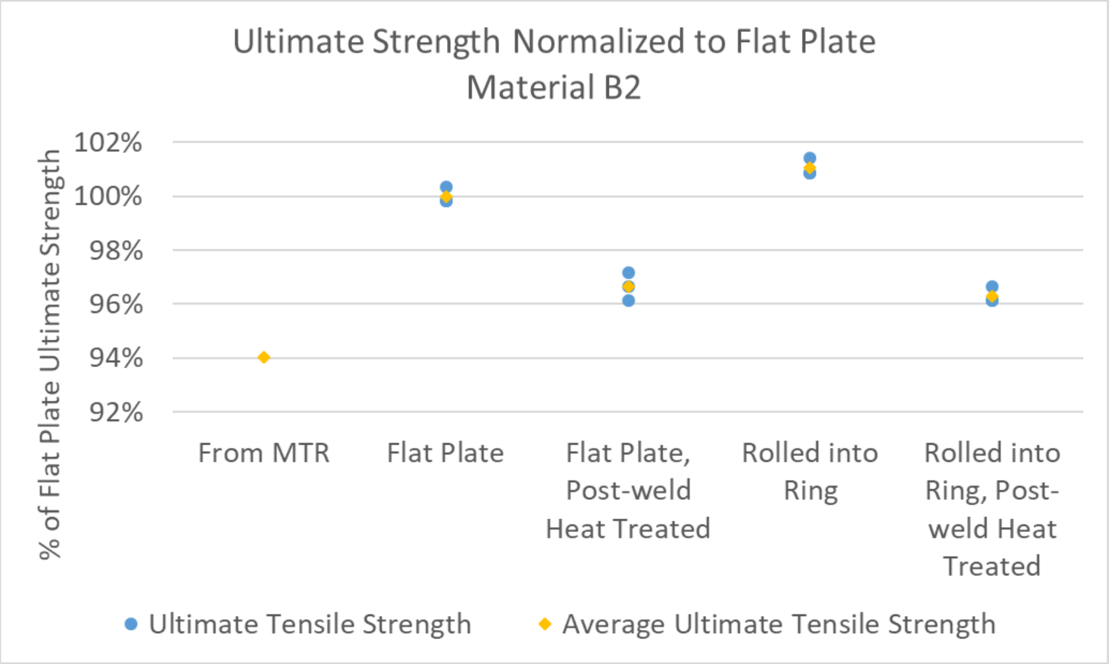


Figure 52. Material B2 – Ultimate Tensile Strength at Each Material Condition Normalized to Average Flat Plate Ultimate Tensile Strength

The effects of fabrication processes on Material B2 are generally as expected. Cold-rolling the flat plate results in a slight increase in the ultimate tensile strength of the material, which is as expected. PWHT results in a decrease in the ultimate tensile strength of Material B2, regardless of whether the sample has been cold-rolled or not.

A plot of Material B2's elongation in 2 inches at each stage of fabrication normalized against the average elongation in 2 inches measured for the as-received flat plate is shown in Figure 53. From this figure it is apparent that the values for elongation in 2 inches measured during this testing program varied from 6 percent below the as-received plate value (after being cold-rolled) to approximately 8 percent higher than the as-received plate value when in the PWHT condition, whether first undergoing cold-rolling or not.

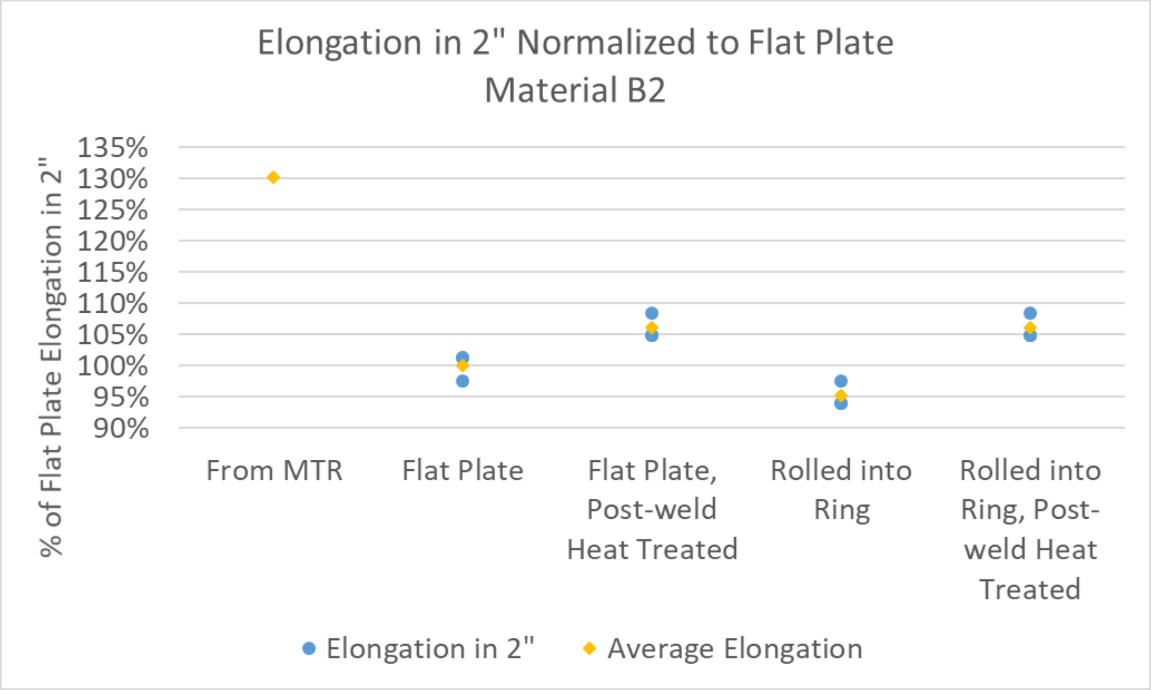


Figure 53. Material B2 – Elongation in 2 inches at Each Material Condition Normalized to Average Flat Plate Elongation in 2 inches

This result for elongation at different stages of fabrication was as expected. Cold-rolling of the tank's ring is a form of cold-working, associated with a decrease in ductility compared to the as-received plate. From these results, heat treatment on either a flat plate of Material B2 or a cold-rolled ring segment of Material B2 resulted in a ductility that exceeded the ductility of the as-received flat plate. However, the increase in ductility after PWHT of Material B2 did not appear to be affected by the cold-working conducted by rolling the flat plate into a ring.

4.2.4 Tensile Test Results Normalized to Minimum Specification Values

The results for yield strength ultimate tensile strength and elongation in 2 inches for Material B2 were normalized by dividing the individual and average values by the corresponding property value from the TC -28B specification minimum material properties. This presentation of results allows for a quick comparison of how the measured properties at each stage of fabrication compare with the minimum values required. The results are presented in Figure 54 through Figure 56, showing that the minimum properties were exceeded by every coupon of Material B2 at every stage of fabrication.

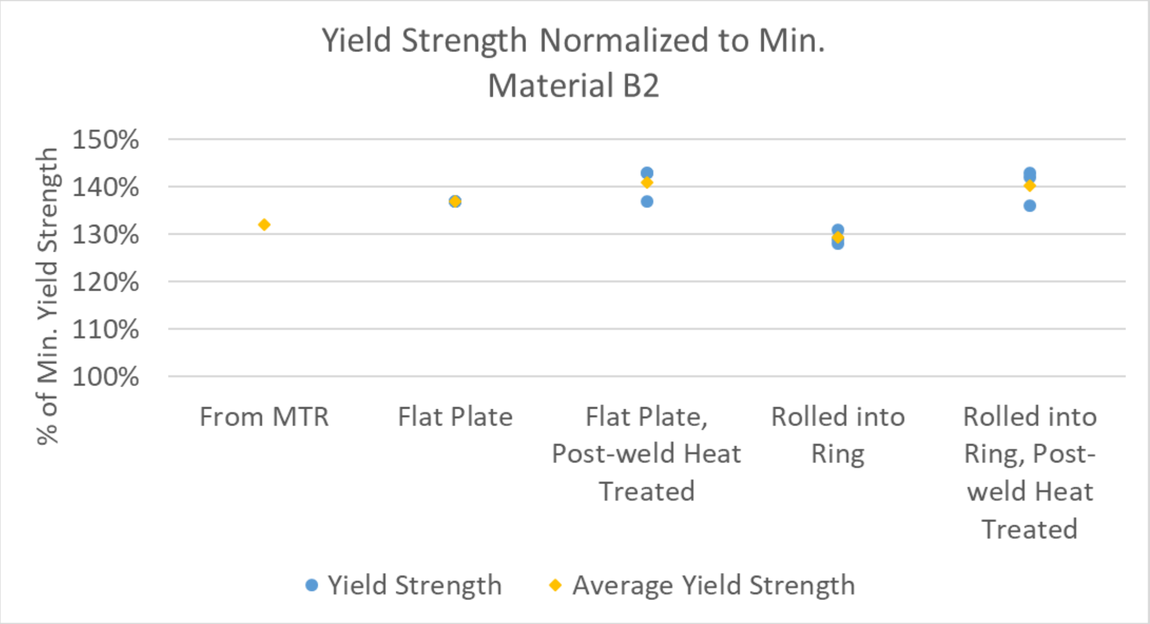


Figure 54. Material B2 – Yield Strength at Each Material Condition Normalized to Minimum Yield Strength in TC-128B Specification

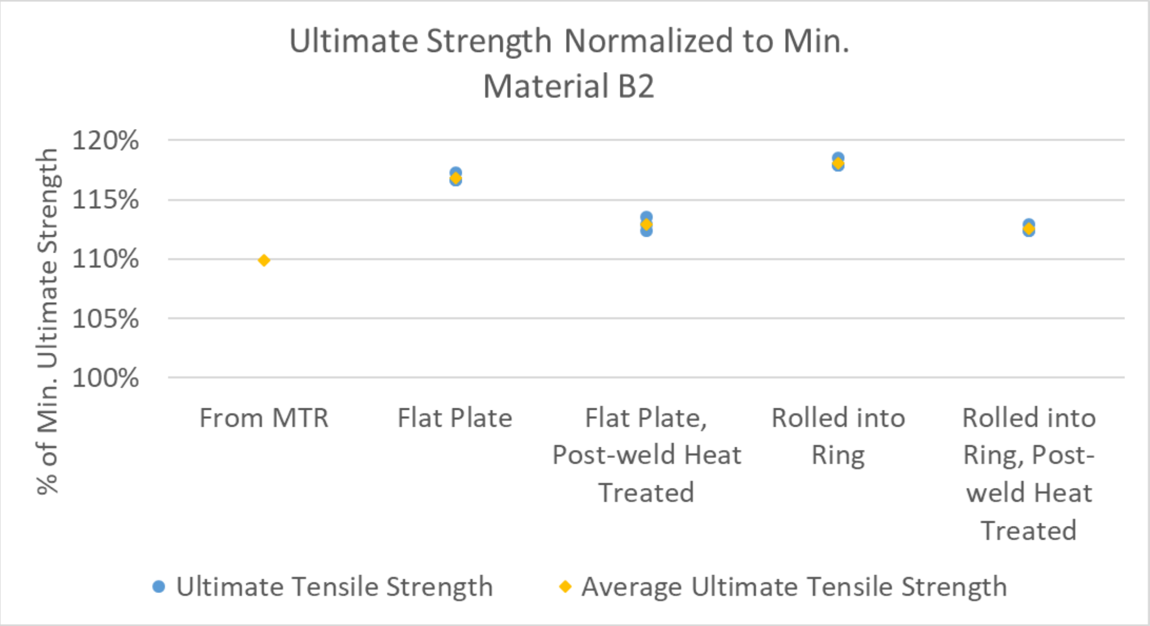


Figure 55. Material B2 – Ultimate Tensile Strength at Each Material Condition Normalized to Minimum Ultimate Tensile Strength in TC-128B Specification

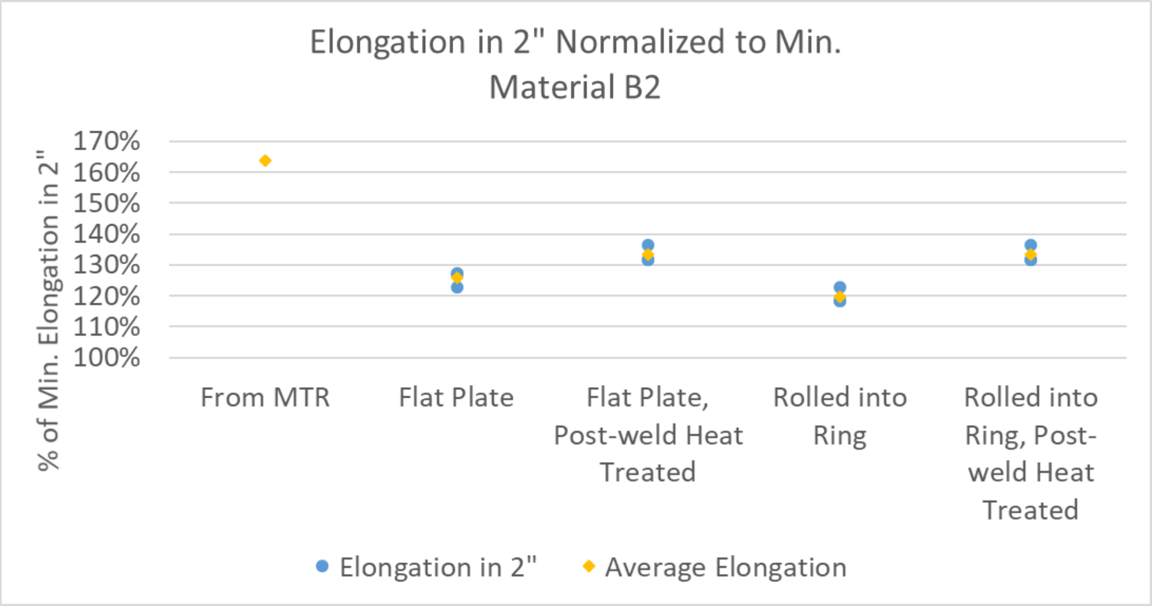


Figure 56. Material B2 – Elongation at Each Material Condition Normalized to Minimum Elongation in TC-128B Specification

4.2.5 Microstructure Evaluation

Figure 57 contains photomicrographs of the microstructure at the mid-thickness of Material B2 samples during each stage of fabrication. Below each image is a description of the material condition observed by the lab making the microstructural examination.

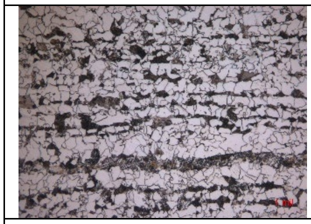
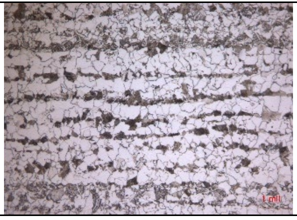
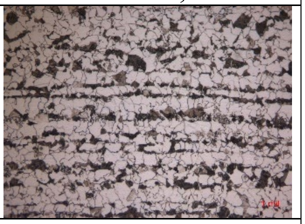
Flat Plate	Cold Worked	Flat Plate, PWHT	Cold Worked, PWHT
			
Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).	Microstructure consists of equiaxed ferrite grains (white) with longitudinal pearlite bands (brown).

Figure 57. Material B2 – Photomicrographs Showing Typical Microstructure at Mid-thickness, 500x Magnification, Nital Etch

Figure 58 contains photomicrographs of the microstructure at the centerline of Material B2 samples during each stage of fabrication. Below each image is a description of the material condition observed by the lab making the microstructural examination.

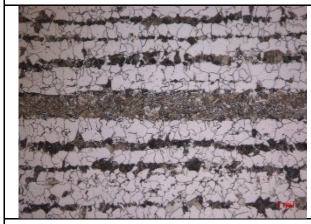
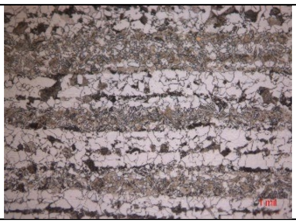
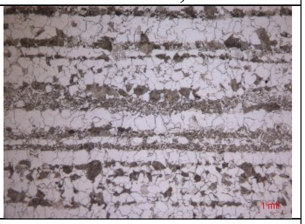
Flat Plate	Cold Worked	Flat Plate, PWHT	Cold Worked, PWHT
			
Microstructure consists of longitudinal bands of martensite (light brown) in addition to the equiaxed ferrite grains (white) and longitudinal pearlite bands (dark brown). Martensite is considerably harder and more brittle than ferrite or pearlite.	Microstructure consists of longitudinal bands of martensite (light brown) in addition to the equiaxed ferrite grains (white) and longitudinal pearlite bands (dark brown). Cold working had no noticeable effects on the martensite.	Microstructure consists of longitudinal bands of martensite (light brown) in addition to the equiaxed ferrite grains (white) and longitudinal pearlite bands (dark brown). The heat treatment appears to have done little to dissolve the martensite bands.	Microstructure consists of longitudinal bands of martensite (light brown) in addition to the equiaxed ferrite grains (white) and longitudinal pearlite bands (dark brown). The heat treatment appears to have partially dissolved some of the martensite bands, but much of the structure of the martensite remains.

Figure 58. Material B2 – Photomicrographs Showing Typical Microstructure at Centerline, 500x Magnification, Nital Etch

4.2.6 Chemical Composition

The MTR provided by Manufacturer B for Material B2 included analysis of the chemical composition of the plate. The chemistry data is shown in Table 11, alongside the chemistry limits for both product and ladle analysis required by M-1002 (Association of American Railroads, 2007). The chemistry of Material B2 was within the limits required by M-1002 for the elements reported.

Table 11. Chemical Composition of Material B2

Element	Material B2	M-1002 Requirement Heat Analysis	M-1002 Requirement Product Analysis
C	0.21	≤ 0.24	≤ 0.26
Mn	1.39	1.00 – 1.65	1.00 – 1.70
P	0.009	≤ 0.025	≤ 0.025
S	< 0.001	≤ 0.015	≤ 0.015
Si	0.25	0.15 – 0.40	0.13 – 0.45
Cu	0.27	0.35	0.35
Ni	0.14	No limit	No limit
Cr	0.16	No limit	No limit
Mo	0.03	No limit	No limit
V	0.042	≤ 0.08	≤ 0.084
Nb	Not reported	Per ASTM A20	Per ASTM A20
Ti	0.003	≤ 0.02	≤ 0.02
N	0.0065	≤ 0.01	≤ 0.012
B	0.0005	≤ 0.0005	≤ 0.0005
Sn	0.009	≤ 0.02	≤ 0.02
C_{eq}	0.52	≤ 0.53	≤ 0.55
Al (total)	0.025	0.015 – 0.060	0.015 – 0.060
Al (soluble)	0.024	≥ 0.015	≥ 0.015
Cu + Ni + Cr + Mo*	0.6	≤ 0.65	≤ 0.65
Ti/N *	0.46	≤ 4.0	≤ 4.0

5. Conclusion

This report describes the results of a testing program examining whether the different stages of tank car fabrication had an observable and consistent effect on the mechanical properties of TC-128B tank car steel. This research was intended to characterize the range of tensile properties of samples of TC-128B tank car steel and to examine if the processes used to manufacture tank cars had an observable and consistent effect on these properties. The specific material properties of interest were the yield strength, ultimate tensile strength, and elongation. By characterizing the material properties at different stages of fabrication, the effect of each manufacturing process on the material's behavior could be isolated. This report did not consider any other grades or types of tank car steels. The work described in this report included only tensile testing and microstructural characterization. While the samples used in this testing program underwent PWHT, no welded samples were included in this study.

As part of the fabrication process, the entire tank goes through a PWHT process in accordance with the requirements of AAR M-1002. The intent of this heat treatment is to reduce the residual stresses in the areas around the welds, and consequently, to improve the fatigue performance. This study focused on the material behavior of the parent material and did not test any welded joints or investigate the fatigue performance of the material. Conclusions cannot be drawn from this study as to the efficacy of PWHT in general or the specific PWHT process(es) used on the samples studied. Any effect of the PWHT on the material properties can be considered a "side effect" of the procedure, since PWHT is not specifically performed to change the puncture resistance of the steel.

5.1 Summary of PWHT Effects on Tensile Properties

Table 12 contains a summary of the yield strength from the flat plates tested before and after PWHT. Table 13 contains a similar summary of the yield strength from rolled rings before and after PWHT. The data do not show any consistent effect on the yield strength of the material in either the flat plate or cold-worked condition. Some samples experienced an apparent decrease in yield strength following PWHT, while others experienced an apparent increase in yield strength following PWHT.

Table 12. Summary of PWHT Effects on Yield Strength, Flat Plates

Material	No PWHT Average (psi)	PWHT Average (psi)	Change after PWHT
A1	65,167	64,667	-0.8%
B1 – 2 inch	66,000	62,000	-6.1%
B1 – 8 inch	62,833	57,667	-8.2%
B2	68,500	70,500	2.9%

Table 13. Summary of PWHT Effects on Yield Strength, Rolled Rings

Material	No PWHT Average (psi)	PWHT Average (psi)	Change after PWHT
A1	63,833	62,500	-2.1%
B1 – 2 inch	63,000	64,167	1.9%
B1 – 8 inch	60,500	60,500	0.0%
B2	64,667	70,167	8.5%

Table 14 contains a summary of the UTS from the flat plates tested in this program before and after PWHT. Table 15 contains a similar summary of the UTS from rolled rings before and after PWHT. These tables demonstrate that all TC-128B samples tested had a lower measured UTS following PWHT, regardless of whether the material had undergone cold-working to form a ring. The magnitude of the decrease in strength varied significantly across the tested samples.

Table 14. Summary of PWHT Effects on UTS, Flat Plates

Material	No PWHT Average (psi)	PWHT Average (psi)	Change after PWHT
A1	82,833	82,500	-0.4%
B1 – 2 inch	93,167	82,667	-11.3%
B1 – 8 inch	91,000	80,000	-12.1%
B2	94,667	91,500	-3.3%

Table 15. Summary of PWHT Effects on UTS, Rolled Rings

Material	No PWHT Average (psi)	PWHT Average (psi)	Change after PWHT
A1	84,333	81,333	-3.6%
B1 – 2 inch	93,500	83,167	-11.1%
B1 – 8 inch	91,833	84,667	-7.8%
B2	95,667	91,167	-4.7%

Table 16 contains a summary of the elongation at break from the flat plates tested in this program before and after PWHT. Table 17 contains a similar summary of the same properties from rolled rings before and after PWHT. These tables demonstrate that all TC-128B samples tested had a higher elongation at break following PWHT, regardless of whether the material had undergone cold-working to form a ring. The magnitude of the increase in ductility varied significantly across the tested samples.

Table 16. Summary of PWHT Effects on Elongation at Break, Flat Plates

Material	No PWHT Average (%)	PWHT Average (%)	Change after PWHT
A1	33	36	9.0%
B1 – 2 inch	25	30	20.0%
B1 – 8 inch	24	26	8.5%
B2	28	29	6.0%

Table 17. Summary of PWHT Effects on Elongation at Break, Rolled Rings

Material	No PWHT Average (%)	PWHT Average (%)	Change after PWHT
A1	34	35	1.0%
B1 – 2 inch	25	30	18.4%
B1 – 8 inch	24	25	5.6%
B2	26	29	11.4%

5.2 Summary of Cold-Working Effects on Tensile Properties

Table 18 contains a summary of the yield strength from the flat plates and rolled rings tested in this program that did not undergo PWHT.

Table 18. Summary of Cold-Working Effects on Yield Strength, No PWHT

Material	Flat Plate Average (psi)	Rolled Ring Average (psi)	Change after Cold-Work
A1	65,167	63,833	-2.0%
B1 – 2 inch	66,000	63,000	-4.5%
B1 – 8 inch	62,833	60,500	-3.7%
B2	68,500	64,667	-5.6%

Table 19 contains a similar summary of the yield strength from flat plates and rolled rings that did undergo PWHT. The data show that in the non-PWHT condition the material exhibited an apparent decrease in yield strength after cold-working. The data also show that after PWHT, there was no consistent effect of cold-working on the apparent yield strength of the material. For samples that were both cold-worked and put through PWHT, the apparent yield strength increased in some samples but decreased in others.

Table 19. Summary of Cold-Working Effects on Yield Strength, PWHT

Material	Flat Plate Average (psi)	Rolled Ring Average (psi)	Change after Cold-Work
A1	64,667	62,500	-3.4%
B1 – 2 inch	62,000	64,167	3.5%
B1 – 8 inch	57,667	60,500	4.9%
B2	70,500	70,167	-0.5%

Table 20 contains a summary of the UTS from the flat plates and rolled rings tested in this program that did not undergo PWHT. Table 21 contains a similar summary of the UTS from flat plates and rolled rings that did undergo PWHT. The data show that in the non-PWHT condition the material exhibited an apparent increase in UTS after cold-working. The data also show that after PWHT, there was no consistent effect of cold-working on the apparent UTS of the material. For samples that were both cold-worked and put through PWHT, the apparent UTS increased in some samples but decreased in others.

Table 20. Summary of Cold-Working Effects on UTS, No PWHT

Material	Flat Plate Average (psi)	Rolled Ring Average (psi)	Change after Cold-Work
A1	82,833	84,333	1.8%
B1 – 2 inch	93,167	93,500	0.4%
B1 – 8 inch	91,000	91,833	0.9%
B2	94,667	95,667	1.1%

Table 21. Summary of Cold-Working Effects on UTS, PWHT

Material	Flat Plate Average (psi)	Rolled Ring Average (psi)	Change after Cold-Work
A1	82,500	81,333	-1.4%
B1 – 2 inch	82,667	83,167	0.6%
B1 – 8 inch	80,000	84,667	5.8%
B2	91,500	91,167	-0.4%

Table 22 contains a summary of the elongation at break from the flat plates and rolled rings tested in this program that did not undergo PWHT. Table 23 contains a similar summary of the elongation at break from flat plates and rolled rings that did undergo PWHT. The data do not indicate any clear or consistent trend following cold-working for either the non-PWHT or the PWHT condition.

Table 22. Summary of Cold-Working Effects on Elongation at Break, No PWHT

Material	Flat Plate Average (%)	Rolled Ring Average (%)	Change after Cold-Work
A1	33	34	3.0%
B1 – 2 inch	25	25	1.3%
B1 – 8 inch	24	24	1.4%
B2	28	26	-4.8%

Table 23. Summary of Cold-Working Effects on Elongation at Break, PWHT

Material	Flat Plate Average (%)	Rolled Ring Average (%)	Change after Cold-Work
A1	36	35	-4.6%
B1 – 2 inch	30	30	0.0%
B1 – 8 inch	26	25	-1.3%
B2	29	29	0.0%

5.3 Summary of Findings

For some plates, values for yield strength and ultimate strength reported on MTRs provided by the steel mill to the tank car manufacturer varied significantly from the properties measured from plates at different stages of fabrication. The tensile testing summarized on an MTR would be performed by a different lab than the lab contracted to perform tensile tests in this study. Some degree of laboratory-to-laboratory variation is expected, even when using standardized test methods. Additionally, the variation of mechanical properties within a single plate may be significant, especially if samples are taken from the start or end of a roll compared to in the center of the rolled plate. Thus, it is difficult to state with certainty why the tensile test results reported on the MTRs varied from the values measured at different stages of fabrication. Further, there was no consistent trend in variation from MTR values observed in this study, with some measured strength values exceeding that reported by the MTR and others falling below the values on the MTR.

The MTRs for Materials B1 and B2 both stated that the tensile testing conducted by the steel mill was performed after applying a PWHT process to the TC-128B plate that was typical of the PWHT prescribed in AAR M-1002. The variation between the UTS reported on Materials B1 and B2's MTRs and the UTS measured for Materials B1 and B2 in the cold-worked PWHT states (i.e., representing the constructed tank car's material state) differed by 3.5 and 2.5 percent, respectively. This small variation is an indication that this approach to estimating the "as-built" mechanical properties by the steel mill appears to be effective.

The results of this study did not demonstrate a clear and consistent relationship between cold-working and yield strength, UTS, or elongation at break for any material in the PWHT condition for the samples tested. The results of the study also did not demonstrate any clear and consistent relationship between cold-working and ductility for material that had undergone PWHT. The results of this study did indicate that for cold-worked material that did not undergo PWHT, the yield strength decreased while the UTS increased in each tested material. This result was somewhat unexpected, as cold-working typically results in an increase to the yield strength of the material that underwent cold-working. There are several complicating factors that were previously discussed in this report associated with making conclusions about the influence of cold-working. The degree of cold-working varies with plate thickness and ring diameter. The residual stresses that develop from cold-working vary throughout the thickness of the sample – from tensile at the outer fiber to compression on the inner fiber – and may be partially-relieved simply by cutting the coupon out of the tank.

The results of this study did not indicate a clear and consistent relationship between PWHT and yield strength in the samples tested. For both the flat plate and cold-worked TC-128B samples, PWHT resulted in an apparent decrease in each material's UTS. Also, for both the flat plate and cold-worked TC-128B samples, PWHT resulted in an apparent increase in each material's elongation at break. For both the decrease in UTS and increase of ductility, the magnitude of such effects varied significantly from material-to-material. The trend of decreasing UTS and increasing ductility after PWHT is consistent with the behaviors previously observed during an FRA-sponsored tank car impact test program (Rakoczy, Carolan, Eshraghi, & Gorhum, 2019).

The consistent effects of PWHT on decreasing UTS and increasing elongation at break can have a mixed effect on puncture resistance. An increase in ductility will generally have a positive effect on puncture resistance, if that increase in ductility is not coupled with a simultaneous reduction in strength. However, decreasing UTS is an undesired side effect of PWHT. A tank made of a lower-strength material is less able to resist service and impact loads without failing than a tank made of a higher-strength material, if all other properties remain equal. Further, this effect may mean that a TC-128B plate that just barely exceeds the minimum UTS requirement in its as-received condition may in fact drop below this minimum after the completed tank car has undergone its PWHT. During this study, two 8-inch gauge length coupons of Material B1 in the PWHT condition had a measured UTS of slightly less than the 81,000 psi required for TC-128B. Note that these samples were flat plates in the PWHT condition, which is not a material condition that would normally occur during tank car fabrication.

PWHT appears to have the added benefit of dissolving or partially dissolving martensite. Samples B1 and B2 both showed martensite bands in the as-received and cold-worked states that were dissolved, at least partially, by the PWHT process. In sample B2, some martensite remained in the cold-worked and PWHT samples after PWHT. This martensite would have been tempered martensite, which exhibits an improved toughness and ductility compared to untempered martensite. As improved toughness and ductility are both behaviors that improve the puncture resistance of tank cars, the tempering effects of PWHT on undissolved martensite are a positive effect.

Note that this study tested three examples of TC-128B material samples provided by two tank car manufacturers. A larger sample size of TC-128B material from additional tank car manufacturers might be appropriate to test to confirm whether these trends are widely observed. Further study could also consider any differences that may exist between TC-128B plates obtained from different steel mills that perform the same tank car fabrication processes. Future work could also consider the effectiveness of PWHT at relieving residual stresses resulting from cold-working and welding, and whether PWHT duration affects the magnitude of the change in mechanical properties. An optimized PWHT process could be sought that maximizes the positive effects (i.e., martensite reduction and stress relief) while minimizing the negative effects (i.e., decrease in UTS) for TC-128B steel.

6. References

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Abbreviations and Acronyms

ACRONYMS	**EXPLANATION**
AAR	Association of American Railroads
ASTM	ASTM International (formerly American Society for Testing and Materials)
FRA	Federal Railroad Administration
PWHT	Postweld Heat Treatment
UTS	Ultimate Tensile Strength