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Observational Study for Developing a Predictive Regression Model for Ultimate Tensile Strength of Gray Iron Class 25A

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ABSTRACT

The ASME Boiler Pressure Vessel Code Section IV, Article 2, has required that each individual tensile strength test of a separately cast test bar be equal to or above 25 ksi (ASTM A48/A48M-03, class 25A) in order to approve a casting lot of cast iron heat exchangers. This is an observational study, where the data are taken from a day-to-day operation and factor levels are not controlled. Therefore, there are many known and unknown nuisance factors that may influence the response variable.

The results of the analyses of this observational study concludes that it’s possible to predict, with a high confidence level (≥ 99.0%), the ultimate tensile strength (UTS) of a new individual observation by controlling the Carbon Equivalent-Liquidus (CEL) measured by thermal analysis and holding the primary and secondary alloying elements within a narrow and process capable range. The melting practice was standardized to deliver a consistent and reproducible CEL and liquidus temperature (TPL) relationship.

The observational study consisted of an exploratory data analysis of one-year (2011) of mechanical and chemical tests taken during the production of heat exchanger castings. A more adequate regression model is selected from several iterations.

The implementation and validation of the model confirmed the effectiveness of using Carbon Equivalent-Liquidus for achieving 100% tensile strength compliance of individual tests in 2012 and more than 99.75% in the following years.

Keywords: gray iron, ASTM Class 25A, ultimate tensile strength, UTS, regression model, and Carbon Equivalent-Liquidus, CEL

INTRODUCTION

The Claim Hypothesis of this study is that the ultimate tensile strength (UTS) of an individual new observation of class 25A gray iron separately cast test bar, can be predicted with a high level of confidence by the Carbon Equivalent-Liquidus (CEL) measured at the liquidus temperature on a white iron cooling curve (thermal analysis).

The thermal analysis for controlling the process has the advantage of being a quick test that allows for immediate corrective actions to maintain the CEL in control.

An individual class 25A separately cast test bar must comply with the minimum tensile strength requirement (UTS) of 25 ksi or 175 MPa, per ASME Boiler Pressure Vessel Code Section IV, Article 2, and ASTM A48/A48 M-03. If a valid test (not a defective bar) fails to conform to the requirement with a UTS not lower than 90% of 25 ksi, a duplicate test bar poured from the same ladle must be tested. If the second test fails, it will result in rejecting the whole lot produced since the last approved test.

In 2011, approximately 1.8% of failed tensile strength tests resulted in a large amount of castings to be rejected and scrapped. This observational study, using production data, has had the main purpose of reducing or eliminating the failures by developing an effective predictive regression model and process control.

The study consists of an exploratory data analysis of one-year mechanical tests. Production data of chemistry and tensile strength were analyzed and used to develop a statistical model. The more adequate regression model is selected from several iterations that include the following explanatory variables: CEL, Mn, S, Cu, Sn, P, Cr, and Al.

In 2011, extreme outliers were present below the lower limit requirement, mainly in January. The special causes of extreme outliers are explained and remedies were put into practice. Therefore, these outliers are excluded from the data used to develop a model. The result of the selected model is analyzed and interpreted to determine the most influential independent variables on the tensile strength.

The CEL is measured from the white iron cooling curve with a tellurium cup at the liquidus temperature every two-to-three hours. The CEL value is plotted on a developed run chart with a target and calculated control limits based on the process capability.

Some of the alloying elements could potentially have an important effect on the UTS if their composition values fall outside the ranges of this study; so, the gray iron chemistry is frequently monitored. The effect of certain elements on the UTS will be discussed later. Composition ranges of the alloying elements are in Table 1.

The effect of alloying elements in the gray iron solidification and microstructure[2,5,7] is not within the scope of this study.

THERMAL ANALYSIS (TA)

There are two typical cooling curves for cast iron: the gray iron cooling curve originated with a non-tellurium cup and the white iron cooling curve generated with a tellurium cup.

For this study, the carbon equivalent-liquidus (CEL), carbon, and silicon are measured from the cooling curve of carbide-stabilized cast iron (Fig.1) on a thermal analysis (TA) device.

COOLING CURVE NOMENCLATURE

- TPK: Initial temperature of the liquid in the cup.
- TPL: Start of solidification temperature (γ Liquidus Temperature).
- TPS: Carbide eutectic temperature.

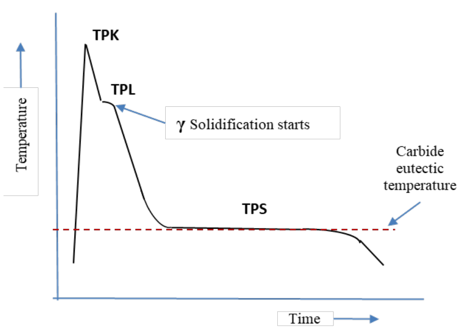


Figure 1. White iron cooling curve with tellurium cup.

MEASUREMENT OF CEL FROM WHITE IRON COOLING CURVE

The TA equipment was validated by developing a regression model (1). The TPL predictor variable significantly relates to the CEL, and it explains 97.22% of the CEL variation.

The constant and coefficient of the TPL variable on this developed predictive regression model, approximate the values of the program model in the TA equipment.

EQUATION MODEL OF CEL

$$CEL = 15.389 + (-0.0052)\,TPL \qquad \text{Eqn. 1}$$

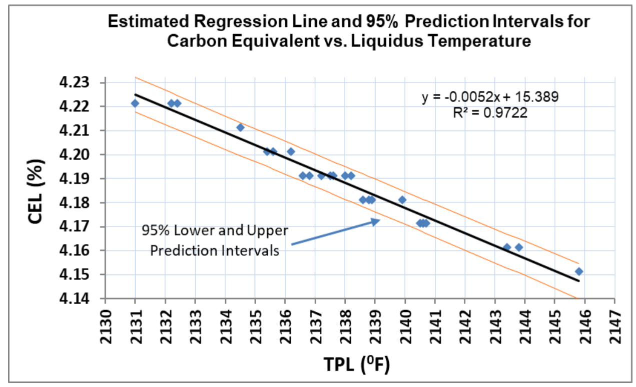


Figure 2. Linear regression of CEL vs. TPL .

EQUATIONS TO ESTIMATE CARBON & SILICON

Multiple regression model for Carbon (C)

$$C = -6.26476 + (0.00936494)TPS + (-0.00435162)TPL \qquad \text{Eqn. 2}$$

The TPL and TPS significantly explain 98.41 % of the Carbon variation determined by the TA equipment.

The silicon (Si) is inferred from the formula:

$$CEL = C + \frac{1}{3}\,Si \qquad \text{Eqn. 3}$$

$$Si = 3\,(CEL - C) \qquad \text{Eqn. 4}$$

INFLUENCE OF THE ALLOYING ELEMENTS ON EQUILIBRIUM EUTECTIC TEMPERATURES

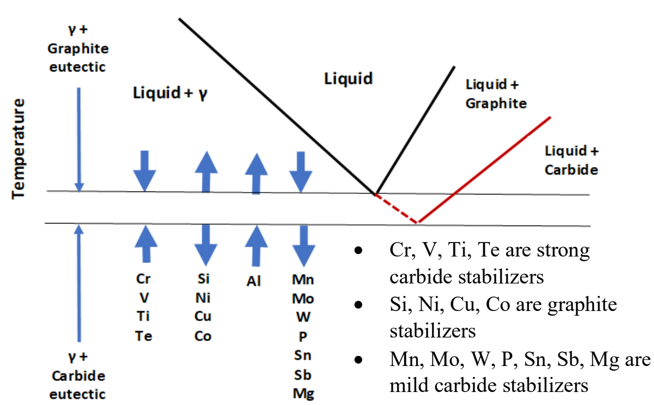


Figure 3. Influence of primary and secondary alloying elements on equilibrium eutectic temperatures.[3]

The liquidus temperature (TPL) could rise if the melting conditions are altered.[6] Large variations of alloying elements may affect the cementite eutectic temperature and the graphite eutectic temperature.[7]

A standardized melting practice can deliver a consistent and reproducible carbon equivalent and liquidus temperature relationship.

OBSERVATIONAL STUDY

In an observational study, data are taken from a day-to-day operation; therefore, studied factor levels are not controlled and there are many known and unknown nuisance factors that may influence the response variable. This is a long-term study, so the variability increases over time. It's an interesting challenge, to be able to predict the response variable UTS with a high level of confidence in a real environment.

The Weil-McLain foundry one-shift operation in Michigan City, Indiana, has produced cast iron heat exchangers for boiler manufacturing. The melting practice consists of 40 tons electric channel furnaces and a 13 tons electric holding furnace. The molten metal is transferred to the holding furnace in a 4-ton ladle and then tapped out into a pouring ladle. Inoculation in the pouring ladle was done with 48% Si, 0.44% Al, 0.04% Ca and 0.90% Sr inoculant. The amount of inoculant is monitored by a chill test bar.

The effect of alloying elements into gray iron solidification and microstructure[2,5,7] is not within the scope of this study.

CAPABILITY ANALYSIS OF CLASS 25A ULTIMATE TENSILE STRENGTH (UTS)

A process capability analysis was performed using 966 valid tests from the whole of 2011 year. The "actual performance" shows that 1.76% of the tests didn't meet the UTS minimum requirement, which resulted in a considerable quantity of rejected products.

In order to improve the capability, it will be necessary to shift the process mean to the right.

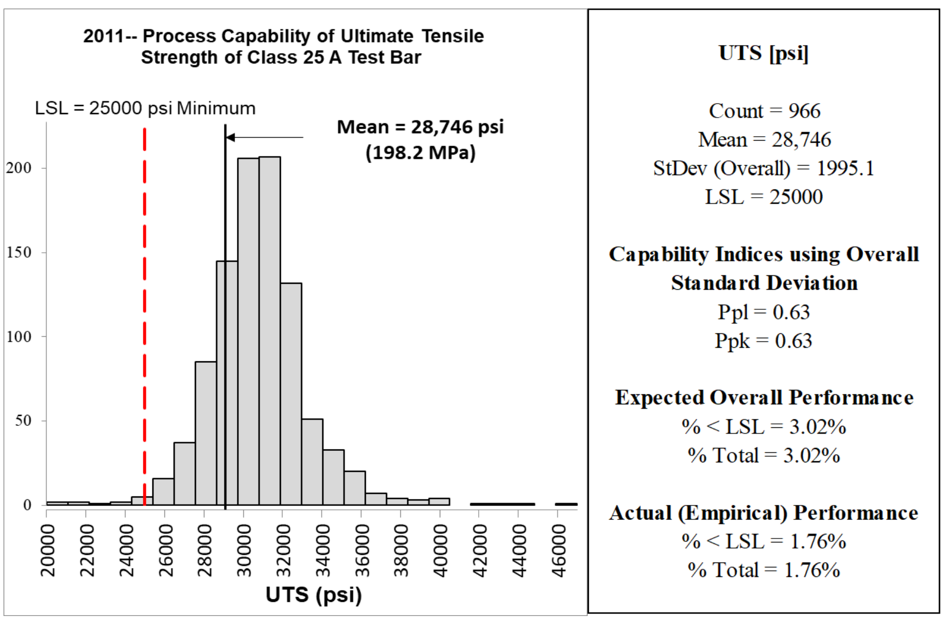


Figure 4. Histogram and capability analysis of UTS (1 MPa = 145.0377 psi).

ESTIMATE FUTURE UTS TARGET

The UTS data spread approximates to normality. By eliminating the special causes of excessive variation of past performance and assuming that the future process will be in control, we can determine the new target of the process:

- Hypothetical standard deviation of a stable process is, s = 1,403.13 psi (9.674 MPa);
- Assuming a Cpk = 1.3;
- The estimated new target is:

$$UTS\ Target = 1.3\ x\ 3\ x\ 1403.13 + 25000 \cong 30{,}500\ psi\ (210.3\ MPa)$$

MODEL DEVELOPMENT FOR PREDICTING UTS

Daily test data of tensile strength and chemistry were gathered for one year, 2011. A total of 952 tests are included in the regression analyses.

An iterative process of regression analyses of the UTS vs. CEL and alloy elements Cu, Sn, P, Mn, and S, is performed in order to select the best model for predicting UTS. Table 1 shows the descriptive statistics of the potential predictor variables used in the analyses.

Table 1. Descriptive Statistics of Gray Iron Chemistry (2011)

Descriptive Statistics of Gray Iron Chemistry (% weight) -- 2011								
Variable	**Method**	**Mean**	**Maximum**	**Minimum**	**Range**	**Overall St.Dev.**	**Notes**	
Ultimate Tensile Strength	T.O.	**28756.5 psi (198.3 MPa)**	41690 psi (287.4 MPa)	23060 psi (159 MPa)	18630 psi (128.4 MPa)	1872.15 psi (12.90 MPa)		
Carbon Equivalent (CEL)	Thermal Analysis	**4.221**	4.33	3.87	0.46	0.043		
Carbon (C L)	Thermal Analysis	**3.552**	3.67	3.19	0.48	0.041		
Si	Spectrometry	**1.977**	2.199	1.656	0.544	0.077		
Mn	Spectrometry	**0.597**	0.820	0.372	0.448	0.086		
S	Spectrometry	**0.070**	0.112	0.052	0.060	0.006	**Combustion sulfur** from 643 tests: Mean = 0.076; Max.= 0.097; Min. = 0.043	
P	Spectrometry	**0.074**	0.099	0.050	0.049	0.012	Two outliers above and below the max. and min.	
Cu	Spectrometry	**0.082**	0.233	0.002	0.231	0.026	Cu in the furnace charge	
Cr	Spectrometry	**0.057**	0.070	0.049	0.021	0.004		
Ti	Spectrometry	**0.013**	0.046	0.008	0.038	0.003		
Sn	Spectrometry	**0.012**	0.148	0.004	0.144	0.016	High Sn: Added into pouring ladle	
Al	Spectrometry	**0.003**	0.009	0.000	0.009	0.001		
Excess-Mn	(*)	**0.478**	**0.715**	0.254	0.462	0.086		No extreme outliers
MnS	(*)	**0.042**	**0.062**	0.023	0.039	0.007	(*) Highly correlated to Excess Mn (%).	No extreme outliers
Sulfur-departure from equilibrium	(**)						(**) Highly correlated to Excess Mn (%).	
Pig Iron-to-Steel Ratio		**0.835**	1.361	0.178	1.183	0.360		No extreme outliers

The Excess-Mn and MnS variables are significantly correlated; therefore, to avoid collinearity only Excess-Mn is used in the analyses, which is the Manganese departure from the stochiometric balance of Manganese and Sulfur in Eqn. 5.

$$Excess - Manganese = wt\%\, Manganese - 1.7(wt\%\, Sulfur) \qquad \text{Eqn. 5}$$

Ti and Cu not included because somehow, they correlate with phosphorus.

BEST MODEL SELECTION

The criterion used to select the best model is the R^2-Predicted (Table 2). The level of significance: $\alpha = 0.05$

Table 2. Model Selection with R^2-Predicted as Criterion

Step	Predictor Term	Mode	# Predictors	# Model Terms	P	S	R-Sq	R-Sq(Adj)	** R-Sq (Pred) **
1	CEL	Add	1	2	0.0000	1563.61	30.36%	30.29%	29.83%
2	P	Add	2	3	0.0000	1527.26	33.64%	33.50%	32.99%
3	Excess Mn	Add	3	4	0.0026	1520.79	34.27%	34.06%	33.48%
** 4	Sn	Add	4	5	0.0953	1519.35	**34.46%**	**34.18%**	**33.60%**
5	Cr	Add	5	6	0.2654	1519.16	34.55%	34.20%	33.53%
6	Al	Add	6	7	0.7364	1519.87	34.55%	34.14%	33.36%

R^2-Predicted indicates how well a regression predicts responses for new observations. Four predictor variables are selected with the highest R^2-Predicted Value of 33.60%.

There is no violation of the model assumptions (the tests are not included in this paper), and no interaction between predictor variables was identified.

MULTIPLE REGRESSION MODEL

$$UTS\ (psi) = 137643 + (-26399)CEL + (5186.08)Sn + (2324.51)Excess\ Mn + (18431.5\ )P \quad \text{Eqn. 6}$$

Table 3. Analysis of Variance (ANOVA) for Model

Analysis of Variance for Model					
Source	**DF**	**SS**	**MS**	**F**	**P**
Model	4	1148156557	287039139.31	124.3436	0.0000
Error	946	2183779537	2308435.03		
Total (Model + Error)	950	3331936094	3507301.15		

(Conversion: 1 MPa = 145.0377 psi)

The analysis led to the conclusion that there is a statistically significant effect of the model on the ultimate tensile strength (model *p*-value = 0.0000 << $\alpha = 0.05$).

MODEL VALIDATION

The close values of R^2, R^2-Predicted, and R^2-Adjusted indicate the appropriateness of the model.

Table 4. Goodness-of-Fit Indices for Model

Model Summary	
R-Square	34.46%
R-Square Adjusted	34.18%
R-Square Predicted	33.60%
S (Root Mean Square Error)	1519.3535

Table 5. ANOVA for Predictors

Analysis of Variance for Predictors (Adjusted Type III)						
Predictor Term	**DF**	**SS**	**MS**	**F**	**P**	**R-Square**
CEL	1	1120069374	1120069374	485.2072	0.0000	33.62%
Excess Mn	1	24786616.71	24786616.71	10.7374	0.0011	0.74%
Sn	1	6434791.598	6434791.598	2.7875	0.0953	0.19%
P	1	29923084.4	29923084.4	12.9625	0.0003	0.90%

MODEL INTERPRETATION

Meaning of Regression Coefficients (Eqn. 6)

The predictor variable coefficient (or parameter) indicates the change in the mean response (UTS) per unit increase when the other predictors are held constant. For instance, if the carbon equivalent-liquidus (CEL) increases by 0.1%, the mean response UTS may decrease by -2,639.9 psi or -18.20 MPa (-26,399 x 0.1 = -2,639.9 psi) when other variables are held constant.

Contribution to Ultimate Tensile Strength Variation

The CEL has the highest contribution (97.6%; i.e., 33.62% out of 34.46% R^2) to UTS variation. The Excess-Mn, P, and Sn together contribute with only 5.30%.

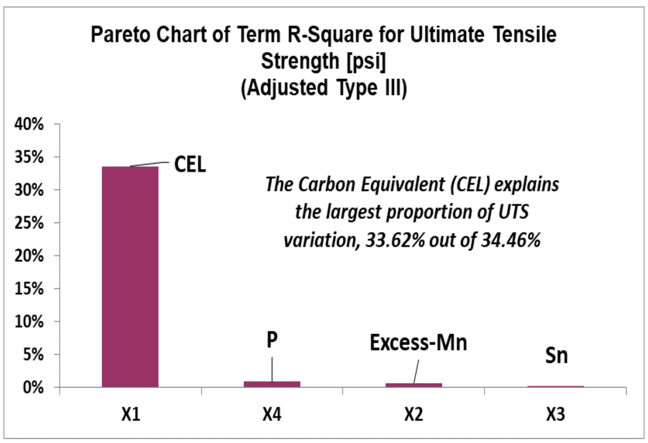
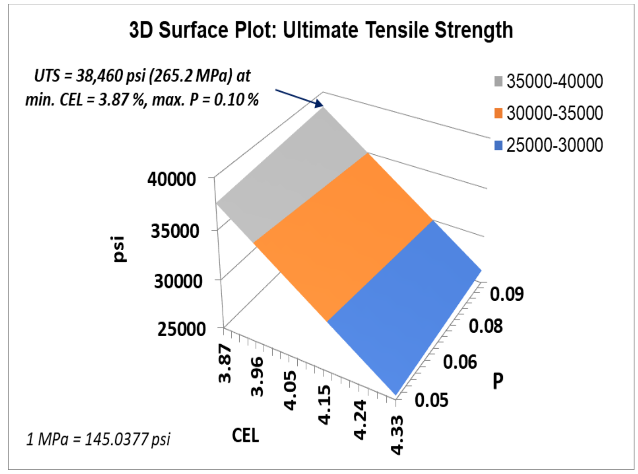


Figure 5. Pareto Chart of predictors terms R^2 for UTS.

Contour Plot and Additive Effect

A regression function in multiple regression is called a regression surface or a response surface. In Fig. 6, the response surface is a plane.

When the two predictors CEL and Phosphorous (P) do not interact, the two are said to have additive effects. The maximum additive effect is 38,460 psi (265.2 MPa) when the other predictors are held constant. Similar reasoning applies to CEL and Excess-Mn.



Predictors	Hold Values
Excess Mn	0.478
Sn	0.012

Figure 6. Surface plot of UTS vs. CEL and phosphorous.

Main Effects of Predictor Variables

Increasing factor CEL from the low level (3.87%) to the high level (4.33%), causes an average response decrease of -12,144 psi units (-83.7 MPa), holding the other factors at their mean value (Fig.7a). The P change from 0.05% to 0.10% (Fig. 7c) causes an average response increase of 903 psi (6.23 MPa); likewise, for a change of Excess-Mn from low level to high level, causes an increase of 1081 psi average (7.45 MPa) for UTS response variable (Fig.7b).

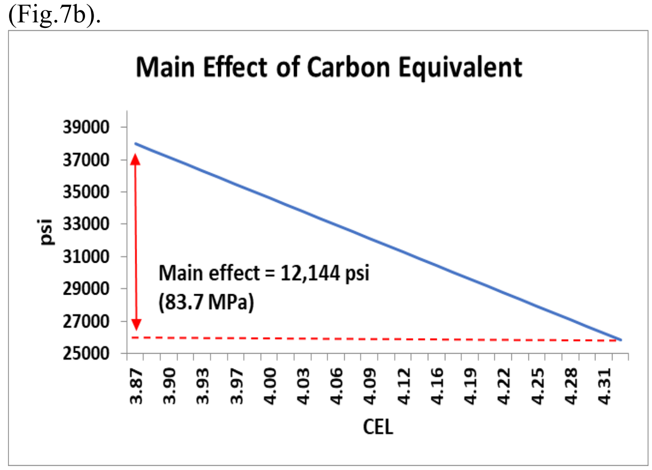


Figure 7a. Main effect of CEL on UTS.

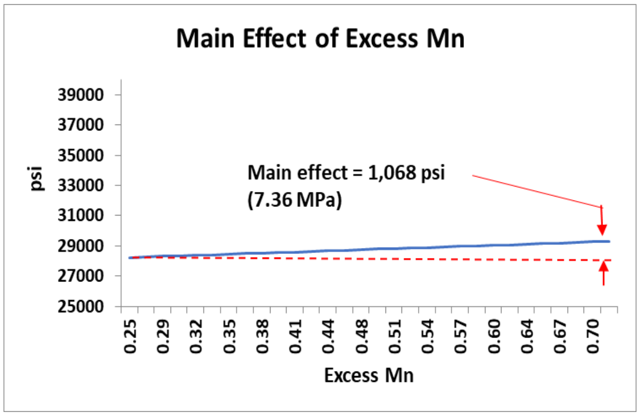


Figure 7b. Main effect of Excess-Manganese on UTS.

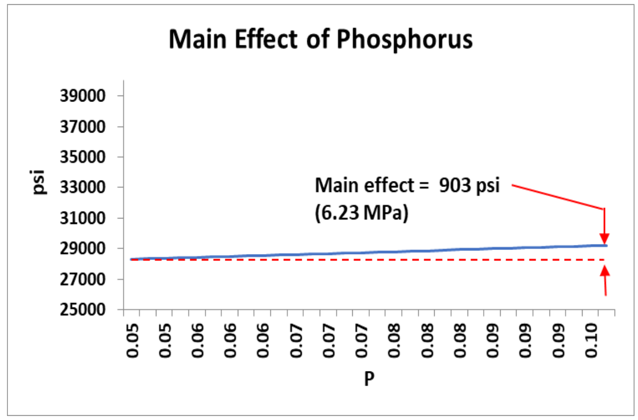


Figure 7c. Main effect of phosphorous on UTS.

PREDICTION INTERVAL FOR A NEW OBSERVATION

The centerline of the plot below (Fig. 8) represents the mean of fitted or predicted ultimate tensile strength (UTS) values. Individual observed values are distributed around the regression fitted line. With a 99% confidence level, the CEL variable can predict a new observation above the 99.5 % Lower Prediction Interval (LPI) of UTS.

The interception of the 99.5% LPI line with the horizontal line of minimum UTS, gives us the approximate maximum CEL value of 4.25%. We may use this value as an upper control limit to estimate a target and a lower control limit based on the CEL process capability.

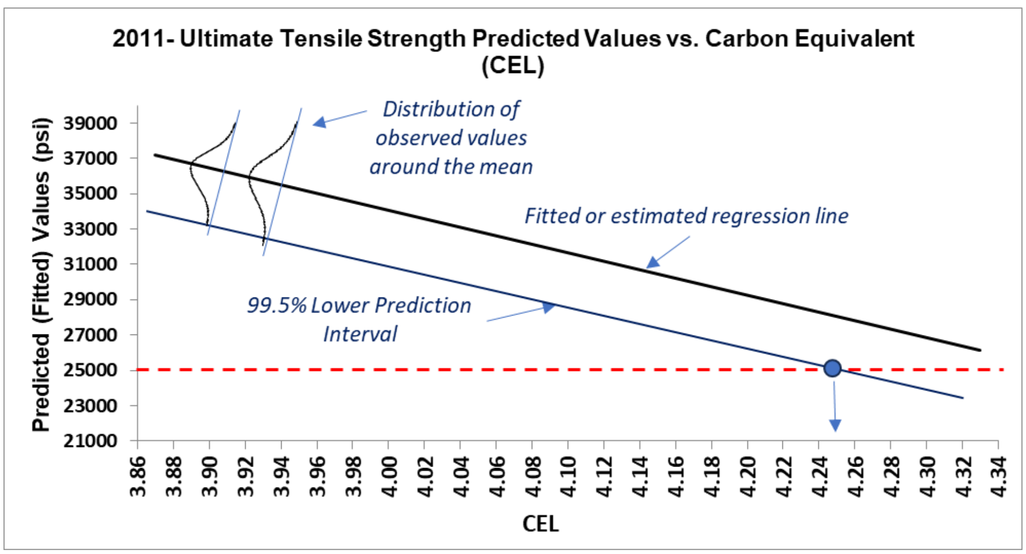


Figure 8. Prediction interval for new observation.

CAPABILITY ANALYSIS OF CEL

The CEL process mean must be shifted to the left for improving the process capability (Fig.9), assuming same process variability.

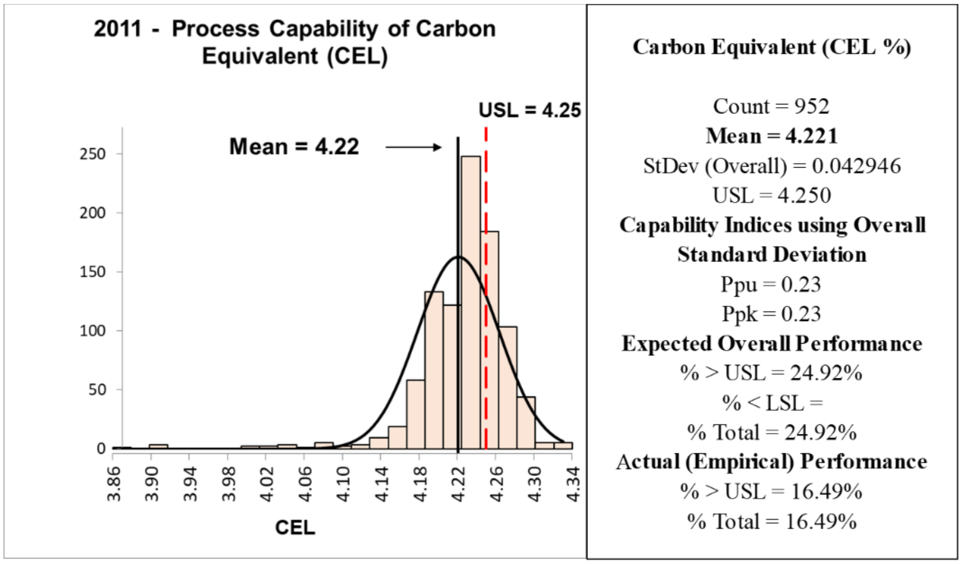


Figure 9. CEL Process Capability in 2011.

ESTIMATE OF CEL UPPER CONTROL LIMIT & TARGET

The CEL data spread approximates a normal distribution. Assuming that the future process will be in control, we can establish a CEL target and process control limits as follows:

Hypothetical standard deviation of a stable process is,

- $s = 0.0266$;
- Assume Cpk ≥ 1;
- Upper Control Limit = 4.25%;
- Estimated CEL target = 4.17%

For a process control chart, the process control limits are:

$$CEL = 4.17 \pm 3x0.0266 \cong 4.17 \pm 0.08 \quad \text{Eqn. 7}$$

The CEL target value can also be estimated by interpolating the target UTS = 30,500 psi in the regression Eqn. 6.

RESULTS AND VALIDATION

The findings of the significant effect of CEL and P on UTS in the 2011 study were confirmed by the regression analysis performed on the 2012 production data, using the same predictor variables. The analysis of 2012 data is not included in this work.

The CEL parameter of the 2012 regression equation (-27,003 psi) approximates the 2011 CEL parameter (-26,399 psi) previously discussed.

The established process control, based on the developed 2011 regression model, is proved by the successful results achieved in 2012 explained below.

PROCESS CAPABILITY OF ULTIMATE TENSILE STRENGTH IN 2012

The process capability has improved ($Ppk_{2012} = 0.84 > Ppk_{2011} = 0.63$) and the process mean has been shifted to the right (Fig.10).

In 2012 there wasn't any valid test below the minimum requirement; i.e., no one casting was rejected because of mechanical test failure.

The 2012 data distribution is close to normality. There are a few outliers to the right of the distribution that affect the overall standard deviation but they do not influence much on the response mean. The Median = 30,330 psi (209.1 MPa) and the Mean = 30,512 psi (210.4 MPa) are very close.

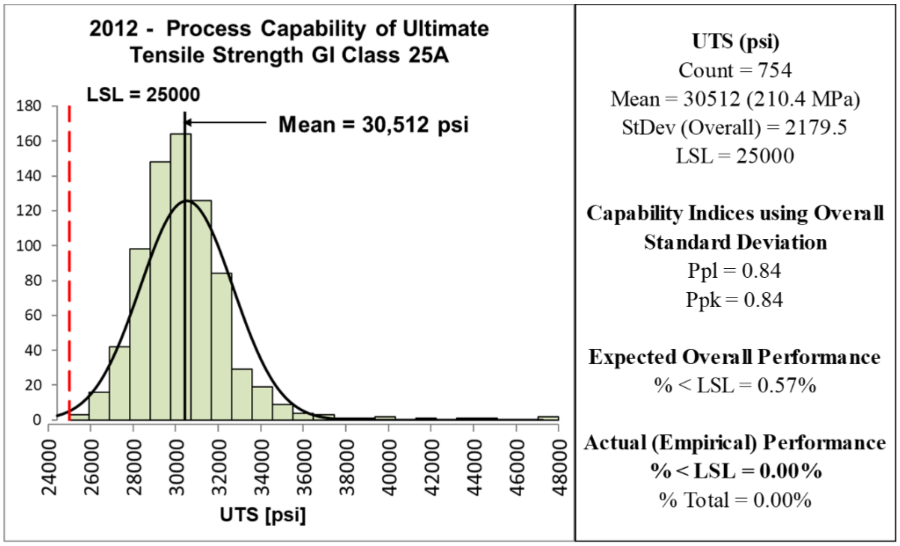


Figure 10. Process capability of GI UTS in 2012. (1 MPa = 145.0377 psi)

COMPARISON OF NORMAL DISTRIBUTION BETWEEN 2011 AND 2012 FOR UTS

Comparing the UTS normal distributions from 2011 and 2012 (Fig. 11), two important remarks can be made: the process mean shifted to the right and reduced potential observations below LSL represented by the tail area on the left of minimum UTS specification.

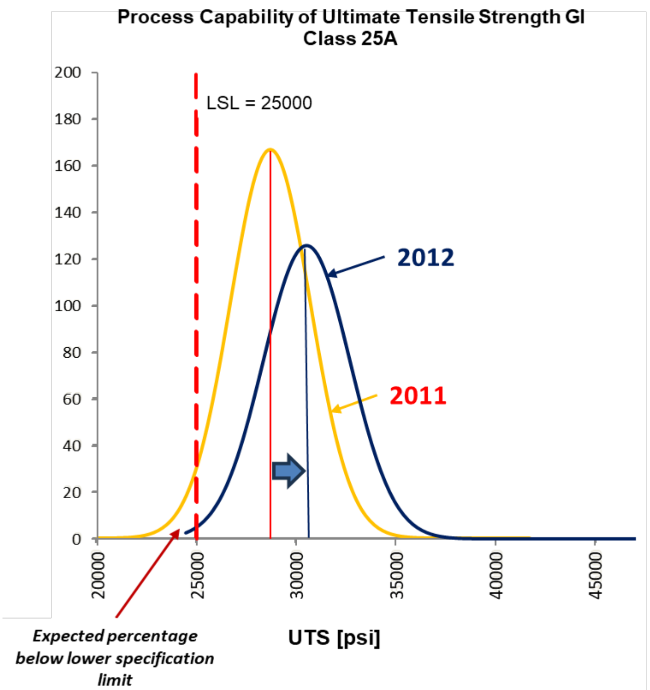


Figure 11. Overlay of Ultimate Tensile Normal Curves from 2011 & 2012.

OBSERVED PERFORMANCE OF UTS

The UTS process capability improved in 2012 as well as in the following years. The observed performance of individual tests was above 99.5% (Fig. 12).

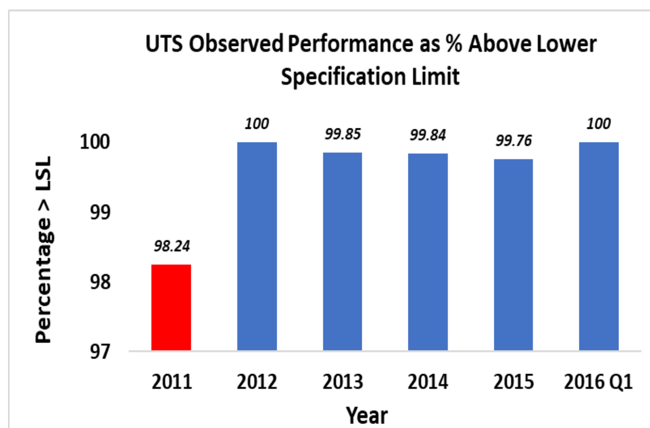


Figure 12. Observed performance above the minimum requirement of UTS in percentage.

From 2013 and going forward the overall variation and within variation have decreased (Table 6).

Table 6. Statistics of UTS Performance Year-over-Year

Ultimate Tensile Strength Performance									
Year	Observed Performance < LSL (%)	Observed Performance > LSL (%)	Mean (psi)	*Mean (MPa)*	Sample size, N	Std. Dev. (within, psi)	*Std. Dev. (within, MPa)*	Std. Dev. (overall, psi)	*Std. Dev. (overall, MPa)*
2011	1.76	98.24	28,722.5	*198.03*	987	1,490.00	*10.27*	2,012.65	*13.88*
2012	0.00	**100**	30,512.0	*210.4*	754	1,623.90	*11.20*	2,179.53	*15.03*
2013	0.15	**99.85**	30,335.6	*209.2*	659	1,445.43	*9.97*	1,792.05	*12.36*
2014	0.16	**99.84**	30,867.2	*212.8*	607	1,258.55	*8.68*	1,486.07	*10.25*
2015	0.24	**99.76**	30,572.0	*210.8*	848	1,413.60	*9.75*	1,792.84	*12.36*
2016 Q1	0.00	**100**	30,854.7	*212.7*	147	999.38	*6.89*	1,098.66	*7.57*

DISCUSSION

1. Low Tensile Strength Outliers

The extreme outliers (circled) are very distant from the 99.5% Lower Prediction Interval. Most of the extreme outliers were produced in January 2011. An important change in the melting occurred from 2010 to 2011: The production was reduced significantly. This change extended the frequency of molten metal delivered to the holding furnace and molding line.

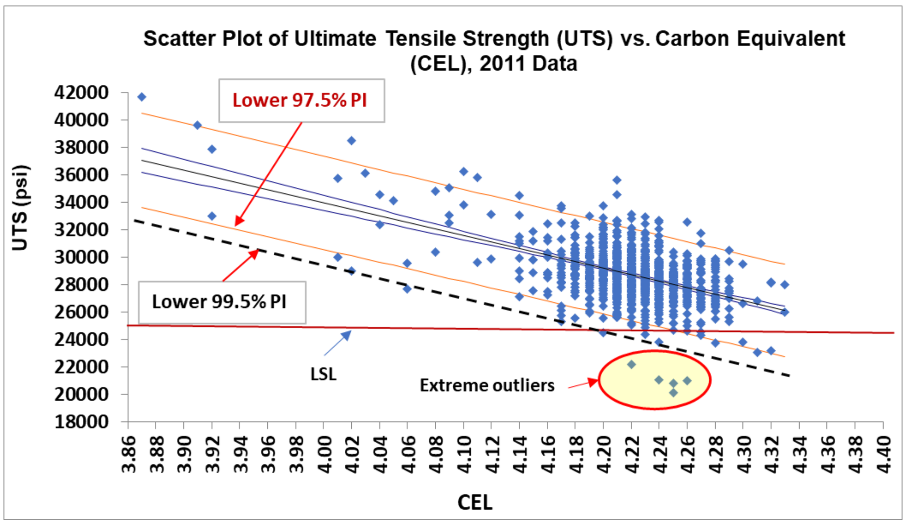


Figure 13. Raw Data of UTS vs. Carbon Equivalent.

POSSIBLE CAUSES OF EXTREME OUTLIERS

The potential **s**pecial causes that could have contributed to those low tensile strength outliers are as follows:

1. The initial base iron (beginning of the shift) had been held in the holding furnace for a long time at superheating temperature overnight and on weekends. The foundry worked one shift only.
2. Very low tensile strength has been caused by the initial base iron being "dead". The effect of holding molten metal for prolonged periods of time in a furnace is to reduce the degree of nucleation.
3. Higher superheating temperature, longer holding time, and probably oxidizing melting conditions, raised the liquidus temperature[6] (TPL) giving a lower carbon equivalent (CEL) value.
4. For instance, on the production date shown in Table 7 below, the first test bars poured at the beginning of the shift (2:30 AM) failed, after the molten iron was held at superheating temperature overnight.
5. Apparently the CEL= 4.25% corresponded to a higher UTS within the prediction interval (Fig.13), if better melting condition had been existed.

Every pouring ladle was inoculated with 48% Si, 0.44% Al, 0.04% Ca and 0.90% Sr.

Table 7. Properties of Gray Iron from One Production Day

Date	Day	Order of poured test bars during the day	Time	Chill (mm)	Si	Mn	S	P	Cu	Cr	Ti	Sn	Al	Excess Mn	Tensile [psi]	Tensile [psi]	UTS Highest value of two tests	CEL	C (TA)	Si (TA)
12-Jan-11	Wednesday	First	**2:30 AM**	**3**	1.988	0.509	0.077	0.073	0.067	0.061	0.013	0.005	0.002	0.3785	20,850	19,353	**20,850**	**4.25**	3.58	2.02
12-Jan-11	Wednesday	Second	5:30 AM	1	2.082	0.525	0.073	0.074	0.062	0.063	0.013	0.005	0.002	0.4003	26,690		26,690	**4.23**	3.54	2.09
12-Jan-11	Wednesday	Third	7:30 AM	2	2.050	0.520	0.070	0.074	0.061	0.062	0.013	0.005	0.002	0.4004	24,900	27,600	27,600	**4.25**	3.57	2.08
12-Jan-11	Wednesday	Fourth	10:30 AM	4	2.022	0.521	0.075	0.071	0.059	0.061	0.013	0.005	0.002	0.3928	28,690	29,910	29,910	**4.27**	3.59	2.09

(TA) : Determined by thermal analysis

MICROSTRUCTURE OF FAILED TEST BAR

The microstructure of the low tensile strength first test bar (Table 7) had a significant amount of ferrite and type E and D graphite caused, more likely, by poor nucleation (Fig.15).

Carefully standardized melting procedures can produce a consistent and reproducible CEL and TPL relationship.

The remedy to this problem has been to tap out "dead" iron from the holding furnace into the melting furnace, and then, the iron from the melting furnace transferred back into the holding furnace, before starting production.

Description

% Graphite in Microstructure	19.60%
Tensile Strength	20,850 psi
Cast Date 1/12/11 @ 2:30 AM	

100X, Unetched

200X, Nital Etched

Figure 15. Microstructure of lower tensile strength (Metallography at ICRI).

MICROSTRUCTURE OF APPROVED TEST BAR

After three hours between the first and second tests, at least two ladles of molten iron were transferred into the holding furnace.

The microstructure of higher tensile strength test bar (Second test, Table 7) had a smaller amount of ferrite and much less interdendritic graphite types E and D, indicating better nucleation (Fig.16).

Description

% Graphite in Microstructure	14.85%
Tensile Strength	26,690 psi
Cast Date 1/12/11 @ 5:30 AM	
Smaller amount of ferrite [white area]	

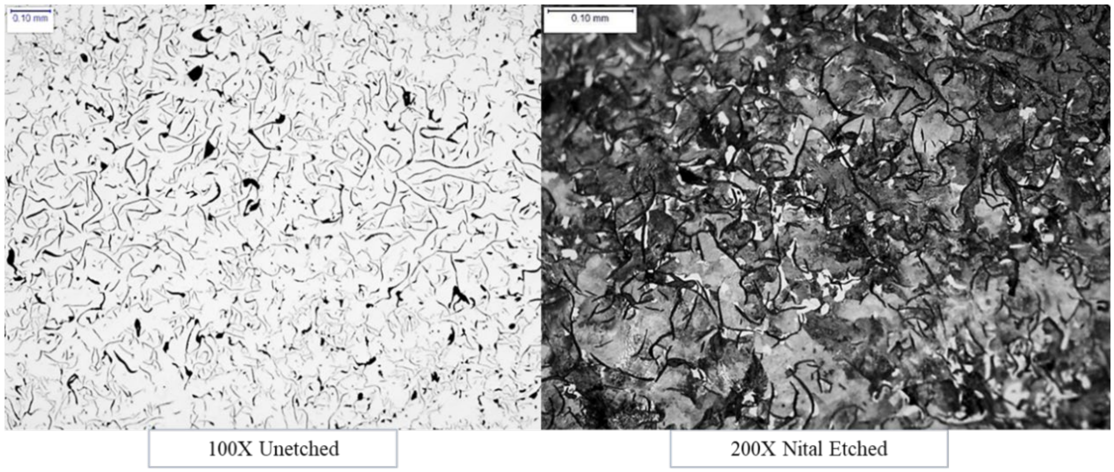


Figure 16. Microstructure of test bar above the UTS lower specification limit (metallography at ICRI).

2. <u>Tin (Sn) Effect</u>

Although the Tin is a good perlite stabilizer, it does not have a significant effect on the tensile strength of a size A (0.88 in. diameter) test bar when it changes from 0.004% to 0.148%. Normally, the size A test bar microstructure contains a high percentage of perlite phase; therefore, the addition of Sn may not have any important effect. [4 & 5]

3. <u>Phosphorous (P) Effect</u>

The significant and positive effect of phosphorous on the ultimate tensile strength (UTS) is confirmed by the regression analysis from 2012 production data. The main effect of P is 9.70 MPa (Fig. 17); when the P changes from 0.06% to 0.14% (0.08% range).
Proportionally, the increment of UTS per 0.01% P is very similar between 2011 (1.21 MPa) and 2012 (1.25 MPa), or we may also say that the main effect slopes are almost equal.

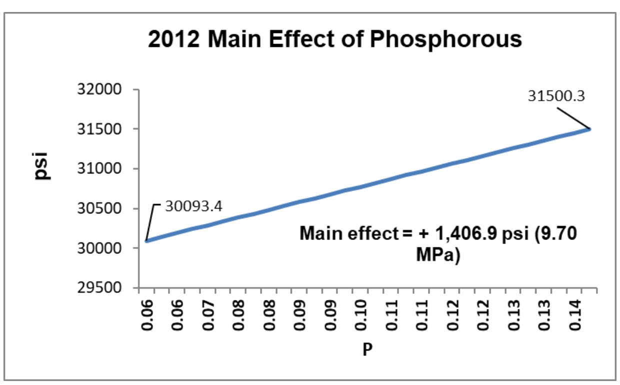


Figure 17. Main effects of phosphorous on tensile strength, 2012 data.

4. <u>Effect Of Excess Manganese</u>

In the study from 2011 data, the Excess-Manganese varied between 0.25 wt.% - 0.71 wt.%. The increase of Excess-Mn had a positive effect on the UTS when it changed from the lower percent value to the higher percent value, as shown on the main effect plot (Fig.7b). But that positive effect of Excess-Manganese is not confirmed on the regression analysis performed from 2012 data. The main effect plot (Fig.18) shows that the tensile strength significantly decreases (p-value = 0.025) when the Excess Mn changes from 0.33 wt.% to 0.64wt.%.
Therefore, the effect of Excess-Mn on the UTS is inconclusive.

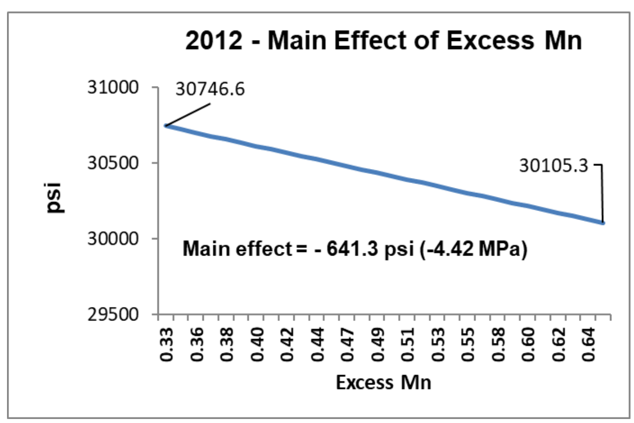


Figure 18. Main effects of excess Mn on tensile strength, 2012 data.

EXCESS-MANGANESE AND SULFUR

The following plots are from Fuller's work.[2] Figure 19-A, plots the tensile strength of 30 mm cast test bars (size B) vs. excess manganese, at two levels of carbon equivalent. Figure 19-B plots the tensile strength of 30 mm cast test bars of carbon equivalent between 3.73 and 3.84 vs. sulfur content,[2] at four levels of excess-manganese.

The excess-manganese and sulfur composition ranges from our study are marked on both Fig. 19 plots, just for illustration of the ultimate tensile strength trends, at different levels of manganese and sulfur contents.

Although the chemistry (the carbon equivalent is not obtained from the liquidus temperature of a cooling curve) and test bar size differ from our study, the Fig. 19-A graph illustrates that the excess manganese higher than 0.25%, for cast iron of CE between 4.03 and 4.29, does not show any clear trend of tensile strength.

Similar observation for the 19-B graph of lower carbon equivalent, there is not a clear trend of tensile strength for sulfur content lower than ~0.11% sulfur, at 0.2% and 0.3% of excess-manganese.

The observations made from Fig. 19 in some way coincide with our finding, that the effect of excess-manganese is inconclusive. for the composition levels in our study.

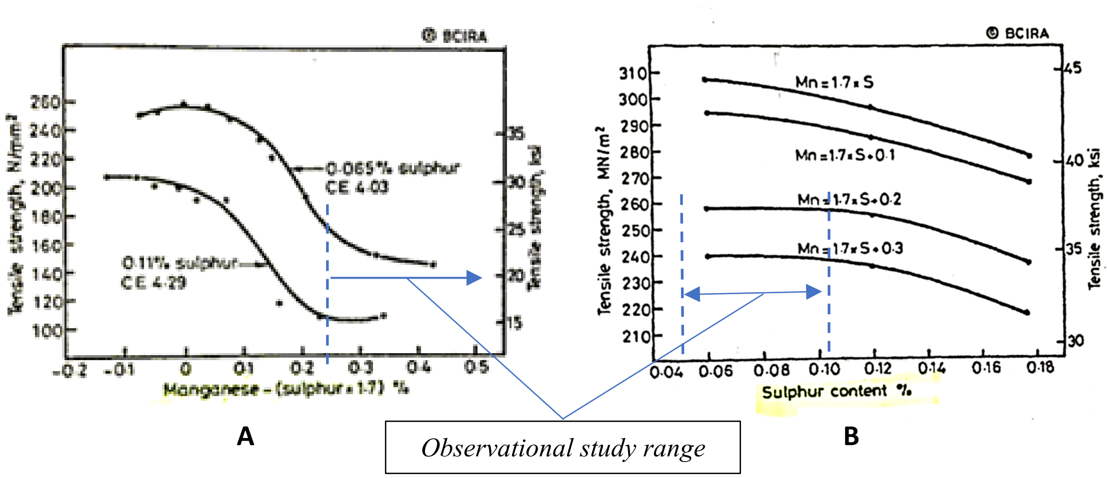


Figure 19. Effect of sulfur and manganese on tensile strength of lower and higher carbon equivalent cast irons (Artwork courtesy of A.G. Fuller.)

CONCLUSIONS

The results of the analysis led to the following conclusions:

- The carbon equivalent-liquidus (CEL) significantly and negatively affects the gray iron Class 25A ultimate tensile strength.
- It has been demonstrated that individual new observations of ultimate tensile strength can be predicted with a high confidence level of > 99.5%, by CEL within the studied range.
- The CEL is the predictor variable that has the highest contribution to the ultimate tensile strength variation if the alloying elements are held within the composition ranges used in this study.
- The Base Iron (iron before inoculation) held at superheating temperature for extensive time reduces the degree of nucleation and raises the liquidus temperature (TPL).
- Carefully standardized melting procedures can produce a consistent and reproducible carbon equivalent and liquidus temperature relationship.
- The phosphorous (P) significantly increases the tensile strength when it changes from 0.04% to 0.10%.
- The P present in cast irons, especially gray iron, often occurs as steadite, a eutectic of iron and iron phosphide of low melting point. Excessive P content raises the hardness and brittleness of gray iron because of the steadite formed.
- The phosphide eutectic content increases with the increment of chromium or molybdenum content. Chromium and molybdenum may have an additive effect on the increase of the phosphide eutectic.[8]
- It's recommended not to exceed 0.10 weight % of phosphorous in the gray iron.

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