CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 14-002
UILU-ENG-2014-2002
ISSN: 0197-9191

FORMABILITY OF NEW HIGH PERFORMANCE A710 GRADE 50 STRUCTURAL STEEL

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Research Report No. FHWA-ICT-14-002

A report of the findings of
ICT-R27-106
Formability of New High Performance Grade 50 Structural Steel
Illinois Center for Transportation

January 2014

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-ICT-14-002		
4. Title and Subtitle Formability of New High Performance A710 Grade 50 Structural Steel		5. Report Date January 2014 6. Performing Organization Code
7. Author(s) Semyon Vaynman and Morris E. Fine, Northwestern University Christopher Hahin, Illinois Dept. of Transportation		8. Performing Organization Report No. ICT-14-002 UILU-ENG-2014-2002
9. Performing Organization Name and Address Northwestern University Dept. of Materials Science & Engineering 2220 N. Campus Drive Evanston, IL 60208		10. Work Unit No. (TRAIS) 11. Contract or Grant No. R27-106
12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Materials and Physical Research 126 East Ash St. Springfield, IL 62704		13. Type of Report and Period Covered Final, 2011-2013 14. Sponsoring Agency Code

15. Supplementary Notes This project was completed through the joint efforts and technical work of Northwestern University and the Illinois Department of Transportation on behalf of the State of Illinois and the Federal Highway Administration.

16. Abstract

This project compared the formability of modified ASTM A710 Grade B50 ksi yield strength steel, jointly developed by Northwestern University and the Illinois Department of Transportation, with ASTM A606 Type 4 weathering steel used in Illinois and many other states for sign and signal structures, light poles, and other highway structures. ASTM E290 Type 1 free-bend 180° guided-bend test was used to evaluate formability, with side clearances as per ASTM E190. Bend and tensile specimens were cut in longitudinal and transverse directions from plates and sheets of numerous thicknesses (from 0.38" down to 0.10" thick). Mandrels of three diameters (0.25", 0.313", and 0.375") were used, each having a rounded nose with radius of bend equal to ½ of the mandrel diameter. All specimens of A710 and A606 steels of all thicknesses passed the guided-bend tests. No cracks, side tears, or fractures were observed. Tensile tests showed excellent ductility in both longitudinal and transverse rolling directions, making the modified ASTM A710 steel very suitable for use in sign and signal structures, light poles, and highway structures, along with structural tubing and other applications requiring weathering steel sheets and plates.

Comparable A606 Type 4 steel had a yield strength range of 65 to 73 ksi and an ultimate tensile strength range of 79 to 89 ksi. The elongation to failure for the A606 steel sheets was in the range of 41% to 49%, averaging 43% ± 2.5% based on a 1" gage length. The microstructure of A606 steel is primarily ferrite with a limited amount of pearlite. The grain size of A606 in thinner plates was much smaller; grains were more rounded in thicker plates.

Two heats of modified A710 Grade B steel were tested. Variations in mechanical properties were a function of steel composition, hot-rolling procedures, and thickness of the plates or sheets. In the first heat, yield strength varied in a range of 48 to 119 ksi, and tensile strength ranged from 64 to 119 ksi. The variation in the strength in the first heat was most likely caused by excessive section reduction during hot-rolling. The microstructure of the A710 steel was fine-grained ferrite and was significantly smaller than the A606 steel grains of similar thickness, which accounted for the higher strengths of the A710 steel in the first heat. Some bands of pearlite and fine-grained ferrite were observed in the modified A710 sheets, but did not affect the formability of the steel.

Copper, nickel and manganese contents were decreased and better rolling procedures were used in the second heat, which had a uniform 49 to 56 ksi yield strength range. The second heat also had a uniform yield to tensile ratio of 0.74, high ductility and formability, making this alloy a very attractive weathering steel for many transportation and structural applications. An optimized 50 ksi minimum yield strength composition with an ASTM G101 index of 6.0 or more was developed for A710 sheet steel, and is proposed for general use in transportation and other construction applications.

17. Key Words	18. Distribution Statement
Steel, formability, yield strength, ultimate tensile strength, ductility, ASTM A710 Grade B	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	40	

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ACKNOWLEDGMENTS AND DISCLAIMER

This publication is based on the results of ICT-R27-106, **Formability of New High Performance Grade 50 Structural Steel**. The project was conducted in cooperation with the Illinois Center for Transportation (ICT); the Illinois Department of Transportation (IL DOT); and the U.S. Department of Transportation, Federal Highway Administration (FHWA).

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This project was jointly completed by Northwestern University and the Illinois Department of Transportation. Professors Semyon Vaynman and Morris E. Fine acknowledge Professor Yip-Wah Chung of Northwestern University for his review and editing of the report, and also acknowledge Mr. Christopher Hahin, MetE, CorrE, PE, of IL DOT for his input on steel alloying and development, and for bend and mechanical property testing at IL DOT facilities. The hot-rolling of ingots into plates and sheets by the Arcelor Mittal Global R&D facility is gratefully acknowledged.

Mr. Hahin acknowledges the many discussions and joint efforts of the co-authors of this report to make this a successful project. He also cites the helpful input of several steelmakers and potential users of this HP alloy weathering steel sheet and plates for use in sign and signal structures, light poles, tubing, and other structural applications in the transportation, fabrication, and construction industries. The particular assistance of the following individuals are hereby acknowledged: Mr. James Patterson of Sophisticated Alloys for preparation of heats and hot-rolling; Mr. William Peppler of Gerdau Ameristeel, Mr. Dan Edelman of Nucor Steel Crawfordsville, and Mr. James Biernat of Nucor Steel Auburn for their advice on commercial production of alloy steels; and Mr. Larry Watzke of Valmont Industries for his advice on production of tapered tubing.

Mr. Hahin also acknowledges the cutting, processing, and testing of bend, tensile, and notch impact test specimens by Mr. Terry Havard, Mr. Chris Murphy, and Mr. Steve Blickhan of the Metals Laboratory of the Bureau of Materials and Physical Research.

EXECUTIVE SUMMARY

Illinois, like many other large states, has several microclimates where temperature and rainfall can vary. These variations can affect the corrosion rates of sign and signal structures, light poles, and other highway structures. Each atmospheric zone, whether they are rural, semi-rural, suburban, industrial, or marine areas, may be subjected to salt fall or salt spray, which can affect metals or coatings after prolonged exposure. These highway structures are typically fabricated from weathering steel, galvanized steel, painted steel, or aluminum. Each of these metals and their coatings bear a fabrication cost and have distinct ranges of durability in different atmospheres.

Rural and semi-rural atmospheres cause the least corrosion damage to metal and coated surfaces. Suburban environments generally have moderate effects, compared to industrial and saline areas, which have the most corrosive atmospheres. Weathering steels have greater durability in moderate and many industrial atmospheres compared to carbon steels, such as ASTM A36 or SAE 1020. The cost differences between ASTM A36 and ASTM A588 vs. the ASTM A710 Grade 50 steel described in this report are small. Based on data obtained from WorldSteelPrices.com, as of July 2013, the price of ASTM A36 was about $0.295 per lb compared to $0.340 per lb for ASTM A588. Because A710 has slightly higher nickel and copper contents than A588, its cost is estimated to be about $0.36 per lb, based on a metric tonne.

Coating steels with hot-dip or sprayed zinc, or using inorganic zinc-rich primers with epoxy, polyurethane, or acrylic top coats, adds more cost to the initial steel cost, which includes price per lb, delivery, and installation. These costs vary from about $1.67 per ft^2 for galvanizing to about $2.00 to $2.62 per ft^2 for steels coated with inorganic zinc primers with high-build epoxies or polyurethanes (2008 prices). In addition, organic coatings incur additional maintenance costs after 15 years of exposure because they require either touch-up or repainting. Life-cycle costs over a 30-year period can increase over their initial cost by 30% or more.

In contrast, weathering steels have superior atmospheric corrosion resistance in many environments compared to both unpainted carbon steels such as ASTM A36 or steels coated with epoxies or polyurethanes, and they do not have the additional zinc coating costs of galvanized steels. The durability of weathering steels in industrial atmospheres is about 5 to 7 times better than the durability of unpainted carbon steels.

In addition, many of the commercial weathering steels used today do not always have high fracture toughness, particularly if they have been cold-rolled. Because of the very low carbon content of the ASTM A710 Grade 50 steel described in this report, it has a minimum required impact toughness of 35 ft-lb or more at -10ºF or lower temperatures compared to the minimum requirements of 15 ft-lb at +40ºF for redundant structures (25 ft-lb at +40ºF for fracture-critical), as listed in ASTM A709, *Structural Steel for Bridges*.

The most cost-effective solution to atmospheric corrosion problems for highway structures is a better and improved weathering steel with high crack tolerance and improved impact toughness and corrosion resistance. Previously, Northwestern University jointly developed with the Illinois Department of Transportation (IL DOT) a high-performance steel with 70 ksi yield strength, excellent fracture toughness at low temperatures, and weldability. This steel was produced by the former Inland Steel (now Arcelor Mittal), Oregon Steel, and the former Bethlehem Steel (now Arcelor Mittal). The 70 ksi composition was subsequently standardized in ASTM A710 *Precipitation-Strengthened Low-Carbon Nickel- Copper-Chromium-Molybdenum-Columbium Alloy Structural Steel Plates* as Grade B. Based on its copper content, A710 Grade B weathering steel has the highest resistance to atmospheric corrosion in the United States today.

This steel was used for unpainted plate girders in the construction of the Illinois 83 bridge over the Canadian National Railroad near Lake Villa, IL. Recently this steel was modified by reducing the concentration of several alloying elements to decrease the yield strength to a 50 ksi minimum yield strength in order widen its application to the vast majority of bridge designs. The 50 ksi A710 steel has excellent ductility and fracture toughness at freezing and lower temperatures. Wide-flange beams of 30" depth made of 50 ksi yield strength A710 Grade B weathering steel were produced by Steel Dynamics of Columbia City, IN for the superstructure of the Dixie Highway Bridge (near US 30) in Flossmoor, IL in 2010.

Because of its high ductility and weatherability, enhanced impact toughness, high fracture toughness at low temperatures, and very good weldability due to its low carbon equivalent, the 50 ksi yield strength makes A710 Grade B a very appropriate steel for many transportation and construction applications. In general, this new steel can significantly extend the life of structures at an estimated 6% cost increase compared to conventional lower-performance steels in use today.

In this project, the formability of A710 Grade B50 steel was compared to that of ASTM A606 Type 4 weathering steel, which is currently used for highway structures in Illinois and many other states. A710 Grade B with 50 ksi yield strength was not available from steel service centers, so 300 lb (first heat) and 100 lb (second heat) heats were produced and then hot-rolled to various thicknesses. A606 Type 4 steel was obtained in seven thicknesses from an industrial steel service center.

All A710 B50 and A606 Type 4 steel specimens successfully passed guided U-bend tests to determine their formability at the IL DOT Bureau of Materials and Physical Research facility. Rounded-tip mandrels of 1/8", 5/32", and 3/16" radii were forced through the mid-length of the specimen between two supporting roller guides separated by a side clearance of 0.063". Bend tests were performed in accordance with ASTM Standards E190 and E290. No cracking, fracture, or other surface irregularities during a continuous bend were observed for any thickness of the steels that were tested.

The tensile properties of the A606 and A710 steels were measured in longitudinal and transverse directions. The yield and ultimate tensile strengths of the A606 steel varied in comparatively narrow ranges, 65 to 73 ksi and 79 to 89 ksi, respectively. A606 is ferritic and exhibited good ductility. There were some variations in mechanical properties of A710 steel as a function of composition and hot-rolling procedures, as well as the thickness of the plates and sheets. Yield strengths of the first heat varied from 48 to 119 ksi, and tensile strength ranged from 64 to 119 ksi. The higher than expected strength of the first heat was most likely caused by excessive reductions to thickness during hot-rolling.

To counteract this variation of the yield strength, the composition of the second heat was adjusted by use of predictive ferrite multiplier equations of key alloying elements that contribute to the strength of pure ferrite. Copper was decreased to a target range of 0.60% to 0.70%, nickel to 0.35% to 45%, and manganese was reduced to a range of 0.60% to 0.70%. The second heat had lower yield and tensile strengths due to lesser levels of these alloying elements added to ferrite, and to better hot-working procedures than those used in Heat 1. The microstructures of the A710 50 ksi steel sheets were fine-grained ferrite. The grains in A710 steel sheets were smaller than the grains in A606 steel of similar thickness, which also accounted for higher strengths of the A710 steel in Heat 1. Some bands of pearlite and fine-grained ferrite were observed in A710 sheets; however, these intermittent bands did not significantly affect formability.

The 50 ksi range of yield strength makes the composition of the second heat ideal for forming tubing, light poles, sign and signal structures, and other structural elements without incurring significant wear-and-tear on shop forming and fabrication machinery.

However, because its copper content was decreased, its G101 index decreased to less than 6.0. Accordingly, an optimized composition based on the results of Heat 2 was proposed, which has the ideal yield strength of 54 to 60 ksi for formability of steel sheets and has an ASTM G101 Townsend atmospheric corrosion resistance of 6.0 or more. The optimized composition was determined to be 0.03% to 0.09% C, 0.65% to 0.75% Mn, 0.025% P max, 0.005% S max, 0.40% Si max, 0.25% Cr max, 0.65% to 0.75% Cu, 0.45% to 0.55% Ni, 0.030% V max, 0.060% Mo max, and 0.100 Ti max.

This project demonstrated that A710 Grade B50 steel has excellent ductility, corrosion resistance, and weldability and can be easily formed. Because ASTM A710 Grade B50 has better atmospheric corrosion resistance and has formability equivalent to ASTM A606 Type 4 weathering steel, it is recommended that ASTM A710 Grade B50 sheet steel be used instead of A606 Type 4 in suburban, urban, industrial, and saline atmospheres in Illinois and other states for light poles, sign and signal structures, and other highway structures.

CONTENTS

FIGURES

TABLES

CHAPTER 1 INTRODUCTION

Light poles, sign and signal structures, and other highway structures in Illinois are fabricated from structural tubing. Materials used include weathering steel, galvanized steel, painted steel, and aluminum.

Aluminum Alloy Tubular Structures

Aluminum alloys are used because of their low maintenance, bright appearance, and general corrosion resistance to areas where salt spray or fog are frequent conditions during the colder months of the year. While aluminum is more corrosion resistant, it has markedly lower fracture toughness than steel. In addition, weldments of aluminum alloys have very low fatigue strengths, leading to catastrophic rupture upon impact, cracking and failure during windstorms, and general accumulation of fatigue damage over long-term service. The plane-strain fracture toughness for 6061-T6 aluminum alloy is 35 ksi $[in]^{1/2}$ (Kaufman 2001) compared to 77 to 110 ksi $[in]^{1/2}$ for several of the A710 steel sheets produced in this study. Examples of catastrophic rupture due to truck impact and windstorm damage to aluminum sign structures and light pole hand holes are shown in Figures 1a and 1b.

(a)

(b)

Figure 1. (a) Collapse of an IL-29 sign structure caused by truck impact to the aluminum walkway that was supported by a tubular aluminum frame. Rupture occurred at the span mid-point welded junction flanges that join the multiple sections of the overhead space frame. (b) Failures of aluminum light poles induced by high stress concentrations at hand hole welds stemming from wind forces of a major storm near Galesburg, IL (photos courtesy of C. Hahin, IL DOT).

Aluminum alloys are also significantly more expensive than steel. The London Metal Exchange as of September 2013 listed the unit price of aluminum as $1805 per tonne (3 months' buyer), which is equivalent to $0.82 per lb. In contrast, ASTM A36 steel per WorldSteelPrices.com was $0.295 per lb and ASTM A588 was $0.34 per lb. ASTM A710 Grade B, based on its higher copper and nickel content, was estimated to be about $0.36 per lb.

Given the cost of steel and its superior strength, toughness, and fatigue resistance, steel is a very cost competitive alternative to aluminum alloys. Because carbon steels have limited resistance to exposure to aboveground atmospheres, underground burial, or immersion in water or other aqueous environments, several means have traditionally been used to protect steel from corrosion. This report covers only the means to limit the effects of atmospheric corrosion on steel by use of weathering steels and comparing them on a cost basis to steels coated with hot-dip zinc or organic coatings.

Coatings vs. Weathering Steels

The State of Illinois is 384 miles long and 225 miles wide at its points of greatest length and width. Like many other large states, it has several microclimates where temperature and rainfall can vary. Structures may have proximity to large metropolitan areas that emit industrial pollutants and gases or to large rivers that can change relative humidity. All of these factors can affect the corrosion rates of light poles, sign and signal structures, bridges, and other highway facilities that use steel for load-bearing members. These atmospheric zones have been classified by corrosion engineers as rural, semi-rural, suburban, industrial, and marine atmospheres. Although Illinois is not a coastal state like Florida or California, its highway maintainers frequently use deicing salts during the colder months of the year, resulting in the airborne dispersal of salt or salt fog under certain conditions of high humidity or wind speed. Rural and semi-rural areas have the least atmospheric corrosion, suburban locations have moderate effects, whereas industrial and saline atmospheres are most corrosive to bare steel.

When carbon steels are coated with zinc or hybrid coatings like inorganic zinc primers topped with epoxy or polyurethane, they incur an additional acquisition cost to the tubular steel. Organic coatings also require additional touch-up or repainting after 15 or more years of service. Zinc coatings on tubular structures are generally limited by the thickness of the pure zinc eta layer, which typically ranges from 0.001" to 0.003" thick. Coating thickness of hot-dip zinc is determined by the gage thickness of the tubing, according to Table 1 of ASTM A123 *Standard Specification for Zinc Coatings on Iron and Steel Products*.

Numerous studies of the corrosion rates of zinc in various atmospheres have been summarized by the Zinc Institute (Slunder and Boyd 1971). The atmospheric corrosion rate of zinc is heavily dependent on relative humidity and the concentrations of sulfur dioxide and airborne salt. In Illinois, there are several industrial locations where atmospheric sulfur dioxide levels are elevated, particularly in the south Chicago lakefront area, Rockford on the Rock River, Peoria on the Illinois River, Decatur on the Sangamon River, and East St. Louis and Moline along the Mississippi River. In rural areas, zinc corrodes in the atmosphere at a low rate of about 0.08 mils per year (0.00008" per year). Assuming an initial zinc thickness of 1.8 mils, first corrosion of the steel would occur at 22.5 years. In areas subject only to salt spray in a suburban atmosphere, the average corrosion rate was about 0.2 mils per year. In that environment, first rusting of the steel tubing would occur at about 9 years. For industrial atmospheres where substantial amounts of sulfur dioxide are consistently present, the atmospheric corrosion rate of zinc was about 0.5 mils per year, resulting in first corrosion of the base steel in 3.6 years. After sustaining loss of additional zinc in four more years, the corrosion rate of the carbon steel would be about 3 to 4 mils per year. For a 10 gage thick (0.1382") light pole, complete section loss, not including pitting, would take 35 years. Pitting rates are three times that of the overall corrosion rate in carbon steel, rendering the pole susceptible to collapse because of partial section penetrations after 11.5 years.

Organic coatings, augmented by inorganic zinc primers, can also provide additional life to light poles, signs, and signal structures. However, these coatings are subjected to disbonding, expansion, and contraction due to daylight heating and night cooling, ingress of moisture through the coatings, and degradation of the polymers from ultraviolet light. They also add significant costs to the steel tubing. A comparison of the durability of these coated steel products and their life cycle costs is shown in Table 1.

Atmospheric Corrosion Resistance of Weathering Steels

As noted in Table 1, weathering steels do not confer any additional coating cost, but do provide a durable, complex protective layer of oxides that form if the steel is not continually wetted. Weathering steels show remarkable corrosion resistance to many atmospheres, even in the more corrosive industrial or marine atmospheres. The corrosion rating index of weathering steels is frequently cited by use of the Larabee-Leckie-Coburn equation in ASTM G101 *Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels* as follows:

$$I = 26.01\,(Cu) + 3.88\,(Ni) + 1.2\,(Cr) + 1.49\,(Si) + 17.28\,(P) - 9.1\,(Ni \times P) - 33.39\,(Cu)^2$$

Where I = the G101 index rating, and the various elements are in % by weight.

Unfortunately, this equation limits copper contents to less than 0.51%, and it is not meaningful for alloys with greater copper content. The more accurate, but more complicated, method of Townsend is described in ASTM G101 Section 6.3.2, and can also be used to predict atmospheric corrosion rates in various environments. Fortunately, G101 calculators for this method are available from ASTM and were used in this report to optimize compositions of A710 Grade B50.

Table 1. Initial and Maintenance Cost Analysis of Weathering Steel and Various Coatings

Type of Steel and Coating	Years of Exposure						
	0	5	10	15	20	25	30
Weathering, no coating	Cost of steel only						
Galvanized, 1.8 mils zinc	Steel + $1.67/ft^2						
Inorganic Zn primer and high-build epoxy	Steel + $1.99/ft^2			$0.31/ft^2 touch-up		$0.31/ft^2 maintenance repaint	
Inorganic Zn and waterborne acrylic	Steel + $1.89/ft^2			$0.33/ft^2 touch-up	$0.31/ft^2 maintenance repaint	$0.46/ft^2 maintenance repaint	
Inorganic Zn with high-build epoxy-urethane	Steel + $2.62/ft^2				$0.34/ft^2 touch-up		$0.43/ft^2 maintenance repaint

NOTE: The above table is based on 2008 data taken from a 250 ton project with a 30 year service life. Paints were conventionally sprayed, with an SP6 surface condition, and exposed to an eastern United States moderate industrial environment. To estimate current prices, multiply by 1.15, which is based on an estimated 3% annual price growth rate. Data source: American Galvanizers Association web site.

The most cost-effective solution to the deterioration of highway structures subject to atmospheric corrosion is a better alloy steel with high crack tolerance, increased impact toughness, good weldability, and improved atmospheric corrosion resistance. Northwestern University and the IL DOT, in conjunction with Arcelor Mittal, Oregon Steel, and Gerdau Ameristeel, had previously developed a high-performance 70 ksi yield strength A710 Grade B steel with excellent fracture toughness at low temperatures and weldability with minimal preheat. A710 Grade B steel was used for unpainted plate girders for the Illinois 83 bridge over the Canadian National Railroad near Lake Villa, IL (Vaynman et al. 2007).

A710 Grade B was recently modified by reducing concentrations of several alloying elements to decrease yield strength to the 50 ksi range in order to accommodate most bridge designs. Wide-flange beams of 30" depth with 50 ksi minimum yield strength were commercially produced by Steel Dynamics of Columbia City, IN, for the Dixie Highway bridge (near US 30) located in Flossmoor, IL (Vaynman et al. 2010).

Impact and Fracture Toughness

The fracture toughness of steel can be indirectly determined from Charpy V-notch impact toughness by use of the Barsom-Rolfe conversion equation $K = [4 (CVN) E]^{1/2}$ where CVN is its impact toughness in ft-lb, and E is the modulus of elasticity of steel at 30×10^6 psi (Barsom and Rolfe, 1987). The dramatic effect of impact toughness on critical crack length at stress levels between 10 to 20 ksi in side-cracked plates in tension is shown in Figure 2. However, when stress levels increase and approach 50 ksi or more, critical crack lengths sharply decrease to 1.3" or less.

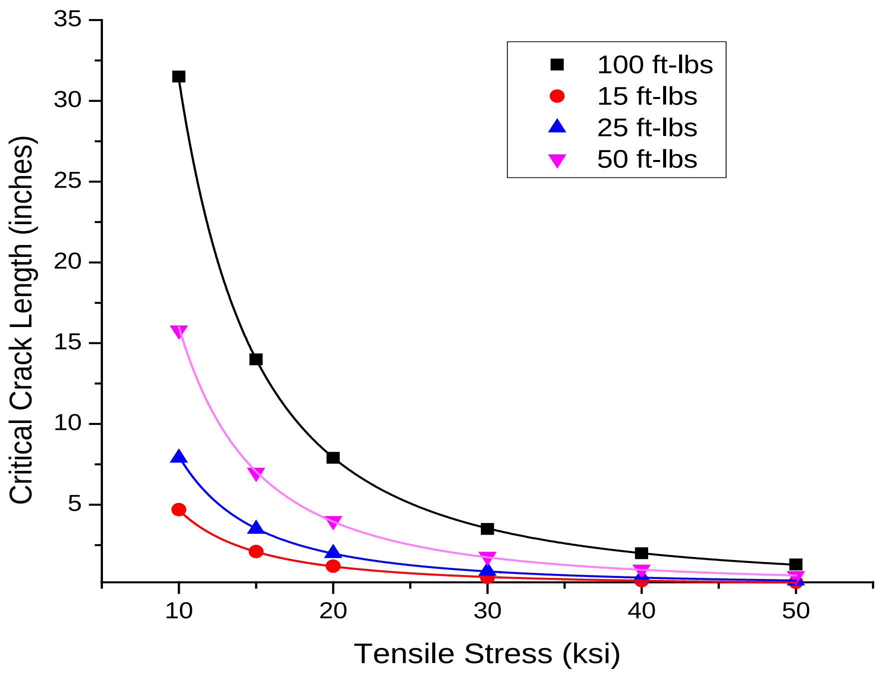


Figure 2. The relationship between fracture toughness in terms of critical crack length for steels with different V-notch impact toughness values in ft-lb at stress levels from 10 to 50 ksi. These curves were determined for a side-cracked plate in tension from the basic fracture mechanics relationship $K = 1.1\sigma [\pi a]^{1/2}$.

Due to its high ductility, enhanced weatherability, high impact and fracture toughness at low temperatures, and low carbon equivalent, the 50 ksi yield strength version of A710 Grade B steel is a very appropriate weathering, crack-tolerant steel for many transportation and construction applications. In general, this new steel can significantly extend the life of structures at only a 6% estimated cost increase compared to lower-performance conventional steels in use today.

The formability of this steel needed to be evaluated before manufacturing it into various shapes and sizes by tubing producers, and that was the principal focus of this project. Because weathering characteristics of the steel are also relevant, careful consideration was given to adjustments of key alloying elements to optimize both formability and atmospheric corrosion resistance. The formability of this steel was compared to that of ASTM A606 Type 4 weathering steel, which is currently used for highway structures by Illinois and many other states and public agencies.

CHAPTER 2 STEELS EVALUATED IN THIS PROJECT

ASTM A710 Grade B with 50 ksi yield strength (referred to in subsequent text as A710 Grade B50) is not available in steel service centers, so 300 lb (first heat) and 100 lb (second heat) steel heats were ordered from Sophisticated Alloys, Inc. of Butler, PA. The chemical compositions of Heat 1 and Heat 2 are shown in Table 2a. The steel has a very low concentration of carbon to significantly reduce its carbon equivalent for improved weldability. The required strength of A710 Grade B was achieved by three strengthening mechanisms: (1) copper-nickel-manganese precipitation, (2) solid solution strengthening, and (3) interstitial strengthening of ferrite. Nickel was added at approximately 70% of the amount of copper to prevent the hot-shortness of the steel, because nickel increases the solubility of copper in austenite. Columbium (niobium) was added at 0.07% for grain refinement. Titanium was added to combine with nitrogen, carbon, and oxygen. As will be discussed in Chapter 3, the yield strength of the first heat exceeded the target yield strength of 50 ksi; therefore, the amounts of copper, nickel, and manganese were reduced in the second heat.

Chemical Compositions of the A710 and A606 Steels

The first heat of A710 was cast as a 2" thick ingot and was then further hot-rolled to seven different thicknesses without charge to the project by Arcelor Mittal Global R&D Laboratory. The 0.128" to 0.350" thick plates were hot-rolled from a 2" thick ingot. The 0.114" and 0.122" thick sheets were hot-rolled from a 0.75" thick plate, which was cut from the original ingot to reduce the amount of hot-working that could significantly increase the yield strength of the steel above the target of 50 ksi.

The second heat was hot-rolled at Sophisticated Alloys into three thicknesses, 0.150", 0138", and 0.180". For both the first and second heats, their ingots were soaked at temperatures not exceeding 1130 °C (2066 °F) before hot-rolling to prevent formation of Widmanstatten ferrite, which renders the steel brittle.

Table 2a. Chemical Composition of A710 Grade B50 Steel Heats by Weight %

	C	Mn	P	S	Si	Cu	Ni	Cr	Nb	Ti
1st Heat	0.07	0.95	<0.005	<0.005	0.34	0.92	0.70	0.14	0.07	…
2nd Heat	0.03	0.64	0.006	<0.005	0.31	0.66	0.38	<0.01	0.06	0.102

Different thicknesses of ASTM A606 Type 4 weathering steel sheets and plates were acquired from Central Steel Service of Pelham, AL. Some of the steel sheets and plates were produced by Severstal North America (NA) at their Rouge Plant in Dearborn, MI, and some were produced by Gallatin Steel at their Ghent, KY plant, as labeled in Table 2b. The compositions of the A606 steels of different thicknesses are given in Table 2b. ASTM A606 steels are micro-alloyed with vanadium for grain refinement, and they contain copper, nickel, silicon, and chromium to improve atmospheric corrosion resistance.

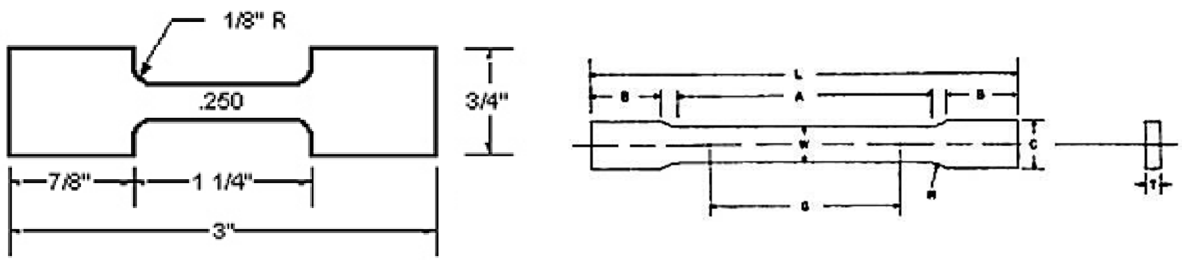
Table 2b. Chemical Composition of ASTM A606 Type 4 Steel by Weight %

	Plate Thickness, in						
Element	0.101	0.116	0.167	0.186	0.378	0.131	0.247
Carbon	0.06	0.05	0.05	0.04	0.05	0.05	0.05
Manganese	0.91	0.87	0.89	0.89	0.91	0.81	0.83
Phosphorus	0.012	0.014	0.006	0.011	0.014	0.022	0.020
Sulfur	0.003	0.004	0.003	0.003	0.005	0.002	0.005
Silicon	0.33	0.34	0.35	0.31	0.34	0.30	0.32
Copper	0.34	0.33	0.33	0.34	0.33	0.29	0.32
Nickel	0.21	0.20	0.19	0.19	0.19	0.06	0.04
Chromium	0.49	0.50	0.49	0.50	0.48	0.47	0.48
Molybdenum	0.02	0.02	0.02	0.02	0.02	0.01	0.02
Vanadium	0.037	0.034	0.032	0.034	0.035	0.023	0.024

CHAPTER 3 MECHANICAL PROPERTY EVALUATIONS

Tensile tests of the first heat and A606 steels were performed in both longitudinal and transverse tensile specimens using a modified ASTM tensile bar geometry as shown in Figure 3a. Longitudinal specimens have their long axis parallel to the direction of hot-rolling. Transverse specimens have their long axis cut perpendicular to the direction of hot-rolling. The 1.0" gage length extensometer was used due to restrictions imposed by the type of grips available at Northwestern University.

Tensile tests of the second heat were performed at the Metals Laboratory of the ILDOT Bureau of Materials and Physical Research. Both longitudinal and transverse tensile specimens were tested. The full-sized tensile bars were plate-type flat specimens (Figure 3b) conforming to standard dimensions described in ASTM A370 Figure 3. A 2.0" gage length extensometer was used in those tests.



(a) (b)

Figure 3. (a) Dimensions of the tensile specimens evaluated at Northwestern University. (b) Dimensions of the standard ASTM A370 plate-type tensile specimens evaluated at IL DOT, where L = 12", B = 3", W = 1.5", R = 0.5", C = 2", G = 2", and T = thickness of the steel plate or sheet.

Mechanical Properties of ASTM A606 Steels

Tensile properties of the A606 steels are presented here first. Figure 4 shows the tensile properties of A606 steels in the longitudinal direction (L) in a conventional engineering stress-strain plot. Figure 5 shows a similar plot when the A606 steels were tested in the transverse direction (T). The 0.2% offset yield strength (YS), ultimate tensile strength (UTS), and % elongation to failure measured by a 1.0" gage length extensometer are summarized in Table 3. The YS and UTS of these steels do not appear to be dependent on the testing direction. While there is some variation in YS and UTS for A606 because the various steel samples were rolled from different steel heats by different steel mills, in general, the longitudinal YS ranged from

63.3 to 70.1 ksi, and UTS was in a comparatively narrow range of 79.1 to 86.4 ksi. The longitudinal range of % elongation to failure for all the A606 steels evaluated was 41% to 49%, although this range would be reduced by 2% to 3% if specimens had a 2" gage length instead of a 1" gage length.

The chemical compositions of the A606 steels from Severstal NA and Gallatin Steel have a relatively general uniformity, which accounts for the small variation in tensile and yield strength except for the changes in thickness. The differences in rolling conditions that are proprietary for each steel producer result in different grain sizes and grain morphology, which affect the strength of the steel.

The YS to UTS ratio is an important factor that affects steel formability; it is preferred that the ratio be less than 0.90. If the ratio is higher than 0.90, then there is a probability that the steel could crack or fracture during forming operations. The YS to UTS ratios for all A606 steels tested were in the range of 0.79 to 0.89, as shown in Table 3.

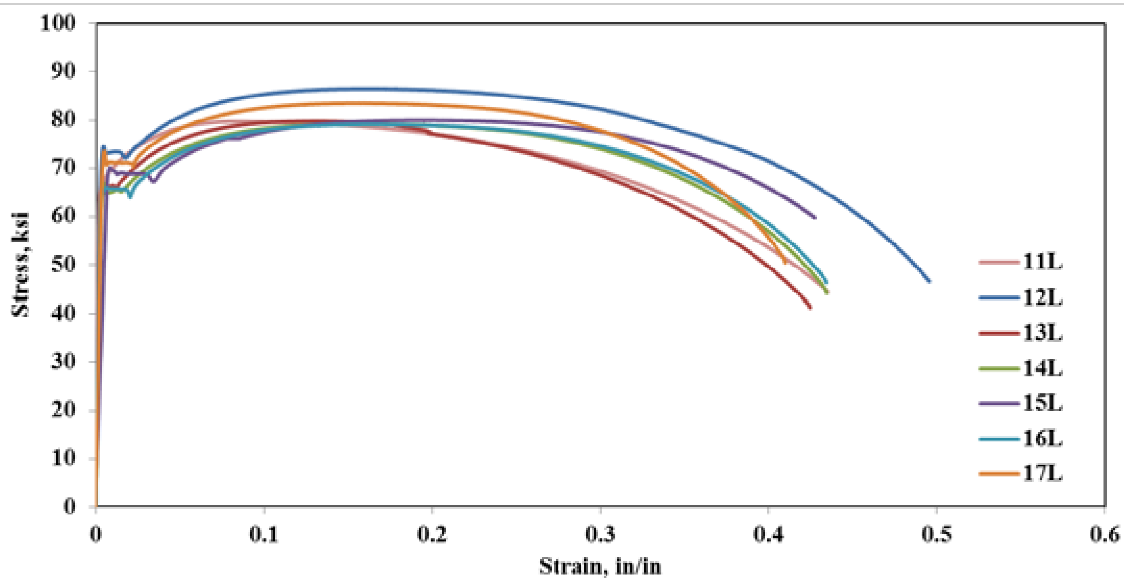


Figure 4. Tensile properties of the Severstal and Gallatin ASTM A606 steel sheets and plates tested in the longitudinal direction.

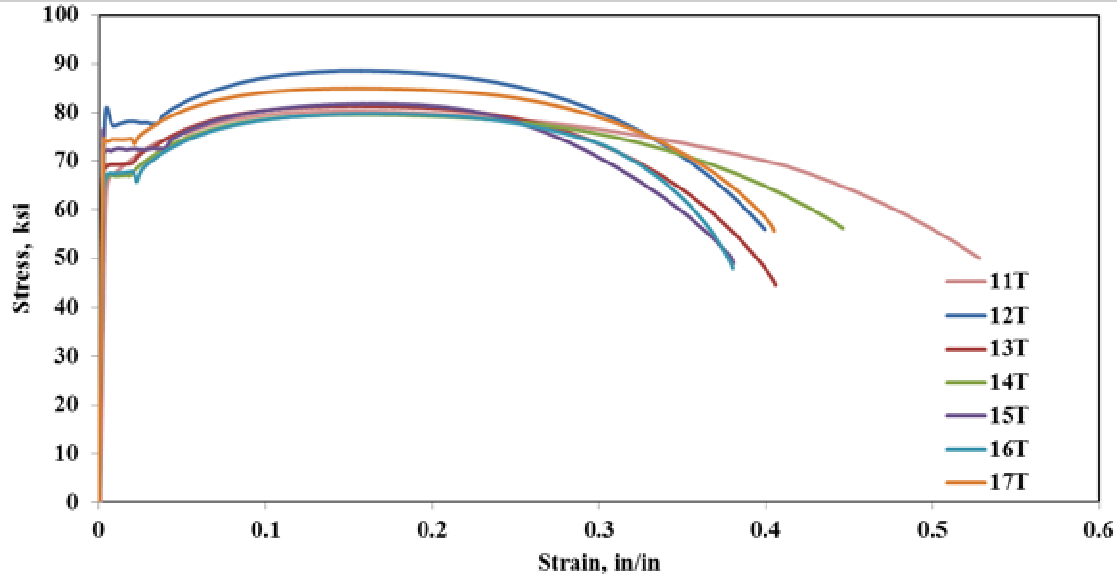


Figure 5. Tensile properties of the Severstal NA and Gallatin ASTM A606 steel sheets and plates tested in the transverse direction.

Table 3. Tensile Properties of ASTM A606 Type 4 Steels

Steel Sheet; Plate	Producer	Thickness, in	YS, ksi		UTS, ksi		Elongation to Failure, %		YS/UTS	
			L	T	L	T	L	T	L	T
17	Gallatin	0.101	70.1	72.9	83.6	84.9	41	40	0.84	0.86
16	Gallatin	0.116	64.3	65.7	78.8	79.6	43	37	0.82	0.83
15	Severstal	0.131	67.2	72.5	79.9	81.7	43	37	0.84	0.89
14	Gallatin	0.167	64.6	67.7	79.1	79.6	43	43	0.82	0.85
13	Gallatin	0.186	63.3	68.0	79.7	81.2	42	40	0.79	0.84
12	Severstal	0.247	73.6	76.4	86.4	88.4	49	40	0.85	0.86
11	Gallatin	0.378	65.2	65.7	79.3	80.0	43	52	0.82	0.82

Mechanical Properties of Heat 1 of A710 Grade 50

Figures 6 and 7 show the tensile properties of the first heat of A710 B50 steel tested in the longitudinal (L) and transverse directions (T), respectively. The 0.2% offset yield strength, ultimate tensile strength, and % elongation to failure were measured by a 1.000" gage length extensometer and are summarized in Table 4. There are observable variations in mechanical properties of the steel as function of testing direction, as well as the thickness of the plates and sheets. ASTM A710 Grade B steel was not available commercially at 50 ksi yield strength, so a 300 lb heat was produced by Sophisticated Alloys of Butler, PA. The heats were cut into small ingots, which were then hot-rolled at the Arcelor Mittal Global R&D Laboratory.

The yield strength of Heat 1 of A710 steel varied in ranges from 57 to 95.7 ksi, and 72 to 119 ksi for tensile strength. Two inch thick ingots were hot-rolled into 0.350" plates, and then further rolled into thinner sheets. There were significant increases in strength as a function of reduction in the thickness of the finished plate into sheet. The YS of the 0.117" sheet was less than that of 0.128" thick sheet because the 0.117" sheet was rolled from much thinner ingot, thereby sustaining considerably less section reduction during the hot-rolling than the other sheets. The YS to UTS ratio for A710 steel was in the range of 0.77 to 0.81 for all thicknesses except for the 0.172" and 0.190" as shown in Table 4. The YS to UTS ratio for 0.172" and 0.190" thick A710 steel of Heat 1 exceeded 0.90. However, the 0.172" sheets passed the formability tests without cracking or fracture due to their 37% to 44% elongations and ample ductility.

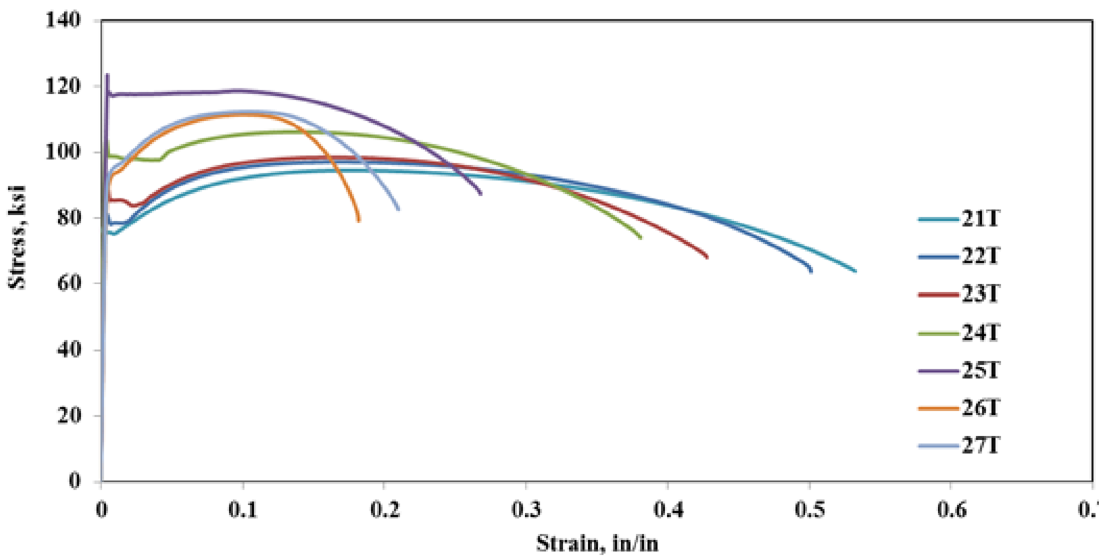


Figure 6. Tensile properties of first heat of A710 Grade B50 steel tested in the longitudinal direction.

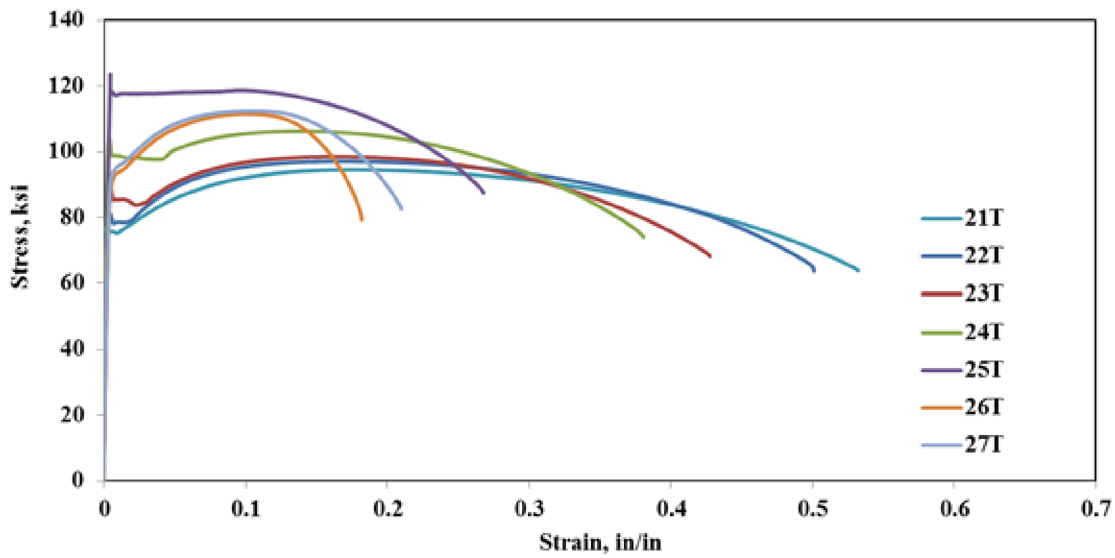


Figure 7. Tensile properties of first heat of A710 Grade B50 steel tested in the transverse direction.

Table 4. Tensile Properties of Heat 1 of A710 Grade B50 Steel

Steel Sheet; Plate	Thickness, in	YS, ksi		UTS, ksi		Elongation to Failure, %		YS/UTS	
		L	T	L	T	L	T	L	T
27	0.117	95.7	90.4	111.4	112.2	34	21	0.86	0.81
26	0.125	98.6	90.4	119.1	111.3	35	19	0.83	0.81
24	0.172	95.4	97.8	101.4	106.2	44	37	0.94	0.92
23	0.190	83.9	84.9	97.1	98.4	44	42	0.86	0.86
22	0.264	75.4	76.7	94.2	97.0	54	49	0.80	0.79
21	0.350	57.2	72.6	72.0	94.5	47	52	0.79	0.77

Impact toughness properties of the first heat were determined by use of the Charpy V-notch (CVN) test. Standard V-notch specimens were directly cut from the plates and sheets and tested in accordance with ASTM A370 *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, Sections 19–27, at the IL DOT Bureau of Materials and Physical Research. Test temperatures were –10 °F, 20 °F, 32 °F, and 70 °F Because many of the sheet specimens are less than 1 cm thick, their subsized results were proportionally scaled up to a standard thickness. For example, a 0.125" thick specimen has only 31.7% of the fracture area of a standard 0.394" thick CVN specimen. To normalize the subsize value in this case, it was multiplied by 3.154 to obtain a standard CVN value. Normalized values of impact toughness of sheets and plates of varying thickness in the transverse direction are summarized in Table 5.

A longitudinal CVN test was run on the thinnest sheet at 0.117" thickness for comparison purposes.

In general, transverse toughness was good to very good, generally increasing as the material increased in thickness. The data also indicated that the transition temperature of the A710 Grade B50 steel was less than –10 °F because the carbon content of this heat of steel was so low at 0.09%. Heat 2, with a much lower carbon content at 0.028%, would be expected to have even higher impact toughness values.

Table 5. Transverse CVN Impact Toughness of Heat 1 of A710 Grade B50

Thickness, in	Subsize Value, ft-lb	Normalized Value, ft-lb	Test Temperature, °F
0.117 (transverse)	16	54	–10
	16	54	20
	14.5	49	32
	15	51	70
0.117 (longitudinal)	27	91	–10
	31.5	106	20
	34	114	32
	32	108	70
0.125	16.5	52	–10
	15.5	49	20
	17	54	32
	15	47	70
0.181	29	63	–10
	29	63	20
	29	63	32
	28.5	62	70
0.272	54	78	–10
	54.5	79	20
	55	80	32
	58.5	85	70
0.359	77	85	–10
	86	94	20
	87	96	32
	93.5	103	70

Determination of Tensile and Yield Strengths by Revising the Composition

The yield strengths from Heat 1 in sheet form (less than 0.25" thick) were clearly out of the of 50 to 60 ksi range required for forming tubing without incurring considerable wear and tear on fabrication machinery. The composition for Heat 1 was taken from earlier heats of the 30" deep rolled WF sections produced by Steel Dynamics of Columbia City, IN, which had flanges up to 1" thick.

The tensile strengths of Heat 1 were compared to the tensile strengths obtained by the ferrite multiplier method that predicts the strength of low-alloy steels. An appropriate gage factor was applied to compensate for the reduction of thickness from 0.350" to 10 gage.

The ferrite multiplier method used to predict tensile strength in this work was based on the remarkable work of Walters (1943) of the Naval Research Laboratory, which determined the tensile strength of steels from test results of several hundred normalized steels, primarily from 3/4" rounds. The prediction of UTS is based on the multiplication of the tensile strength of pure ferrite by factors assigned to particular alloying elements. Other studies around that same time used 0.375" thick as a baseline for determination of gage factor (Quest and Washburn 1940). The determination of strength of low-alloy steels developed in the Walters approach was modified by the IIL DOT to approximate the results of the original graphs as straight lines, even though some of the actual plots have very slight curvatures for several elements. When plotted as best-fit straight lines, they have very high Pearson correlation coefficients, typically 0.99 or better. Because of the general purity of the ferrite in the A710 alloys tested and the relatively small range of alloy contents, the ferrite multiplier method can be used to estimate tensile and yield strength based on composition.

The approach is termed a "ferrite multiplier" of the basic tensile strength of pure iron, which was assumed by Walters to be 36 ksi in his original paper. Each alloying element has a specific multiplier based on its concentration in percentage by weight. The alloying elements are carbon, phosphorus, vanadium, molybdenum, manganese, copper, silicon, chromium, and nickel. Theoretically, if there is only a trace or no presence of each specific element, it has a multiplier of one, with the exception of carbon and vanadium. Several other elements do not have an intercept of 1.0 because of the linear fitting of the data, even though there is a data point start at the origin of 1.0 as assumed by Walters.

Ferrite is either hardened by solid solution strengthening, the precipitation of intermetallic compounds, or by interstitial locking of dislocations. Each mechanism is empirically taken into account by the various multipliers of hardening. The concept of multiplication of the strength directly applies to A710 because it has very low carbon content and is virtually commercially pure ferrite. After one element is alloyed with pure ferrite, the entire matrix is strengthened. The next alloying element therefore multiplies that strengthened matrix, and so on, with each additional alloying element. The tensile strength of ferrite was originally rated as 36 ksi, and the tensile strength of the steel proportionally increases, based on the concentrations of each alloying element in the ferrite.

The ferrite multipliers in linear equation form for each of these elements are as follows:

$$M_C = 1.095 + 2.35 \times (\%C)$$

$$M_{Mn} = 0.979 + 0.277 \times (\%Mn)$$

$$M_P = 1.0 + 1.182 \times (\%P)$$

$$M_{Si} = 1.0 + 0.189 \times (\%Si)$$

$$M_{Cu} = 0.981 + 0.181 \times (\%Cu)$$

$$M_{Ni} = 1.0 + 0.079 \times (\%Ni)$$

$$M_{Cr} = 0.989 + 0.136 \times (\%Cr)$$

$$M_{Mo} = 1.0 + 0.710 \times (\%Mo)$$

$$M_V = 1.015 + 0.699 \times (\%V)$$

Calculation of the 0.350" Thick A710 Grade B50 Tensile Strength (UTS)

To validate the accuracy of the multipliers, the composition of Heat 1 of A710 Grade B50 melted by Sophisticated Alloys was used to compare the tensile strength obtained by the ferrite multiplier method with the actual longitudinal tensile strength of the 0.350" thick flat subsequently rolled by Arcelor Mittal.

The composition of Heat 1 was 0.07 C, 0.95 Mn, <0.005 P, <0.005 S, 0.34 Si, 0.92 Ni, 0.14 Cr, and 0.07 Cb. Since the concentrations of P and S were negligible, they were assigned multipliers of 1.0. Because Cb had a very low concentration and was not included in the Walters data, it was also assigned a multiplier of 1.0.

Using the multiplier equations in the direct order of the elements listed above, here is the calculated value of UTS of the composition of Heat 1:

$$UTS = 36\ (1.258)(1.242)(1.0)(1.0)(1.064)(1.148)(1.055)(1.008)(1.0) = 73.1 \text{ ksi}$$

The actual tensile strength determined by testing at Northwestern University of the 0.350" thick flat plate, based on a 1" gage length, was 72.0 ksi. The difference of the ferrite multiplier estimate, compared with the actual UTS, was 73.1 ÷ 72.0 = 1.015, or 1.5% difference.

Gage Factors

Due to the reduction in thickness, an increase in tensile strength occurs from 0.350" when rolled down to 0.117", called the gage factor. Because tubing is formed in the transverse direction, the change in transverse tensile strength was considered instead of the change in longitudinal strength. The change in transverse yield and tensile strength vs. sheet thickness for Heat 1 is plotted in Figure 8. The YS to UTS ratio is relatively constant for each thickness at approximately 0.8, where each best-fit line for tensile and yield strength would be parallel if it were not for the anomalous YS data point at 0.172". The mathematical relationships between thickness and strength for this heat were determined to be linear fits, based on their high Pearson correlation coefficients:

$$UTS = 119 - 77.5\,t; \quad YS = 103.8 - 90.4\,t$$

Where t = thickness, inches; UTS and YS are in ksi.

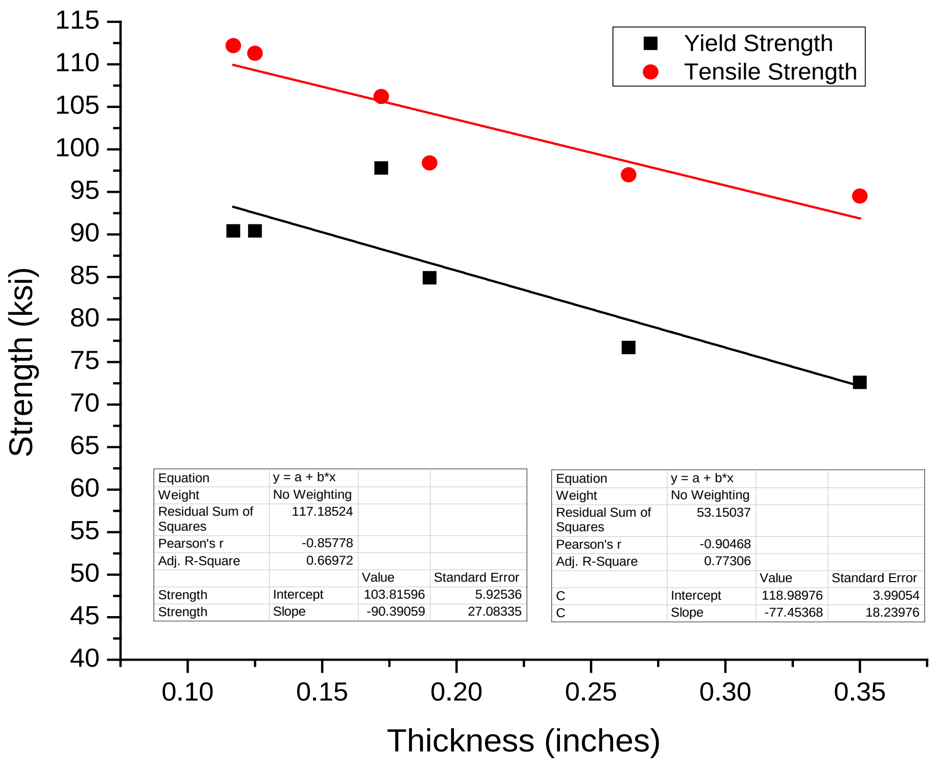


Figure 8. The yield and tensile strengths of Heat 1 transverse to the rolling direction have a relatively constant yield to tensile ratio of 0.8. The increasing tensile strength as a function of decreasing thickness is linear, with the deviation of yield about ±4 ksi from the mean. The increase in both the tensile strength from 0.35" to 0.125" thick is about 77.5 ksi per in.

Comparison with the A606 Gallatin and Severstal Sheet Steels

For the A606 steels supplied by Gallatin Steel and Severstal NA, their actual tensile strengths were compared with the UTS values calculated by ferrite multiplying factors. The actual compositions of the A606 steel heats were used to determine their predicted strength, and then the difference as a function of thickness was measured vs. the calculated value at 0.350". Table 6 summarizes the differences in calculated tensile strength vs. actual strength and thickness for the A606 Gallatin and Severstal NA steels.

Table 6. Change in UTS vs. Thickness for A606 Steel Heats

Thickness, in	Ferrite Multiplier UTS, ksi	Actual Transverse UTS*, ksi	Actual Transverse YS*, ksi	Thickness Difference from 0.350"	Change in UTS/in
0.101	69.7	84.9	72.9	0.249	60.9
0.131	65.2	81.7	72.5	0.219	75.3
0.167	66.2	79.6	67.7	0.183	73.4
0.186	66.4	81.2	68.0	0.164	90.3

*These UTS values were obtained from actual tensile specimens from sheets of specific thickness. The ferrite multiplier UTS was predicted from the chemical composition of the sheet.

The mean change in UTS in thickness from 0.101" to 0.186" from the 0.350" baseline for the A606 Gallatin and Severstal steels was 75.0 ksi per in, which is very close to the 77.5 ksi per in for Heat 1 of A710. The gage factor for the A606 steels provides good confirmation of near equivalence to the difference in the A710 Grade B50 steel sheets based on predictions of the ferrite multiplying factors vs. their actual tensile strengths.

Calculation of Yield and Tensile Strength Based on a Different A710 Composition

A revised composition was determined by the ferrite multiplier method, taking into account commercial conditions, including traces of chromium, molybdenum, and vanadium. The minimum manganese range and Cb to Ti ratios chosen were based on recommendations of Nucor Steel Crawfordsville, a sheet steel producer of A1011, which is a ferritic product of chemical composition with many of the same alloying elements.

The composition range selected for Heat 2 was as follows: 0.03 to 0.05 C, 0.60 to 0.70 Mn, 0.010 P max, 0.006 S max, 0.20 to 0.40 Si, 0.60 to 0.70 Cu, 0.35 to 0.45 Ni, 0.05 Cr max, 0.04 to 0.07 Cb, and 0.10 to 0.20 Ti. Three different values for yield and tensile strength were calculated: (1) for the lower range of values of composition, (2) the mid-range, and (3) the upper range.

1. The lower range composition was 0.03 C, 0.6 Mn, 0.005 P, 0.2 Si, 0.60 Cu, 0.35 Ni, and 0.05 Cr. The calculated UTS for a 3/8" or larger thickness, using multiplying factors for the above order of composition would be:

$$UTS = 36\,(1.164)(1.145)(1.006)(1.038)(1.090)(1.028)(1.0) = 56.1\text{ ksi}$$

The change in thickness from 0.350” to 10 gage (0.1345") is 0.2155. Since the gage factor is 77.5 ksi per in, the tensile strength was predicted to be 16.7 + 56.1 = 72.8 ksi.

2. The mid-range composition was 0.04 C, 0.65 Mn, 0.007 P, 0.30 Si, 0.65 Cu, 0.40 Ni, and 0.05 Cr. The estimated tensile strength at 0.350" or thicker prior to reduction to 10 gage would be:

$$UTS = 36\ (1.187)(1.159)(1.008)(1.057)(1.099)(1.032)(1.0) = 59.9\ ksi$$

Adding the gage factor for reduction to 10 gage of 16.7 ksi, UTS = 59.9 + 16.7 = 76.6 ksi.

3. The upper range composition was defined as 0.05 C, 0.70 Mn, 0.01 P, 0.4 Si, 0.7 Cu, 0.45 Ni, and 0.05 Cr. The estimated tensile strength prior to reduction to 10 gage would be:

$$UTS = 36\ (1.211)(1.173)(1.018)(1.076)(1.108)(1.036)(1.0) = 64.3\ ksi$$

When the gage factor of 16.7 ksi is added, UTS = 64.3 + 16.7 = 81 ksi.

Each of these estimated values obtained from an altered composition are within the realistic ranges of yield and tensile strengths used by tubing manufacturers when they receive either ASTM A1011, A606, or A588 in sheet form.

Tensile and Bend Tests for Heat 2 of A710 Grade B50 Steel Sheet

The yield and tensile strength of the second heat were reduced by decreasing several key alloying elements based on predictions of the ferrite multiplier method. This was done in order to provide yield strengths within the range of 50 to 55 ksi, in comparison to the much higher yield strength values obtained from Heat 1.

Sophisticated Alloys chose the mid-points of the revised composition range provided to them by ILDOT. The first heat at Arcelor Mittal Global R&D Laboratory was hot-rolled in just three passes, resulting in greater section reductions per rolling pass, whereas hot-rolling at Sophisticated Alloys was performed through multiple passes for three thicknesses of Heat 2.

Tensile and bend testing of three sheet thicknesses obtained from Heat 2 were conducted at IL DOT. The nominal sheet thicknesses were 0.150", 0138", and 0.187". Actual thickness was individually measured for each tensile specimen. The test samples were cut to make plate-type flat tensile specimens, conforming to the standard dimensions described in ASTM A370, Figure 3, Rectangular Tension Test Specimens.

Bend test samples were three-point bend test specimens, using the dimensions for a guided bend and a 1/4" thick punch mandrel with 1/8" rounded radius tip with side clearances in conformance with ASTM E190 *Standard Test Method for Guided Bend Test for Ductility of Welds*. All specimens, ranging in thickness from 0.138" to 0.187", passed the bend tests for both 0.25" and 0.375" thick mandrels, and exhibited no overt cracking or presence of surface fissuring, which is indicative of susceptibility to cracking or near rupture.

The composition of Heat 2 provided by Sophisticated Alloys was 0.028 C, 0.64 Mn, 0.31 Si, <0.005 S, 0.006 P, 0.66 Cu, 0.38 Ni, <0.01 Cr, 0.059 Cb, and 0.102 Ti. Results of tensile tests are shown in Table 7.

Table 7. Tensile Tests of Heat 2

Specimen Orientation	Specimen Thickness, in	Yield Strength, psi	Ultimate Tensile Strength, psi	% Elongation, 2" Gage Length	YS to UTS Ratio
Longitudinal	0.138	52016	71821	38	0.724
Longitudinal	0.139	52947	71504	32	0.740
Transverse	0.137	56253	74672	35	0.753
Transverse	0.137	56000	74336	40	0.753
Longitudinal	0.151	51622	64737	40	0.811
Longitudinal	0.150	51618	65213	45	0.792
Transverse	0.149	52497	64725	38	0.811
Transverse	0.150	49911	63684	32	0.784
Longitudinal	0.190	49979	64596	45	0.774
Longitudinal	0.192	45147	64100	48	0.704
Transverse	0.187	49566	66834	45	0.742
Transverse	0.187	49832	67119	48	0.742

The % elongation to failure for both the first and second heats of A710 Grade B50 steel continued to be very ductile. The yield and tensile strengths for Heat 2 are plotted in Figure 9 for both longitudinal and transverse values because they do not vary considerably, as was the case for Heat 1. Also shown are UTS values for this heat predicted by the ferrite multiplier method. Those values were determined from the following calculation:

$$UTS = 36\ (1.161)(1.156)(1.059)(1.007)(1.1)(1.03)(1.0) = 58.4\ ksi$$

The three predicted UTS values at 0.138", 0.150", and 0.190" were 74.8, 73.9, and 70.8 ksi, respectively. The predicted values vary by about 5 ksi vs. the actual test values, an error of about 6% to 7%. The YS to TS ratio is very consistent, averaging 0.76 ± 0.03.

The deviation of the prediction of UTS by the ferrite multiplier method is most likely due to the low concentration of carbon and to the value of 36 ksi assigned by Walters to the tensile strength of ferrite. A very thorough investigation of the tensile strength of pure ferrite was carried out by the former National Bureau of Standards (Neville and Cain 1922), in which electrolytic iron of high purity (0.001% C, <0.001% Mn, 0.011% S, 0.004% P) was pulled in tension. The tensile strength was determined by Neville and Cain to be 32 ksi. When 0.15% to 0.31% Mn was present, the tensile strength was 34 to 36 ksi, which seems to have formed the basis for the assumption by Walters that 36 ksi was the strength of commercially pure ferrite. It appears that 34 ksi is probably the best compromise for the tensile strength of pure ferrite, considering that its strength can fluctuate as a function of grain size and strain rate, and because of the minor presence of alloying elements such as carbon, phosphorus, or manganese, or very small traces of vanadium or molybdenum.

The gage factor changes vs. the calculated UTS based on 34 and 36 ksi for the tensile strength of ferrite for a 0.350" thick section for the three thickness changes in Heat 2 are summarized in Table 8.

Table 8. Gage Factors for Heat 2

Tensile Strength of Ferrite, ksi	Estimated Strength of 0.350", ksi	Gage Factor at 0.138", ksi/in	Gage Factor at 0.150", ksi/in	Gage Factor at 0.190, ksi/in	Average Gage Factor, ksi/in
32	51.9	99.9	63.4	86.0	83.1
34	55.2	84.6	47.2	65.7	66.0
36	58.4	69.3	31.0	45.5	48.6

Of the three values for the tensile strength of ferrite, only 34 and 36 ksi were used for prediction purposes, along with a gage factor range of 66 to 75 ksi per in. These values appear to be the most reasonable for the determinations of tensile strength of A606 and A710 sheet steels. The gage factor range of 66 to 75 ksi per in is in line with those obtained for Heats 1 and 2 and for the A606 steels obtained from Severstal NA and Gallatin Steel.

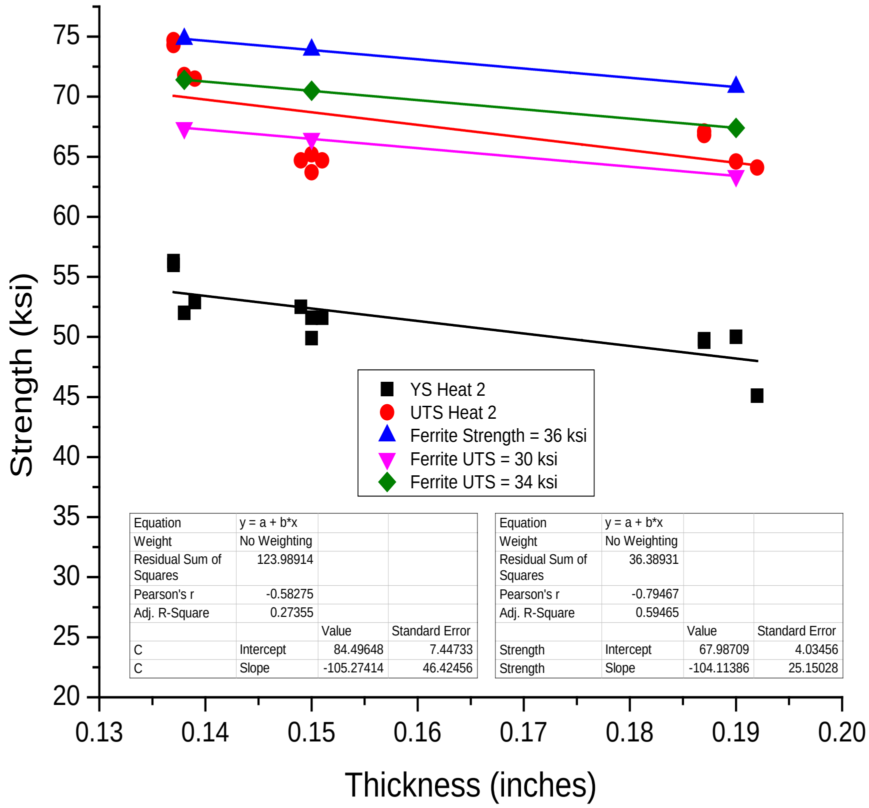


Figure 9. The tensile and yield strengths of Heat 2 are plotted vs. sheet thickness. The yield to tensile ratio is virtually constant. The ferrite multiplier prediction of UTS is off by 6% to 7% when 36 ksi is used for the tensile strength of ferrite, as shown in blue. Other known values for the UTS of ferrite, 32 ksi (in magenta) and 34 ksi (in olive green), are also shown.

CHAPTER 4 MICROSTRUCTURES OF A606 AND A710 STEELS

The microstructures of A606 and A710 steels and how they affect the tensile properties of these steels are discussed in this chapter. Optical microscopy provides an understanding of the differences in mechanical properties between A606 and A710 steels. Metallographic specimens were cut from each steel plate or sheet in two directions, as diagrammed in Figure 10. The specimens were then ground and polished down to 1 μm finish. They were etched in a solution of 5% nitric acid in methanol.

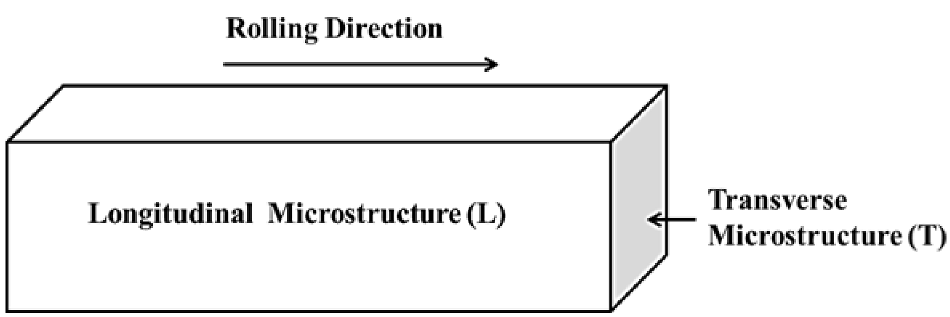


Figure 10. Orientation of metallographic specimens and tensile specimens taken from rolled heats.

Micrographs of the A606 Steels

The optical micrographs of A606 steels are shown in Figures 11 through 17. The microstructures of all A606 steels were ferritic, with small percentages of pearlite. This type of microstructure lends itself to good ductility and formability. The grain size and morphology of the grains are functions of steel thickness and hot-rolling conditions. Rolling practices can vary with each producer or its divisional mills. The grain sizes of the steels in sheet form were much smaller, and grains were more rounded (a thickness of less 0.25" is considered as sheet metal). For the 0.37" thick plate, grains were pancake-like and large because it had undergone significantly less reduction than the thinner sheets. Hot-rolling into sheet produces grain rupture, recrystallization, and subsequent grain growth of the smaller broken grains, resulting in finer grain morphology. The 0.247" and 0.131" thick specimens produced by Severstal had a slightly finer microstructure than the plates and sheets produced by Gallatin of similar thickness. We surmise that these differences are most likely due to minor variations in hot-rolling practices employed by the Severstal NA Rouge and Gallatin Kentucky steel mills.

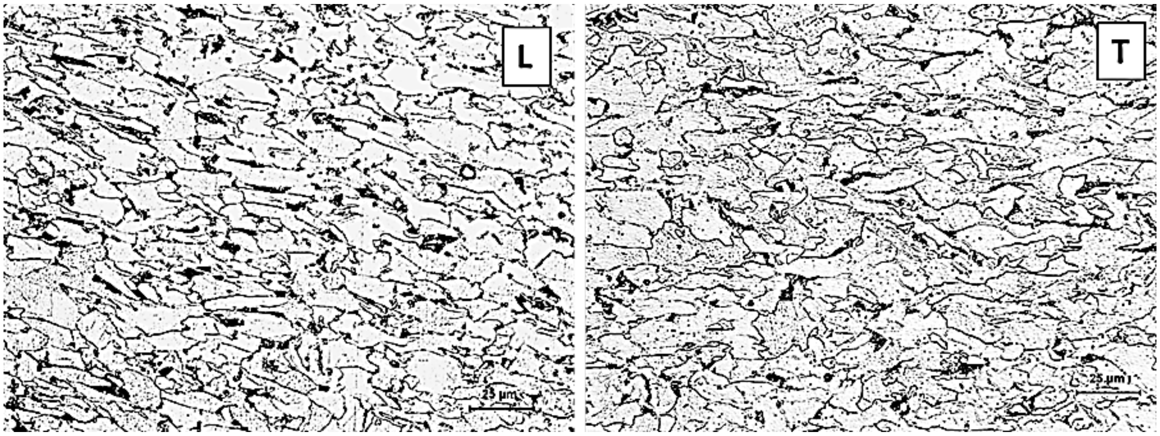


Figure 11. Metallography of 0.378" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

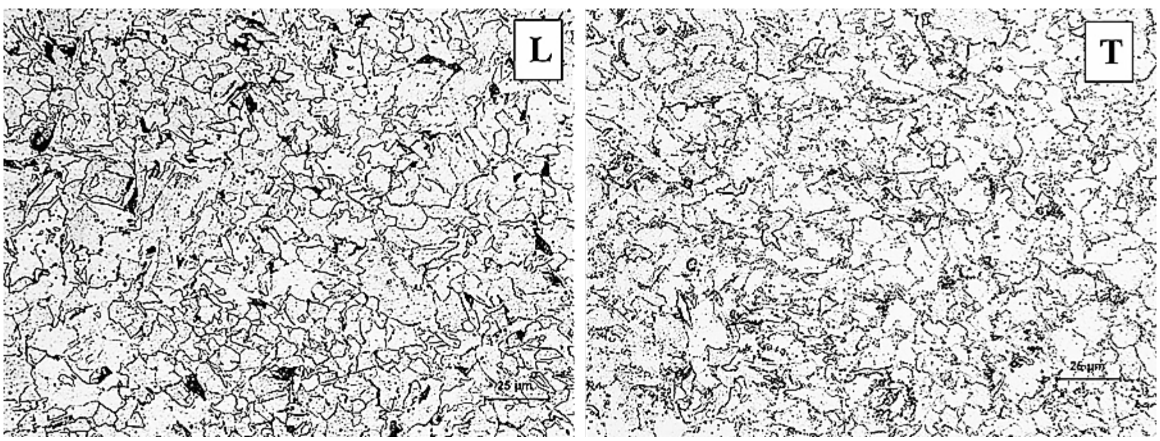


Figure 12. Metallography of 0.247" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

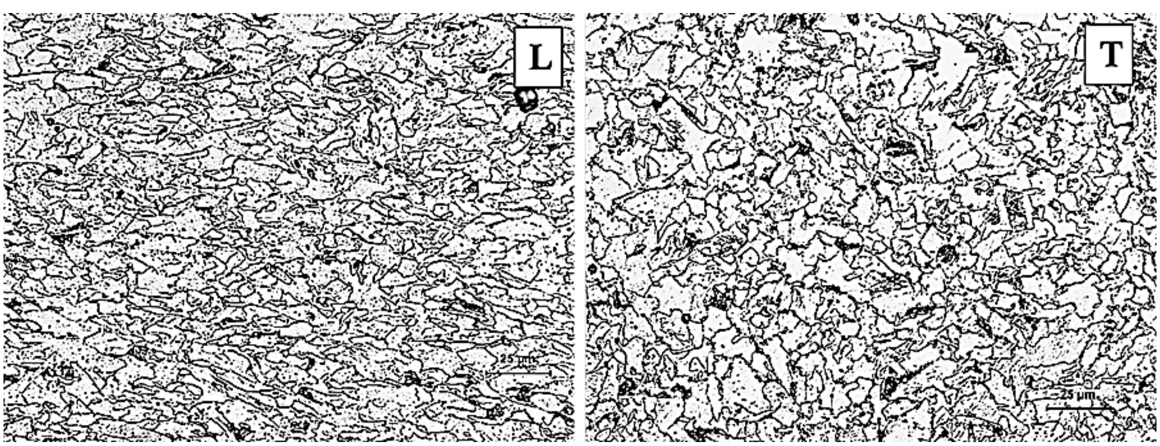


Figure 13. Metallography of 0.186" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

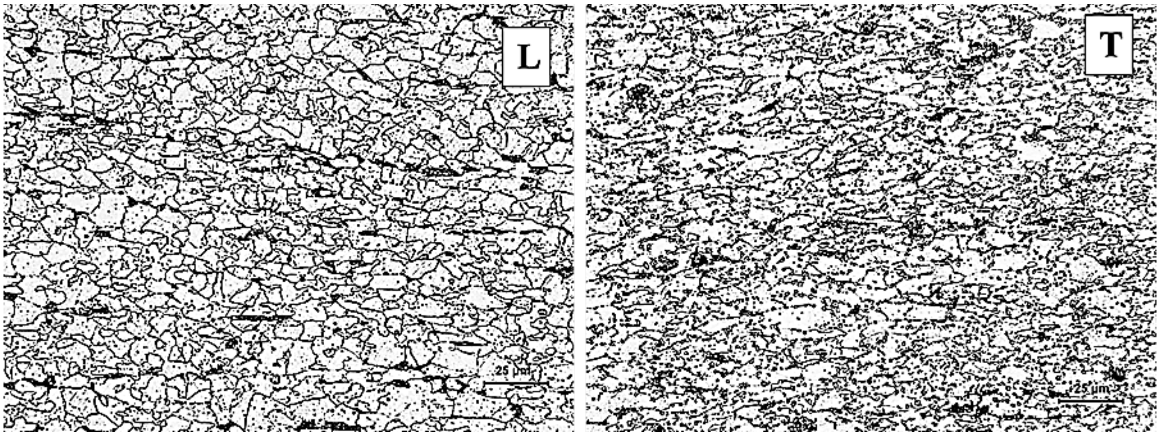


Figure 14. Metallography of 0.167" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

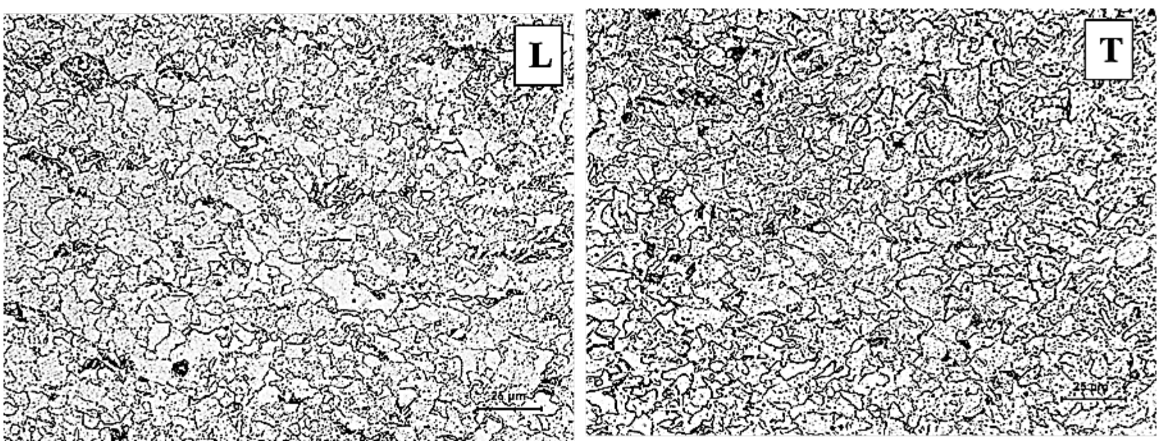


Figure 15. Metallography of 0.131" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

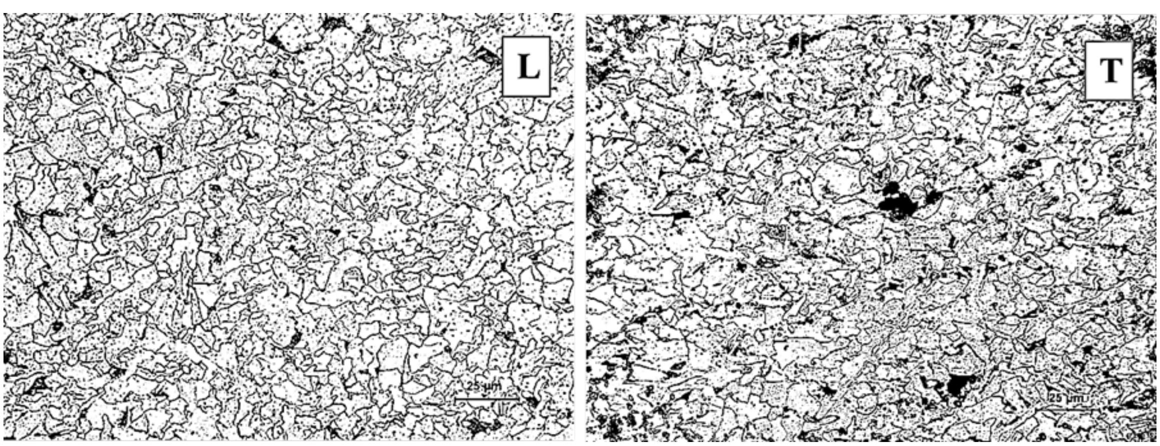


Figure 16. Metallography of 0.116" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

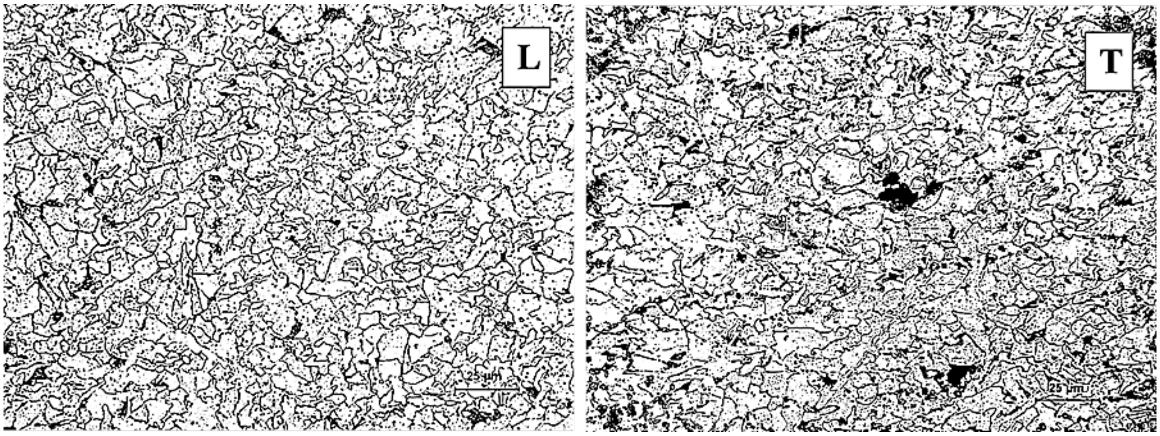


Figure 17. Metallography of 0.101" thick A606 steel in longitudinal (L) and transverse (T) directions at 300X.

Micrographs of the A710 Steels

Micrographs of A710 steels are shown in Figures 18 through 27. The microstructures of Heat 1 are shown in Figures 18 through 22. Ferrite is the main constituent, with some pearlite present in the thicker specimens (0.172" to 0.350"). The ferritic grains in A710 steel were considerably finer than in the A606 steels, which resulted from the hot-rolling schedule of starting temperature, finishing temperature, and only three passes employed at Arcelor Mittal Global R&D. Most likely these are the principal reasons that Heat 1 of A710 steel is much stronger than A606 steels of the same thickness. As grain size of the steels decreases with the reduction in thickness of the steel, this leads to an increase in yield and tensile strength.

There are bands of pearlite and fine-grained ferrite in some specimens of Heat 1, but the pearlite bands apparently did not affect the formability of the A710 steel.

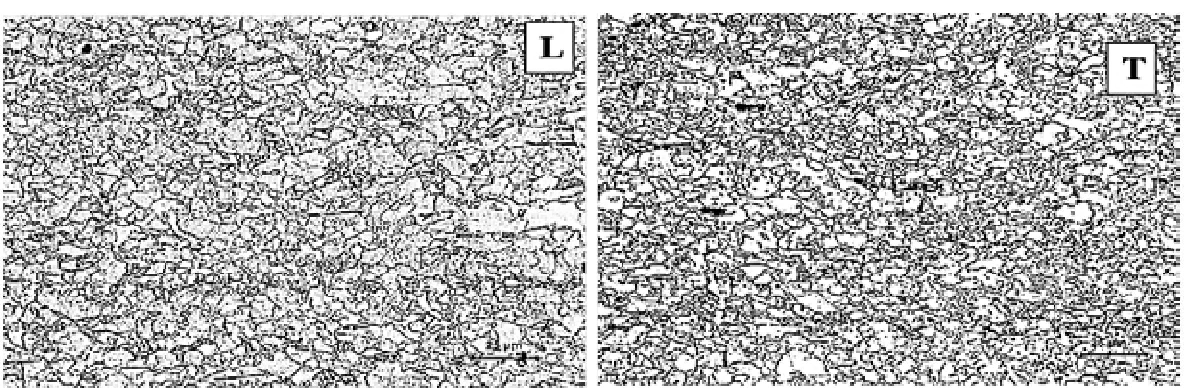


Figure 18. Metallography of 0.350" thick A710 steel (first heat) in longitudinal (L) and transverse (T) directions at 300X.

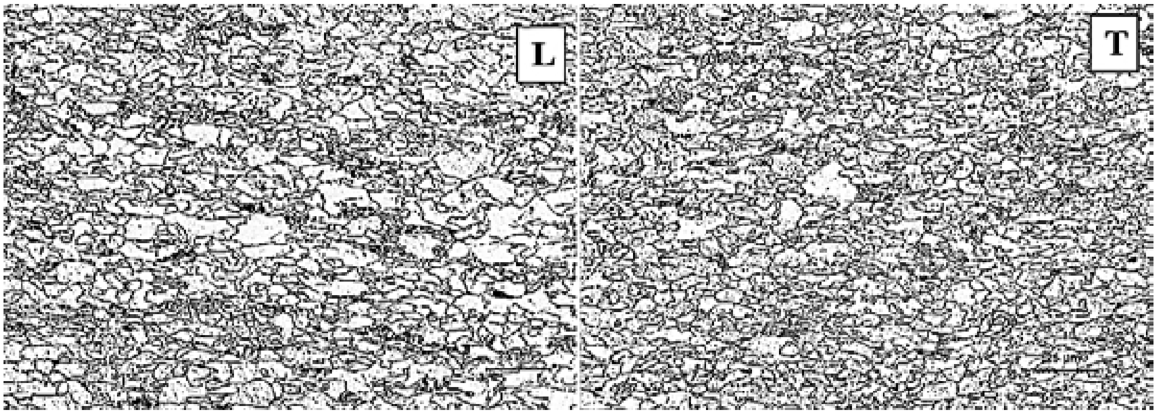


Figure 19. Metallography of 0.26" thick A710 steel (first heat) in longitudinal (L) and transverse (T) directions at 300X.

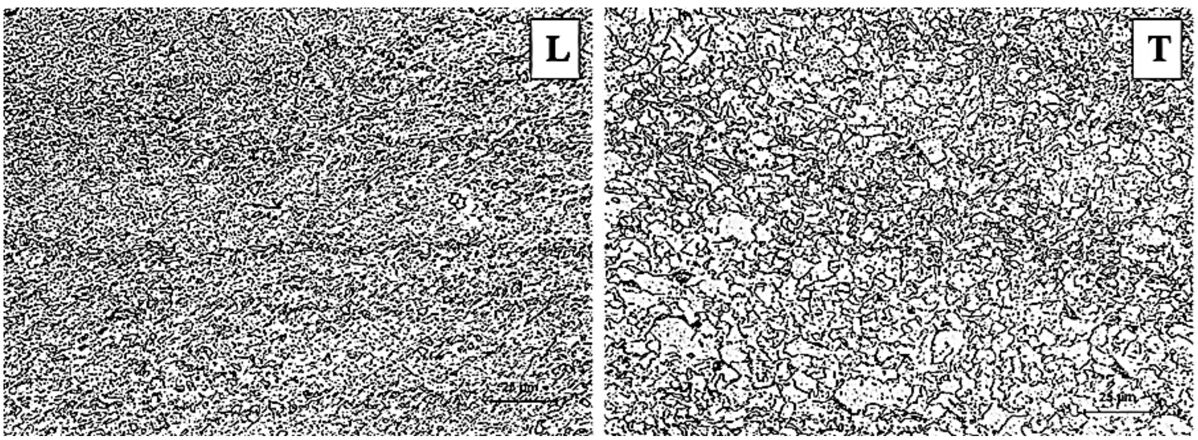


Figure 20. Metallography of 0.190" thick A710 steel (first heat) in longitudinal (L) and transverse (T) directions at 300X.

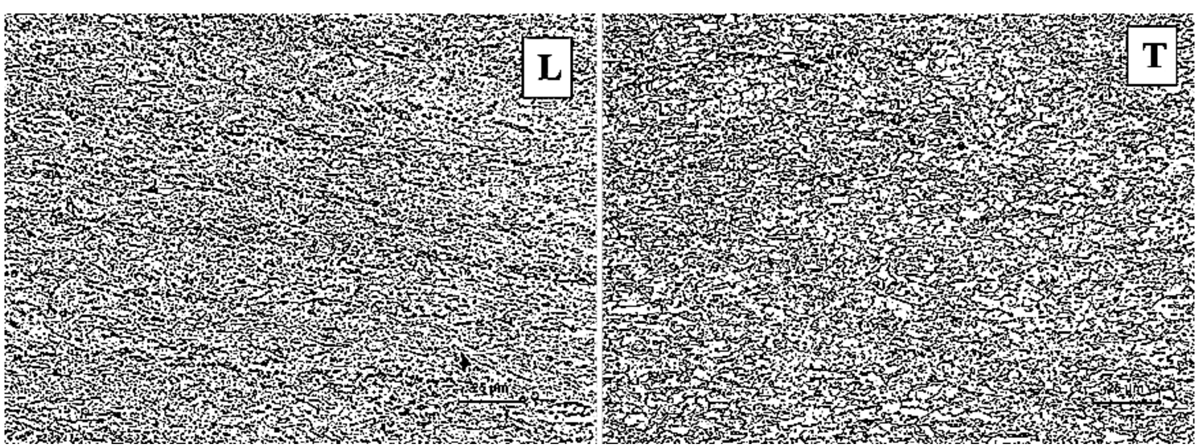


Figure 21. Metallography of 0.172" thick A710 steel (first heat) in longitudinal (L) and transverse (T) directions at 300X.

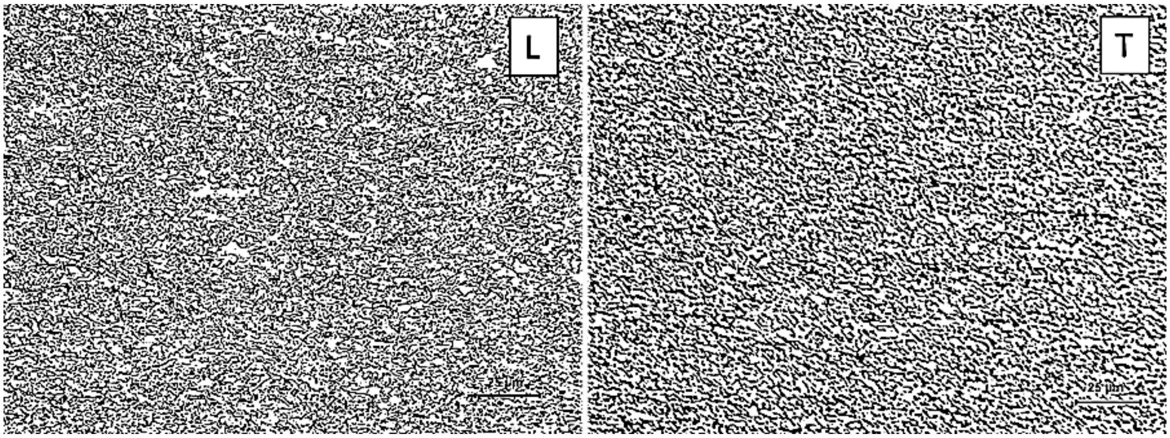


Figure 22. Metallography of 0.128" thick A710 steel (first heat) in longitudinal (L) and transverse (T) directions at 300X.

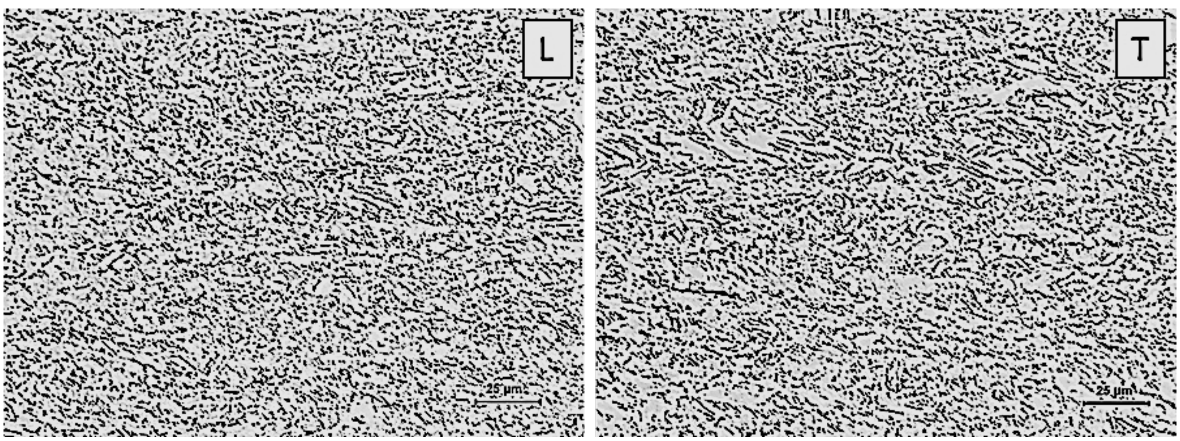


Figure 23. Metallography of 0.125" thick A710 steel (first heat) in longitudinal (L) and transverse (T) directions at 300X.

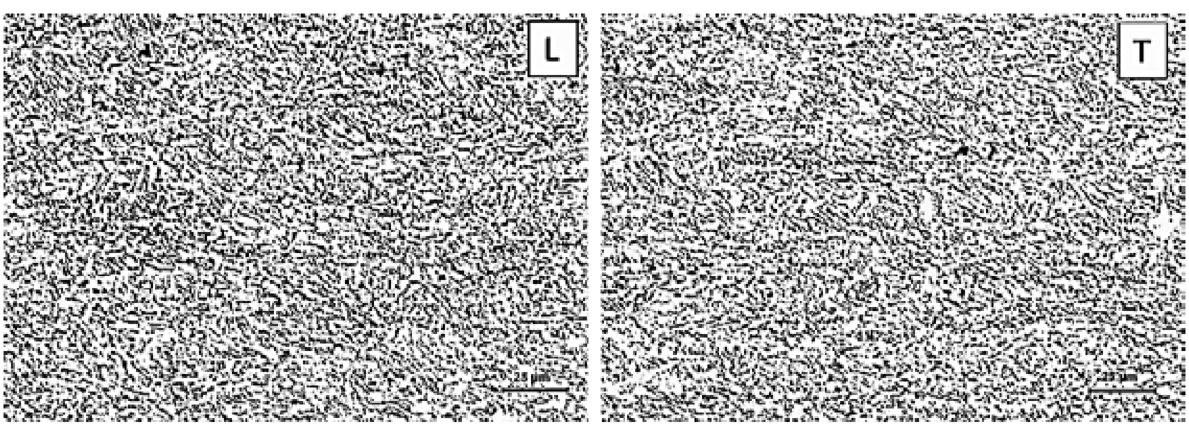


Figure 24. Metallography of 0.117" thick A710 (first heat) steel in longitudinal (L) and transverse (T) directions at 300X.

Figures 25 through 27 show the microstructures of the second heat of A710 steel. Ferrite is the main constituent, with a very small amount of pearlite. The grain sizes of the second heat are larger than those of the first heat most likely due to fewer reductions per rolling pass. The decreased amount of copper and nickel in this heat, combined with larger grain size, resulted in achieving the 50 ksi yield strength target. This steel easily passed the formability tests.

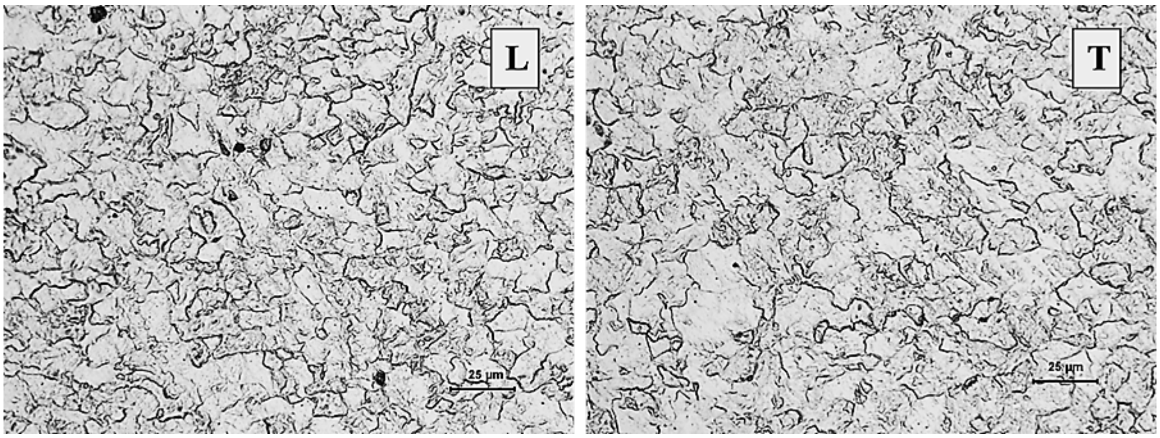


Figure 25. Metallography of 0.138" thick of A710 steel (Heat 2) in longitudinal (L) and transverse (T) directions at 300X.

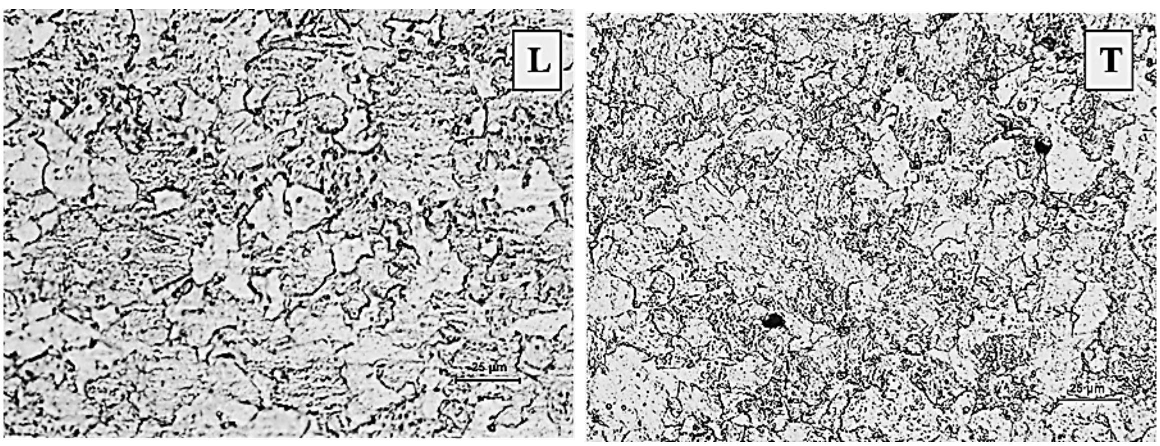


Figure 26. Metallography of 0.150" thick of A710 steel (Heat 2) in longitudinal (L) and transverse (T) directions at 300X.

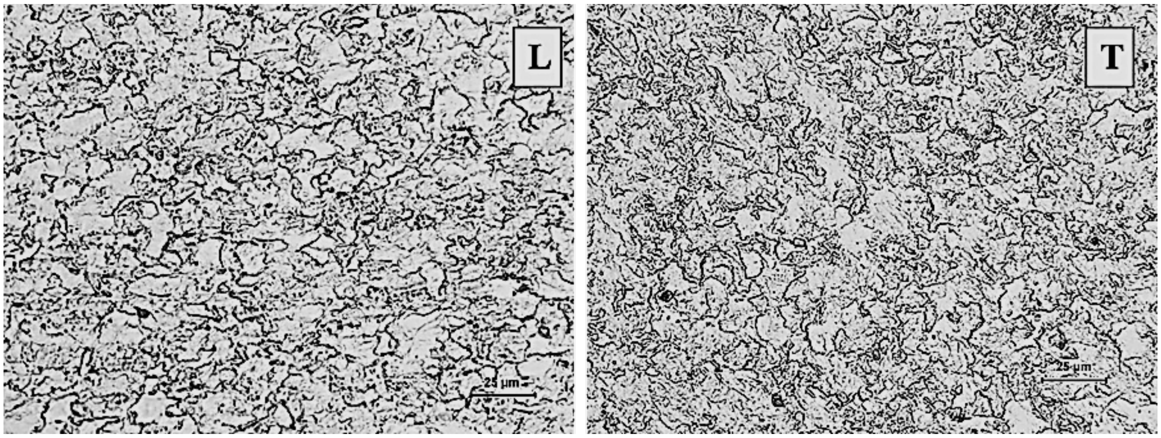


Figure 27. Metallography of 0.190" thick A710 (second heat) steel in longitudinal (L) and transverse (T) directions at 300X.

CHAPTER 5 FORMABILITY STUDIES OF STEELS

Bend tests for ductility provide a simple way to evaluate the quality of steels by their ability to resist cracking or other surface irregularities during a continuous bend. This test gives a visual indication of the ductility of the material. ASTM E290 *Standard Test Methods for Bend Testing of Material for Ductility* (ASTM 2009) and ASTM E190 *Standard Guide Bend Test for Ductility of Welds* (ASTM 2008) contain appropriate tests for steels that are bent into tubing or other shapes that are used for structures and highway construction. Specifically, we used a guided-bend test at ILDOT laboratory facilities with mandrels of defined dimensions to force the mid-length of the specimen between two supporting rollers separated by a space as shown in Figure 28.

The thickness of the mandrel determines the radius of the bend. Mandrels with diameters of 0.25", 0.313", 0.375", 0.50", 1.00", and 1.50" were available at IL DOT, but only the three smallest mandrels were used in order to reduce the number of tests. In general, if steel of certain thickness passes the test with a smaller mandrel, it certainly will pass the test with a mandrel with larger diameter or larger radius tip.

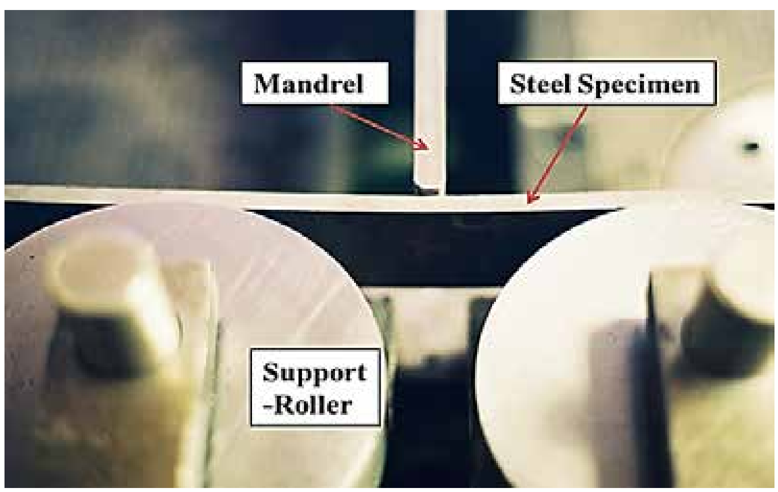


Figure 28. Configuration of the guided-bend test in accord with Figure 3 of ASTM E290. Clearances per side are 0.0625";support rollers and mandrel were lubricated with WD-40.

The specimens (5" to 10" long and 2" wide) were cut from the steel plates in the longitudinal and transverse directions, as depicted in Figure 29, because formability of the steel can vary from one direction to another due to differences in mechanical and properties and microstructure.

The mandrel thickness and the side spacing clearance were in accordance with ASTM Standards E290 and E190. Mandrels with 0.50", 1.0", and 1.50" diameter were not used in tests of A710 and A606 steels after the first sheet samples passed the 1/8" R bends. All specimens cut from A606 steel and the first and second heats of A710 steel were bent around 1/8" R, 5/32" R, and 3/16" R successfully without cracking. As required by ASTM E290, the convex surfaces of the bent specimens were examined by the unaided eye for evidence of cracks or surface irregularities. Two bent specimens made of A710 Grade B50 steel cut in the transverse direction are shown in Figure 30.

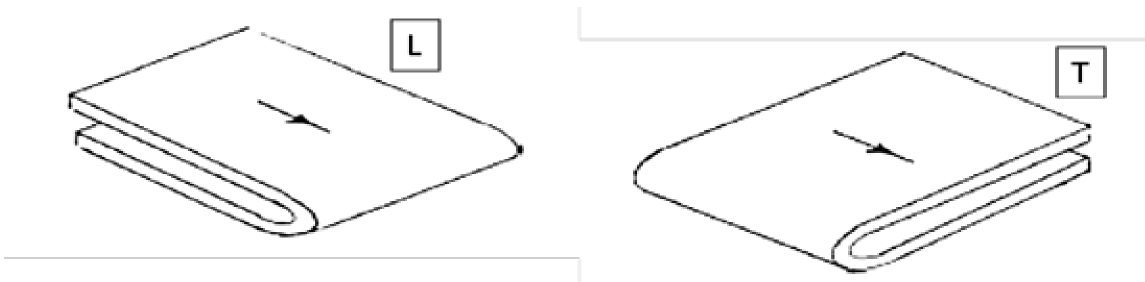


Figure 29. Depiction of test specimens after the E290 bend test, showing longitudinal (L) and transverse (T) bend specimens, where the arrows indicate the direction of steel rolling. This figure is extracted from Figures 1 and 2 of ASTM E290.

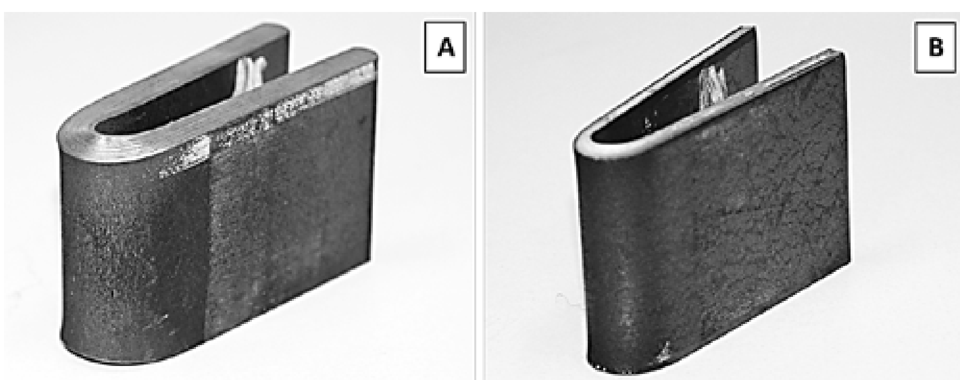


Figure 30. Actual transverse bend test specimens taken from Heat 1 of A710 Grade B50 steel bent around a 5/32" R mandrel. Specimen A is a 0.350" thick plate; specimen B is 0.172" thick sheet.

CHAPTER 6 OPTIMIZING FORMABILITY AND CORROSION RESISTANCE

As discussed in Chapter 3, ferrite multipliers were used to determine the estimated tensile strength of low-alloy weathering steels at 0.350" thick, and then gage factors were applied to calculate how the reduction of thickness increased both tensile and yield strength. It was found that yield strength was a direct function of tensile strength, typically in a fixed ratio ranging from 0.74 to 0.80. For Heat 2, the yield to tensile ratio was essentially constant at 0.74, definitely a favorable result. Formability of both heats easily passed the *1t* standard for sheet steels when bent around a 0.125" radius mandrel tip.

The aim of this research was to provide a low-alloy steel sheet with yield strength slightly above 50 ksi but with sufficient latitude such that it would meet ASTM property-based standards rather than the composition-based standards of the Society of Automotive Engineers (SAE). The mechanical property standards of ASTM specifications indicate that although a minimum yield strength of 50 ksi is established, commercial purchasers generally expect that actual tests of the furnished sheet would provide an increase of 4 to 10 ksi over the 50 ksi minimum.

However, atmospheric corrosion resistance of this steel must be superior to ASTM A588, A242, or A606. The most accurate predictive equations are those of Townsend, as described in Section 6.3.2 of ASTM G101 *Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels.* The mid-range compositions of ASTM A588 and A242 were taken to determine the ASTM G101 Townsend ratings for atmospheric corrosion resistance, as well as two ASTM A606 compositions based on the steels furnished from Severstal NA and Gallatin Steel. These compositions were compared with an optimized A710 steel sheet composition that exceeds 6.0 on the ASTM G101 index scale.

The optimized composition was developed to provide yield strength just below 50 ksi at 0.350" thick or more, which is where the ferrite multiplier method predicts tensile strength. Many heats of A710 Grade B have been previously poured; therefore, a realistic range of alloying additions to the basic ferritic structure can be derived. The new ranges and maxima of the optimized composition were as follows: 0.03% to 0.09% C, 0.65% to 0.75% Mn, 0.025% P max, 0.005% S max, 0.40% Si max, 0.25% Cr max; 0.65% to 0.75% Cu, 0.45% to 0.55% Ni, 0.030% V max, 0.060% Mo max, and 0.100 Ti max.

Table 9 lists the mid-range compositions of ASTM A588, A242, and the A606 steels, along with Heats 1 and 2 and the optimized composition. These compositions were used to evaluate their atmospheric corrosion resistance by ASTM G101 Section 6.3.2 (Townsend) index numbers.

Table 9. Compositions and ASTM G101 Atmospheric Corrosion Indices

Element	A588 Grade K	A242	A606 Severstal	A606 Gallatin	Heat 1	Heat 2	Heat 2 Optimized
Carbon	0.150	0.150	0.050	0.060	0.070	0.030	0.040
Manganese	0.900	1.000	0.810	0.910	0.950	0.640	0.700
Phosphorus	0.040	0.150	0.022	0.012	0.005	0.006	0.020
Sulfur	0.050	0.050	0.002	0.003	0.005	0.005	0.005
Silicon	0.300	0.300	0.300	0.210	0.340	0.310	0.350
Nickel	0.350	0.150	0.060	0.210	0.700	0.380	0.450
Chromium	0.600	0.100	0.470	0.490	0.140	0.010	0.200
Copper	0.400	0.500	0.290	0.340	0.920	0.660	0.700
Vanadium	0.040	0.040	0.023	0.037	0.023	0.010	0.010
Molybdenum	0.100	0.100	0.010	0.020	0.010	0.010	0.010
Corrosion Index*	5.60	5.88	5.52	5.89	6.52	5.05	6.00

*Determined by Section 6.3.2 of ASTM G101 (Townsend method).

Determination of Tensile and Yield Strength of the Optimized Composition

The tensile strength of the optimized composition was calculated based on the ferrite multiplier method. Both 36 and 34 ksi were used for the basic tensile strength of ferrite. The calculation of tensile strength was as follows:

$$UTS = S_{ferrite}\,(M_C)\,(M_{Mn})\,(M_P)\,(M_{Si})\,(M_{Ni})\,(M_{Cr})\,(M_{Cu})\,(M_V)\,(M_{Mo})$$

Where $S_{ferrite}$ = tensile strength of pure ferrite (34 or 36 ksi)

M_C, M_{Mn}, M_P, etc. = ferrite multipliers previously defined in Chapter 3

Using the chemical composition to calculate values for each multiplier, the tensile strength for a 0.350" thick section, when $S_{ferrite}$ = 36 ksi, neglecting V and Mo, and listing them as 1.0, is:

$$TS = 36\,(1.189)\,(1.173)\,(1.024)\,(1.066)\,(1.036)\,(1.016)\,(1.108)\,(1.0)\,(1.0) = 64.4\text{ ksi}$$

Since the YS to TS ratio is 0.74, the predicted yield strength at 0.35" thick is 47.7 ksi. When 34 ksi is used for the tensile strength for ferrite, the tensile strength of the optimized heat is 60.8 ksi, and the YS at a 0.74 ratio is 45.0 ksi.

For light poles, sign structures, towers, and other structures using tubing, the most common wall thicknesses used are 7, 8, 9, and 10 gage. To determine the estimated tensile and yield strength for each of these gage thicknesses, two gage factors were used in the calculations because the optimized composition is between the compositions of Heat 1 and Heat 2. Heat 1 and the A606 steels manifested a gage factor of about 75 ksi per in of thickness reduction, whereas Heat 2 had an average gage factor of 66 ksi per in. In either case, the gage thickness should still have a yield strength in excess of 50 ksi. These calculated values for yield and tensile strength are summarized for the four common gages in Tables 10 and 11.

For both gage factors of 66 and 75 ksi per in, using a yield to tensile ratio of 0.75, and based on either 36 or 34 ksi for the tensile strength of ferrite, the gage factors provide calculated yield strengths of at least 54.1 ksi for 7 gage sheet at 0.1793" thick. If residuals of chromium, vanadium, or molybdenum are present, or are near maximum, the yield strengths will be slightly higher. This composition should be well suited for large-scale production. The decreased levels of copper should be attractive to many steel producers, compared to other A710 grades that have higher copper and nickel ranges. According to reports from Sophisticated Alloys, Heat 2 ran well through rolling operations and was very workable.

This optimized composition provides a new weathering steel with an atmospheric corrosion index of 6.0, which is greater than the A606 grades, and it has equal or better formability plus enhanced weldability without the emissions of toxic hexavalent chromium. The optimized composition should be considered for direct application into new construction after heats are rolled in production quantities and gage factors are better determined by frequent repetition of this composition and its hot-rolling characteristics.

Table 10. Increases in Tensile Strengths for Different Gages of the Optimized Composition

Gage Number	Thickness Difference vs. 0.350"	Difference in Tensile Strength at 0.35"; Gage Factor of 66 ksi/in	Difference in Tensile Strength at 0.35"; Gage Factor of 75 ksi/in
7 gage (0.1793")	0.171"	11.3 ksi	12.8 ksi
8 gage (0.1644")	0.186"	12.3 ksi	14.0 ksi
9 gage (0.1495")	0.201"	13.3 ksi	15.1 ksi
10 gage (0.1345")	0.216"	14.2 ksi	16.2 ksi

Table 11. Estimated Yield and Tensile Strengths for the Optimized Composition

Gage Number	Gage Factor of 66 ksi/in				Gage Factor of 75 ksi/in			
	36 ksi Ferrite		34 ksi Ferrite		36 ksi Ferrite		34 ksi Ferrite	
	TS, ksi	YS, ksi	TS, ksi	YS, ksi	TS, ksi	YS, ksi	TS, ksi	YS, ksi
7	75.7	56.8	72.1	54.1	77.2	57.9	73.6	55.2
8	76.7	57.5	73.1	54.8	78.4	58.8	74.8	56.1
9	77.7	58.2	74.1	55.6	79.5	59.6	75.9	56.9
10	78.6	59.0	75.0	56.3	80.6	60.5	77.0	57.8

CHAPTER 7 CONCLUSIONS

This project compared the formability of A710 steel alloys jointly developed by Northwestern University and IL DOT with the properties and compositions of A606 Type 4 steels which are currently used in Illinois and other states for light poles, sign and signal structures, and other highway structures. The ASTM E190 guided-bend test was employed to determine formability of *1t* or less. Test specimens were cut into both longitudinal and transverse direction from plates and sheets of multiple thicknesses for each steel, ranging from 0.10" to 0.38". Mandrels with rounded noses with three different bend radii (0.125", 0.157", and 0.188") were used. Mandrels were punched through the transverse center lines of the test specimens in a three-point guided bend. All specimens passed the guided-bend tests; no cracks, tears, or fractures were observed. Based on the performance of the second heat of A710 Grade B50, the bend and tensile tests indicate that the A710 optimized composition proposed in this report can be used for mass fabrication of tubing for light poles, signs and signal structures, and other highway applications requiring the use of advanced weathering steels.

A606 Type 4 steels were also evaluated in this study. They had yield and tensile strengths in a narrow range of 65 to 73 ksi and 79 to 89 ksi, respectively. Their % elongation to failure for all steel plates and sheets ranged from 37% to 52% in the transverse direction, using a 1" gage extensometer. In the longitudinal direction, the % elongation ranged from 41% to 49%, although these values would have a deduction of 2% to 3% if a 2" gage length was used. These elongation values generally indicate that A606 steels have about 10% more ductility than plain carbon steels with a range of 0.20% to 0.25% carbon. The mechanical properties of A606 steels stem from their ferritic microstructure that contains a small amount of pearlite. A606 grain sizes and grain morphologies were a function of steel thickness, and were substantially reduced in thinner sheets. Grains were more rounded in thin sheets than in thicker plates.

There were variations in mechanical properties of the first heat of A710 steel as a function of rolling direction as well as the thickness of the plates. Yield strength and ultimate tensile strength varied in ranges from 57 to 119 ksi and 72 to 119 ksi, respectively. The variation in the strength as a function of plate thickness was caused most likely by the excessive hot-working reductions in thickness during rolling of the first steel heat at the Arcelor Mittal Global R&D Laboratory. The microstructure of the first heat of A710 B50 steel was fine-grained ferrite. The grains in A710 steel sheets were significantly smaller than the grains in A606 steel of similar thickness, thus accounting for a higher strength of the first heat of A710 steel. Some bands of pearlite and fine-grained ferrite were observed in A710 sheets, but they did not significantly affect the formability of this steel.

While all A710 steel plates and sheets of the first heat passed the bend tests, the yield strength exceeded the required yield strength target range of 50 to 60 ksi. This restriction was placed on behalf of fabricators of tubing and structures, because higher yield strength steels require more energy for fabrication, and directly affect wear-and-tear on machinery and tooling.

The second heat was ordered with reduced amounts of manganese, copper, and nickel, which are the principal alloying elements that strengthen the steel but have limited effects on ductility. The interstitial hardening elements carbon and phosphorus were kept at low levels. In addition, a multi-pass rolling schedule was specified and used at Sophisticated Alloys to decrease the hot-working reductions during rolling. The yield strength of the second heat reached the goal of 50 ksi, and all sheets of the second heat passed the bend test successfully and had excellent ductility in samples in both longitudinal and transverse directions.

An optimized composition was then determined for ASTM A710 Grade B50 steel by use of the ferrite multiplier method and the Townsend corrosion equations in ASTM G101 to increase its atmospheric corrosion resistance. The optimized composition is 0.03% to 0.09% C, 0.65% to 0.75% Mn, 0.025% P max, 0.005% S max, 0.40% Si max, 0.25% Cr max, 0.65% to 0.75% Cu, 0.45% to 0.55% Ni, 0.030% V max, 0.060% Mo max, and 0.100 Ti max. This composition increased the ASTM G101 atmospheric corrosion resistance index to 6.00 or more and provided yield strengths slightly above 50 ksi for 7, 8, 9, and 10 gage steel sheets for use in deep forming operations and the fabrication of tubing.

CHAPTER 8 FURTHER STUDY

It is recommended for future work that the A710 Grade B50 optimized composition, whose properties were based on heats no larger than 300 lb, be produced in a much larger 100 to 150 ton heat. Prior commercial production of 75 tons of wide-flange beams of A710 B50 steel by Steel Dynamics, Inc. for the superstructure of a steel bridge in Flossmoor, IL, demonstrated that A710 Grade B50 steel can be successfully produced with a yield strength range of 50 to 60 ksi and excellent ductility and impact toughness. Now that an optimized composition for A710 Grade B50 has been determined for 7 to 10 gage thick sheet, refined for improved ductility and forming operations, and possessing improved atmospheric corrosion resistance, it can be adopted for use in the commercial production of tapered and straight tubing for highways, bridges, and other structural applications.

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