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Predicting Cast Steel Alloy Properties Based On Composition and Heat Treatment

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ABSTRACT

Steel casting producers make small heats of specialty alloys for custom products. Unlike bulk producers like steel mills, casting producers frequently make non-standard alloys in small quantities, which requires them to be able to formulate heat compositions and heat-treat cycles for nonstandard alloys. To develop the methodology for estimating the tensile properties from a non-standard composition, a new database of standard steel cast alloys with composition and tensile properties was used. Standard specifications for steel castings require a tensile test to qualify heats. These tensile properties were collected for common steel casting alloys. This SFSA data set has over 30,000 entries. There are numerous formulas used to estimate hardness, hardenability, etc. The data set and an analysis of reported formulas to estimate properties like ideal diameter, carbon equivalent, or estimated hardness in heat treatments or welds have been evaluated for their ability to predict properties for non-standard alloy heats.

Keywords: cast steel, tensile properties, yield strength, ultimate strength, test variability, measurement bias, tempering, carbon equivalent, hardenability, ideal diameter

INTRODUCTION

Most alloy steels are standard grades with specified compositions and mechanical properties. These properties are compiled in commercial literature and in some handbook data.[1] Prior to the last few decades, alloy formulations were not rigidly set, and adjustments were made based on specific needs and also to respond to costs based on changing commercial requirements. The loss of institutional metallurgical expertise, fear of liability, and concern about risk has led to using standard alloys as though they were discrete materials instead of useful but flexible alloy formulations.

The four most popular cast steel alloy families are 10XX, 86XX, 41XX, and 43XX. Steel producers in the U.S. are required to do a tensile test for each heat made to ASTM steel product requirements. From these required specification tensile tests, Steel Founders' Society of America (SFSA) has collected an extensive set of alloy steel heat data, including composition and tensile properties. The data sets used were provided by operating plants that were from tests made to comply with ASTM requirements and were cast as keel blocks, as shown in ASTM A1067 Figure 1.

A challenge for early steel makers and users was the time required to determine the chemistry of the steel using wet titration for each element and the limited number of elements that could be analyzed. To ensure that the heat was not contaminated with unexpected elements, a tensile test provided assurance that the heat of the steel met the expectations of that grade in performance after heat treatment. Tension tests for each heat of steel are not, and have never been, intended to be representative of all the material poured from a heat. The SFSA data set is comprised of heat data. Analysis based off of it should not be assumed as representative of the local properties within a component.

Sometimes due to supply disruptions or unique needs, the steel casting producer needs to provide an alloy variation or even a non-standard alloy. This approach of supplying a non-standard composition is included in ASTM and ISO steel casting specifications. The ASTM Standard A148, issued in 1933, allows the producer to select or modify an alloy to meet the tensile properties of the standard. It remains an active specification and was revised and updated in 2019.[2] ISO 9477 has the same structure, specifying properties to be met, but it allows the producer to select or formulate the alloy required.[3]

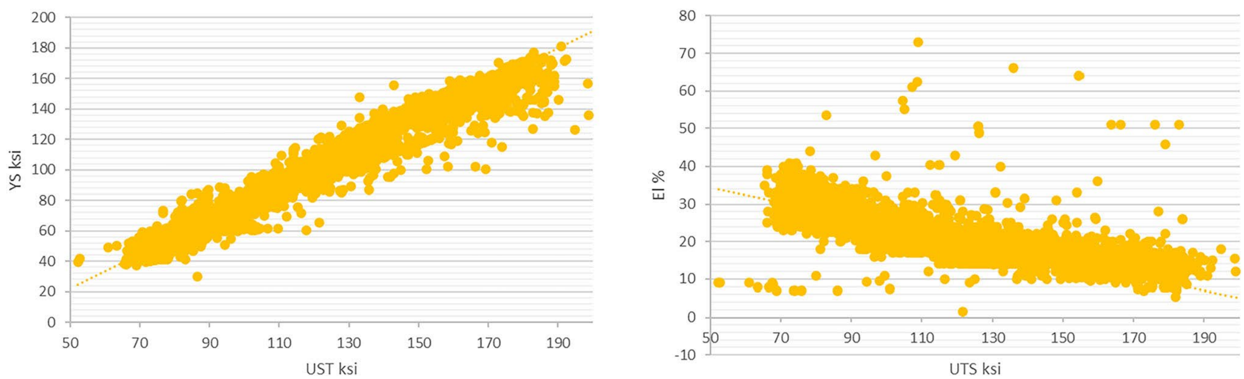

Figure 1. Correlation of data and bin averages for quenched and tempered cast steel alloys between UTS and YS, and between UTS and El.

Traditionally, a new alloy or alloy modification could be formulated from hardenability by selecting a carbon content that meets the required strength and hardness and an alloy content that has the proper heat-treat response. Hardenability can be calculated from composition as the ideal diameter, (DI).4 Weldability and weld procedures have requirements based on strength levels and composition. Alloy composition limits to ensure weldability are defined by the carbon equivalent (CE).[5]

These tools are used by the producer trying to formulate or modify an alloy to meet a unique customer demand or to accommodate changes in available scrap or alloying elements. However, they do not give an estimate of the final properties, as properties are dependent on the alloy's complete composition and the selected heat treatment cycle.

Many of the traditional tools using factors like DI, as a measure of hardenability to characterize the response to heat treatment, are dated and new approaches have been reported. The same is true of the use of CE to indicate the response of the alloy to avoid cracking in welding. For academic work and metallurgical understanding, hardness formulas have also been developed to correlate composition to the as-quenched or as-welded hardness. Steel hardness measurements are commonly reported as Vickers hardness (HV) or Rockwell "C" hardness (HRC). Specifications often use Brinell hardness (HBW) to set casting requirements, since it has a larger penetrator and the reading is more representative of the coarser microstructure of the casting. The relationships between composition and properties have been assessed to provide a predictive tool for tensile properties of alloy cast steel grades that have been quenched and tempered with traditional heat-treat cycles. A predictive tool for tensile properties of alloy cast steel grades that have been normalized and tempered has also been developed.

In this paper, the SFSA data set was used to evaluate the ability of the formulas found in publications to estimate the ultimate tensile strength (UTS) from composition and heat treatment.

SFSA DATA SETS

Steel Founders' Society of America has been developing modern model-based design tools for common structural alloys as steel castings. To facilitate the development and provide confidence in the validity of the design methodology, specification-required test data on heats of alloys has been solicited and received from many commercial producers. Steel foundries make small heats, often over 10 heats per day. Since ASTM steel casting specifications require both a composition analysis and mechanical test for each heat, thousands of heats of data are available and have been supplied by plants.

This data set provides a unique opportunity to develop the tools needed to formulate a charge for a new or modified alloy composition while still meeting the required properties. In this study, reported steel compositions were evaluated with the extensive SFSA data set to find correlations within the data.[6]

The selected formulas needed to be verified with an independent data set. Heats from plants with various compositions and tempering temperatures (TT) were gathered to form a reasonable data set for verifying the approach used. Additional data was solicited for the SFSA data collection, and a supplemental data set of over 3,500 heats was collected. This verification data set (V-data) was used to evaluate the proposed tools for prediction of UTS from reported mechanical properties of heats based on composition and heat treatment, and to avoid overfitting the data.

TENSILE TEST ANALYSIS

Designers often rely on yield strength (YS) as the best measure of reliable performance. Looking at the reproducibility and performance requirements, UTS was determined to be the best property to use for evaluating the ability of reported alloy factors to estimate the properties. The UTS measurement is less subjective, requiring only the maximum load during the test and the initial diameter of the bar. The more complex and subjective measurement of YS, El, and HBW makes the determination of these common properties more variable, as seen in the repeatability and reproducibility shown in Table 1. [7,8] UTS was used as the basis for evaluating the ability of published formulas to indicate properties from composition. The correlation of YS and EL with UTS is shown in Figure 1.

Beginning from UTS allows an estimation of the other tensile properties of interest. For yield strength, the linear regression equation for the data set is:

$YS = 1.13 * UTS * 34.4 \quad R^2\ of\ 0.95$ **Eqn. 1**
Standard error of 7.04 ksi

The correlations for the elongation for the data set was:

$El = 44.1 * 0.195 * UTS \quad R^2\ of\ 0.71$ **Eqn. 2**
with a standard error of 3.55%.

A Brinell hardness test provides a quick check on the properties of a casting or heattreat load. Hardness measures are related to UTS, and the common relationship is that the HBW is twice the UTS in ksi. For the data set, the correlation of HBW with UTS was:

$HBW = 2.04 * UTS + 9.1 \quad R^2\ of\ 0{:}91$ **Eqn. 3**
with a standard error of 17.9 HBW.

These correlations of properties with UTS will allow an estimate of the full set of properties, if the UTS is determined. The standard error for the correlation equations can be compared to the reproducibility values for the individual properties, shown in Table 1. The standard error for these correlation equations was larger than the reproducibility for the individual properties. This was expected since the reproducibility was intended to be only a measure of the test procedure on the same steel in the same location. The standard error includes the variations embedded in the UTS and the other property being correlated. The standard error does suggest the limit on the precision of other estimates on strength. When YS is used to estimate UTS:

$UTS = 0.85 * YS + 34.6 \quad R^2\ of\ 0.95$ **Eqn. 4**
with a standard error of 6.11 ksi.

This is the inverse of Eq 1 and has the same standard error indicating that 6 ksi is likely to be the limit of an estimation for the UTS or YS.

PROPERTIES AND COMPOSITION

The historic approach to identify the alloy formulations for heat-treated cast steel parts was to use the hardenability expressed in the DI.4 DI, calculated from composition, allows an alloy to be selected from available materials, in order to develop the properties required. It has been used to evaluate and formulate alloy compositions and properties, especially heat treatment response for quenched and tempered alloy steels.

A second alloy factor that provided guidance is the CE. This factor was developed to avoid cracking in welding and is also a compositional factor. This factor limits the alloy composition to avoid brittle behavior in the weld in the heat-affected zone (HAZ). [5]

Table 1. Repeatability and Reproducibility of Tension Testing Steel ASTM A105 and Brinell Hardness Testing

Property	Average	In Lab Repeatability Standard Deviation	Between Lab Reproducibility Standard Deviation	Repeatability 95%	Reproducibility 95%
Tensile Strength ksi	86.57	0.60	1.27	1.68	3.55
Yield Strength ksi	58.36	0.83	1.44	2.31	4.03
Elongation % 4D	29.10	0.76	0.98	2.13	2.76
Reduction of Area %	65.59	0.84	1.26	2.35	3.53
HBW 10/3000	197.71	4.47	6.72	12.51	18.80

The tempering temperature after quenching was a third factor that allows the alloy to be dialed in and meet the properties needed. The hardness and composition of the structure can guide the alloy formulation to produce cast parts that are compatible in properties and welding.
The most widely used version of DI is reported in ASTM A255.[12] This ASTM A255 DI formula is referred to as DIA255. DIA255 is the product of hardenability factors for each element considered. The hardenability factor equation for some elements changes based on the nominal amount of the element present. An example of DIA255 can be expressed as:[4,12]

$$DI_{A255} = 0.54 * C * (1 + 3.333 * Mn) * (1 + 0.7 * Si) * (1 + 0.363 * Ni) * (1 + 2.16 * Cr) * (1 + 3 * Mo) * (1 + 0.365 * Cu) * (1 + 1.73 * V)$$

Eqn. 5

This DI_{A255} factor was calculated and used to correlate with UTS. Using DI_{A255} to indicate UTS, using the data set is correlated as:

$$UTS = 13.17 * DI_{A255} + 73.8 \quad R^2 \text{ of } 0.71$$ **Eqn. 6**

with a standard error of 15.18 ksi.

If compared to the standard error in Eq. 1 of 6.35 ksi for YS, which is correlated to UTS as a crude measure of uncertainty in the measurements, DI255 has an added 10 ksi uncertainty. This is likely due to property variability and the failure to include the heat treatment in the correlation. DI_{255} is dependent on composition alone.

The common form of CE used in ASTM casting standards such as ASTM A216 was developed by the International Institute of Welding (IIW). The formula used for CEIIW is:[13]

$$CE_{IIW} = C + Mn/6 + (Cr + Mo + V) / 5 + (Ni + Cu) =15$$ **Eqn. 7**

Like DI, CE is correlated with UTS. The regression of the data set gives Eq. 8:

$$UTS = 210.65 * CE_{IIW} * 3.28 \quad R^2 \text{ of } 0.73$$ **Eqn. 8**

with a standard error of 14.69 ksi.

Based on this initial assessment, the use of DI and CE type of formulations was shown to be possible. In addition to the composition of steel alloys that are quenched and tempered, the tempering cycle is used to get the strength and hardness desired from a given heat. Unfortunately, the initial data set does not have access to the tempering cycles to allow a more precise correlation for these heat-treating factors, but an estimate was made and evaluated.

Table 2. Published Compositional Factors Correlated with UTS From the SFSA Data Ranked by R^2

Factor	slope	Intercept	R^2	P	Standard error ksi
UTS, ksi	1.00	0.00	1.00	1.79E-178	N/A
YS, ksi	0.85	34.01	0.96	1.27E-121	6.35
HBW	0.43	10.34	0.87	4.88E-22	9.71
CE_{my}	209.53	-1.88	0.75	7.97E-90	14.33
CE_{BS}	191.9	0.16	0.74	1.94E-95	14.38
HRC_{j22E7}	2.09	72.67	0.74	1.56E-120	14.42
HRC_{jE4}	1.84	59.5	0.74	5.99E-115	14.47
HRC_{jE}	1.84	28.35	0.74	2.76E-114	14.47
HRC_{jE3}	1.74	85.60	0.74	1.41E122	14.49
CE_{X2}	99.59	19.35	0.74	1.34E-115	14.49
CE_{by}	163.16	2.94	0.74	7.56E-97	15.50
HRC_{jE8}	1.89	54.93	0.4	9.73E-113	14.53
HV_{fpy}	1.91	-216.33	0.74	5.95E-107	14.60
CE_{IIby}	173.27	2.88	0.74	5.95E-107	14.60
CE_{IIW}	210.64	-3.27	0.73	3.37E-87	14.64
DI_p	8.62	73.27	0.72	1.98E-77	15.03
DI_{A255}	13.16	73.86	0.71	1.16E-62	15.19
SFSA R1	1.00	-0.01	0.76	1.16E-62	14.05
SFSA R2	1.00	0.45	0.75	1.16E-62	14.15

Analysis of DI, CE and other Factors to Estimate UTS

A spreadsheet was prepared to evaluate the SFSA data set for all the factors identified in literature review. For most factors, over 9,500 rows of heat data were used. The data was sorted by UTS, and the low and high UTS data sets were used to evaluate the factors for their ability to predict UTS, using the student t-test, which is based on the P-value. The full data set was also used in linear regression to predict UTS to evaluate each factor for its usefulness as a predictive factor, based on the R squared value (R^2). In addition, the SFSA data was used to do two direct regressions using composition to estimate UTS. SFSA R1 and SFSA R2 are the two correlation equations developed from the data set.

Table 2 shows correlations of UTS from the SFSA data set, where factors from literature have the highest correlation coefficients and the lowest standard error.[6] The first column contains the abbreviation of each factor of interest. A linear regression of the full data sets gives the best fit slope and intercept in the next two columns. The fourth column has the R^2 correlation for UTS from the full data set. The fifth column gives the P-value, the probability that the factor data for the high and low values of the property of interest is due to chance alone. For P, the lowest value indicates the strongest factor. The final column is the standard error, which indicates how far from the line the individual data points are located. While there are some of these other formulas providing a better predictive capability, the improvement over the commonly used versions was modest. The standard error of CE_{IIW} compared to the best performing formulation CE_{my} increased the R^2 only 0.011 and showed a lower standard error.

It was anticipated that DI could provide better estimate of UTS from composition given its development to predict composition and heat treatment. This turned out not to be the case. There were few proposed DI formulations; only eight reported formulas were found and evaluated. As shown in Table 2, DI was less effective than CE in predicting UTS. Only two formulations were evaluated based on screening their effectiveness. One was the already commonly used DI_{255}, and the other was a commercial formulation DI_p.

Over 50 formulations to predict hardness were evaluated for their ability to predict UTS. Early formulations were made to predict HRC of a Jominy test, and by extension, the alloy's heat treatment response.[14] It was anticipated that recent formulations created to predict HV from composition, especially formulations based on microstructure, would give the best estimate of UTS. Unexpectedly, the traditional Jominy predictions for HRC from composition gave the best results for these cast alloy data results, as seen in Table 2. These correlations were similar in accuracy and precision to the CE results. CE_{my}

has the best fit with UTS in the SFSA data set. The equation for CE_{my} is:

$$CE_{my} = C + Si/24 + Mn/6 + Cu/15 + Ni/12 + Mo/4 + Cr/8 + \Delta H \quad \textbf{Eqn. 9}$$

The factor, ΔH, is based on boron concentration and was not included, since these alloy grades were not alloyed using boron.

DI_p had the best DI correlation with UTS and is:

$$DIp = (0.56 * C + 0.0795) * (3.331 * Mn - 1.0008) * (0.6993 * Si + 1.0006) * (0.3626 * Ni + 1.001) * (2.1605 * Cr - 0.999) * (3 * Mo + 1) \quad \textbf{Eqn. 10}$$

The best hardness factor found was HRCj22E7, with the formula:

$$HRC_{j22E7} = -29 + 74 * C + 15 * Mn + 5.2 * Ni + 18 * Cr + 21 * V + 33 * Mo \quad \textbf{Eqn. 11}$$

The SFSA data set was examined with multi-linear regression analysis to determine the best fit with the alloying elements. SFSA R1 was the best fit correlation, with an R2 of 0.76 and a standard error of 14.05 ksi shown as Eq. 12:

$$UTS = 188.66 * C + 21.31 * Mn + 0.011 * Si + 21.87 * Cr + 19.09 * Ni + 62.67 * Mo + 18.73 \quad \textbf{Eqn. 12}$$

There were many heats without vanadium reported, and it was not included in SFSA R1; however, an additional regression was done that included vanadium, SFSA R2. SFSA R2 had a lower R^2 value of 0.75 and larger standard error of 14.15 ksi as seen in Eq. 13:

$$UTS = 163.41 * C + 24.90 * Mn\ 0.57 * Si + 12.53\ Cr + 19.06 * Ni + 68.01 * Mo + 34.60 * V + 21.476 \quad \textbf{Eqn. 13}$$

ADDING THE TEMPERING TEMPERATURE TO THE ESTIMATE OF UTS

These factors are based on composition and do not include heat treatment. For QT alloys, the dominant heat-treat factor in determining the properties is TT. Heat treatment is used to get the required properties of these steel cast alloys.

The SFSA data set had limited data on tempering and often the reported value was the specification requirement and not the actual procedure. The published steel data from the handbook, *Modern Steels and Their Properties*, was analyzed to estimate the effect of T_T on the estimated UTS. Assessments of the correlation of UTS with DI_{A255} and CE_{IIW} were done with this handbook data.

This data from the handbook data was evaluated using the Eqs. for cast steels from Table 2. Evaluating the handbook data without considering the effect of TT, the R^2 for DI_{A255} was 0.40 and for CE_{IIW} the R^2 was 0.31. The standard error for predicting UTS via DIA255 was 20.02 ksi and via CE_{IIW} was 18.60 ksi. This limited data set with a wide range of heat treatments, gives a larger standard error than the SFSA data set with these factors alone. The SFSA data set benefits from having commercially practiced tempering cycles, which would tend to center on the most useful tempering cycles. So, while they would not be identical, the SFSA data set would be weighted by the common heat treatment cycles based on their prevalence in the set.

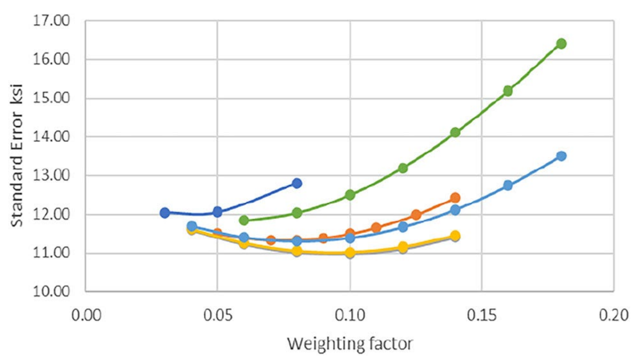

Figure 2. Base Tempering Temperature and Weighting Factor for TT adjustment.

If T_T is included with these two factors, DI_{A255} and CE_{IIW}, the regression for the handbook data becomes more like that of the SFSA data set. For the reported handbook data, the Eq. of DI_{A255} factoring in tempering temperature is:

$$UTS = 220.11 + 8.26 * DI_{255} - 0.111 * T_T \quad R^2 \ of\ 0.58 \text{ with a standard error of 15.64 ksi.} \quad \textbf{Eqn. 14}$$

For the correlation of UTS and CEIIW factoring in tempering temperature, the equation is:

$$UTS = 186.40 + 108 * CE_{IIW} - 0.127 * T_T \quad R^2 \text{ of } 0.53 \text{ with a standard error of 16.45 ksi.} \quad \textbf{Eqn. 15}$$

To determine the best fit for the handbook data, variations of the T_T and weighting factor were evaluated. The lines in Figure 2 represent different base T_T. The standard error was minimized for each base T_T by varying the weighting factor. The smallest standard error was a base T_T of 1100F and a weighting factor of 0.11 as seen in Figure 2. For both DI_{A255} and CE_{IIW}, the coefficient of the tempering temperature term was approximately -0.11 or 11 ksi decrease for every 100°F (68MPa for every 50°C) change in tempering temperature used.

Table 3. Factors for Estimating UTS from Composition and TT for the V-data set. The Linear Regression Equation and the best fit TT Adjustment are Included in the Table.

Factor	Slope	Intercept	Base temperature	Weighting	SFSA data	V-data	
					Standard error ksi	Standard error ksi	?T_T adj
SFSA R2	1.00	0.45	1200	0.12	14.15	13.56	7.63
SFSA R1	1.00	−0.01	1170	0.12	14.05	11.75	7.86
HRC_{jE}	1.84	28.35	1170	0.10	14.47	10.95	8.07
CE_{x2}	99.59	19.35	1170	0.12	14.49	12.30	8.19
CE_{my}	209.53	−1.88	1150	0.10	14.33	10.78	8.41
CE_{by}	163.16	2.94	1150	0.10	14.50	10.78	8.56
CE_{IIby}	173.27	2.88	1130	0.10	14.60	10.96	8.92
HV_{fpy}	1.91	−216.33	1100	0.08	14.60	11.09	8.98
HRC_{j22E7}	2.09	72.67	1100	0.09	14.42	11.45	9.07
CE_{BS}	191.90	0.16	1100	0.08	14.38	11.20	9.13
DI_P	8.62	73.27	1200	0.14	15.03	15.24	9.23
CE_{IIW}	210.64	−3.27	1100	0.09	14.64	11.90	9.66
HRC_{jE8}	1.89	54.93	1050	0.08	14.53	12.63	9.87
DI_{A255}	13.16	73.86	1130	0.10	15.19	13.13	11.28

The average tempering temperature cycle reported and used in the SFSA data set was 1078°F. These factors were used initially for adjusting the factors studied. This allowed proposing a formula for predicting UTS with DIA255 or CEIIW including tempering. For DI_{A255}, the proposed for- mula is:

$$UTS = 13.17 * DI_{A255} + 0.11 * (1078 - T_T) + 73.8$$ **Eqn. 16**

This would then be simplified to:

$$UTS = 13.17 * DI_{A255} - 0.11 * T_T + 192.4$$ **Eqn. 17**

For CE_{IIW} the proposed formula would be:

$$UTS = 259.93 * CE_{IIW} - 0.11 T_T + 88.1$$ Eqn: 18

Using the T_T adjustment with the factors identified in Table 3 reduced the standard error significantly. However, this reduction was based on the handbook data and might not be the optimal adjustment. Different base temperatures than 1078°F and different weighting factors other than 0.11 could provide a more technically sound, or at least a better, fit for factors.

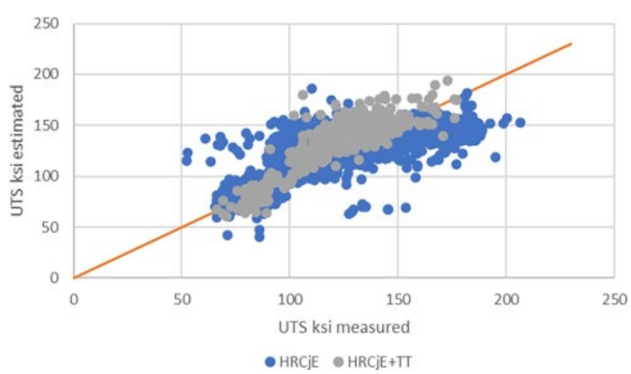

Figure 3. Correlation of estimated UTS from HRCjE for the SFSA data and HRCjE 1 TT for the V-data with measured UTS.

Evaluation for the average of the factors in Table 3 for base temperature and weighting is shown in Figure 2. The optimal TT adjustment for most factors was a base tem- perature of 1150°F and a weighting of 0.10.

VERIFICATION DATA SET

SFSA collected additional data from industrial plants for the data set. Submissions to this data set did have TT as well as composition and properties. These added data sets were used to verify the validity of the proposed equations for estimating UTS that were given above. This type of verification is necessary to ensure that the proposed equations are not unique to the data set for some structural issue and to guard against over fitting in order to get the highest correlation that is unique to that data set. This out-of- sample data set indicates the more general usefulness of the developed relationships. This verification data set (V-data) had over 4,300 entries.

The factors that had strong correlation from Table 3 were used to estimate the UTS for this V-data. The results of using these tempering-adjusted equations are shown in Table 3. The standard error was as low as 7.63 ksi for the SFSA data-regression factor SFSA R2.

Table 4. Direct Estimation of Estimated UTS from Identified Factors that are Additive, Including the T_T Adjustment

Factor	Slope	Intercept	C	Mn	Si	Cr	Ni	Mo	V	Constant	Temperature	Weight
SFSA R2			1.00	0.46	163.68	24.95	-0.57	12.56	19.10	68.15	34.67	21.89
SFSA R1	1.00	-0.01	188.70	21.31	0.01	21.87	19.09	62.68		18.73	1170	0.12
CE_{X2}	99.59	19.35	99.59	33.19	16.60	33.19	16.60	16.60		19.35	1170	0.12
CE_{my}	209.53	-1.88	209.53	34.92	8.73	26.19	17.46	52.38	13.97	-1.88	1150	0.10
CE_{by}	163.16	2.94	163.16	45.32		32.63	18.13	40.79	8.16	2.94	1150	0.10
CE_{IIby}	173.27	2.88	173.27	34.65	7.22	34.65	9.63	69.31	34.65	2.88	1130	0.10
HV_{fpy}	1.91	-216.33	173.27	34.65	7.22	34.65	9.63	69.31	34.65	2.88	1100	0.08
HRC_{j22E7}	2.09	72.67	154.81	31.39		37.66	10.88	69.04		72.67	1100	0.09
CE_{bs}	191.90	0.16	191.90	31.98	8.00	38.38	14.76	14.76	12.79	0.16	1100	0.08
CE_{IIW}	210.64	-3.27	210.64	35.11		42.13	14.04	42.13	42.13	-3.27	1100	0.09
		Average	172.86	32.75	6.74	31.39	14.93	50.51	25.86	13.64	1137	0.10
		Median	173.27	33.92	7.22	33.92	15.68	57.53	34.65	2.91	1140	0.10

The lowest standard error for the published factors was for $HRC_{jE} + T_T$ at 8.07 ksi. The equation for the estimate of the UTS from $HRC_{jE} + T_T$ is given in Eq. 19:

$$UTS = 1.84 * HRC_{jE} + 145.35 - 0{:}10 * T_T \quad \textbf{Eqn. 19}$$

The comparison of the UTS estimation for the SFSA data using composition alone, is shown in Figure 3. Also, in the figure is the UTS estimation for the V-data including the adjustment for tempering temperature.

The best fit is the SFSA R2+T_T, which gives a standard error below 8 ksi. A number of variants of CE show low standard errors below 9 ksi. None of the DI factors evaluated were able to estimate UTS with a standard error lower than 9 ksi. The two common factors used, CE_{IIW} and DI_{A255}, gave standard errors of 9.66 and 11.28 ksi, respectively.

Additive factors based on composition from Table 3 can be converted with the linear regression equation into a com- position-based estimate for UTS and allow the weighting of compositional factors to be made. The results are given in Table 4. This shows the commonality of compositional weighting factors when estimating UTS for the QT cast steel heats.

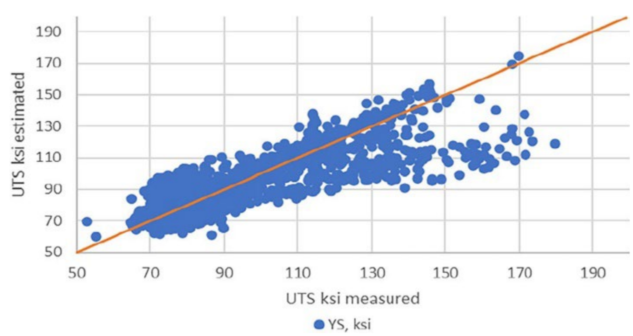

Figure 4. Estimate for UTS from YS from regression of SFSA NT heat data.

For example from the table, the UTS can be estimated from $CE_{my}+T_T$ with the equation:

$$209.53 * C + 34.92 * Mn + 8.73 * Si + 26.19 * Cr + 17.46 * Ni + 52.38 * Mo + 13.97 * V + 0.10 * (1150 - TT) - 1.88$$

Eqn. 20

This would then be simplified to:

$$UTS = 209.53 * C + 34.92 * Mn + 8.73 * Si + 26.19 * Cr + 17.46 * Ni + 52.38 * Mo + 13.97 * V - 0{:}10 * TT + 113.12$$

Eqn. 21

Estimating the UTS for cast steel non-standard alloys can be done with a standard error of less than 9 ksi with the SFSA R2 + T_T, $HRC_{jE}+T_T$, $CE_{x2}+T_T$, $CE_{my}+T_T$, $CE_{by}+_T$, $CE_{IIby}+T_T$, or $HV_{fpy}+T_T$. Other CE and hardness formulas give similar estimates for UTS but with higher standard errors. No DI formulas were identified that were as capable as CE or hardness. This was determined in an evaluation of the SFSA data for formulas.

ESTIMATING TENSILE PROPERTIES FOR NORMALIZED AND TEMPERED CAST STEEL ALLOYS

The full NT SFSA data set was correlated with the YS to show the variability of the data for UTS and YS as seen in Figure 4. This had an R^2 of 0.89 with a standard error of 4.88 ksi. These strength properties are measured on the same sample and are an indication of how low the standard error could be in the data set.

A regression based on composition was done on the large SFSA data set of over 17,500 NT heats, which was dominated by carbon steel WCX data. The linear regression gave an R^2 of 0.72, shown in 22:

$$UTS = 59.27 * C + 1.64 * Mn + 2.44 * Si + 29.34 * Cr + 20.83 * Ni + 2.89 * Mo - 36.43 * V - 18.89 * Cu + 58.32$$

Eqn. 22

with a standard error of 5.58 ksi.

Table 5. Formulas to Estimate UTS for NT heats evaluated by SFSA data

SFSA data		Standard Error ksi	V-data Standard Error ksi	V-data $+T_T$ Standard Error ksi
Factor	Formula			
$SFSAT_T$	UTS=102.01*C-12.97*Mn+12.39*Si+8.07*Cr +12.68*Ni+59.12*Mo -0.053*T_T+116.09	7.74	7.69	
SFSA+T_T	UTS=59.27*C+1.64*Mn+2.44*Si+29.34*Cr+20.83 *Ni+2.89*Mo-36.43*V-18.89*Cu+0.05*(1150-T_T)+58.32	5.58	9.10	8.51
HRCJ24T_T	UTS= 1.79*HRC_{j24}+54.49+0.05*(1150-T_T)	6.05	10.25	9.24
DI_P+T_T	UTS = 6.44*D_{ip}+67.5+0.05*(1150-T_T)	6.07	9.41	8.71
$CE_{Br}+T_T$	UTS = 173.86*CE_{BR}+27.29+0.05*(1150-T_T)	6.34	9.83	9.07

The correlation including the tempering temperature was an R2 of 0.74 for the following equation:

$$UTS = 102.01 * C - 12.97 * Mn + 12.39 * Si + 8.07 * Cr + 12.68 * Ni + 59.12 * \mathrm{Mo} - 0.053 * T_T + 116.09$$

with a standard error of 7.74 ksi. **Eqn. 23**

When these formulas were applied to the V-data for verification, the standard error for composition alone, as in Eq. 22, was 9.10 ksi. When Eq. 23 with TT was included, the standard error was 7.69 ksi.

To apply the T_T to the other formulations, the average T_T for the SFSA data of NT heats was 1139°F, and the factor was 0.053. To adjust the compositional factors for the T_T, UTS linear regression estimates the T_T adjustment used was - 0.05*TT+57.5. When this T_T adjustment was used with Eq. 22, the standard error fell from 9.10 to 8.51 ksi. This adjustment could be used with all the other factors evaluated to estimate UTS from composition to gain the effect of T_T.

All of the factors were evaluated to estimate the UTS. The best fit to the SFSA data identified based on composition was HRC_{j12} that is calculated from DIH and HRC_{j1} with an R^2 of 0.68. Eq. for DIH, HRC_{j1}, HRC_{j2}, and the UTS pre- diction from HRC_{j2} are shown in Eqs. 24-27:

$$DI_h = (0.8240 * C)^{1/2} * (1 + 0.2211 * Si + 0.1280 * Si^2) * (1 + 0.2353 * Mn + 0.5698 * Mn^2) * (1 + 1.634 * Cr + 0.0270 * Cr^2) * (1 + 0.7671 * Ni + 0.1229 * Ni^2) * (1 + 1.572 * Mo + 0.5893 * Mo^2) * (1 + 1.176 * Cu + 0.3339 * Cu^2)$$

Eqn. 24

$$HRC_{j1} = 35.55 + 22.26 * C + 177.5 * C^2 - 305.1C^3 + 132.6 * C^4$$ **Eqn. 25**

$$HRC_{j12} = HRC_{j1}/(1 + \exp(1.516 - 0.6507 * DI_H))$$

Eqn. 26

$$UTS = 1.40 * HRC_{j12} + 57.83$$

with a standard error of 5.98 ksi. **Eqn. 27**

There are a number of similar factors with similar estimation ability based on this type of formulation; HRC_{j16}, HRC_{j20}, HRC_{j24}, HRC_{j8}, HRC_{j28}, and HRC_{j32}. These factors are all highly correlated with similar formulations with R^2 from 0.68 to 0.67 and standard error from 5.98 to 6.11 ksi. The V-data had over 500 NT heats and gave a standard error for these factors from 10.25 to 11.65 ksi. When the TT adjustment was made to these factors, the standard error was 9.24 to 10.72 ksi. The lowest standard error was with $HRC_{j24} + T_T$, which is defined in Table 5.

The DI factor that correlated best with the SFSA data was the DI_p, with a R^2 of 0.67.

$$UTS = 6.44 * DI_P + 67.50$$

with a standard error of 6.07 ksi. **Eqn. 28**

The factors for $DI_{M\&R}$ and DI_{A255} both were also correlated with R2 of 0.66 and standard errors of 6.14 and 6.17 ksi. When the DI factors were utilized for the V-data, the standard error for composition alone for DI_p, $DI_{M\&R}$, and DI_{A255} was 9.41, 9.50 and 9.65 ksi. When the T_T adjustment was applied, the standard error fell to 8.71, 9.01 and 8.87 ksi. $DI_p + T_T$ gave the best estimate of UTS.

The best formulation of CE to estimate the UTS was CEf_{p100y}:

$$CE_{fp100y} = C + 1.14 * Mn + 1.06 * Ni + 2.02 * Cr + 2:33 * Mo$$ **Eqn. 29**

$$UTS = 12.19 * CE_{fp100y} + 56.52$$

Standard error of 6.11 ksi. **Eqn. 30**

The factors of CE_{x2}, CE_{Br}, and CE_{my} had a correlation of R^2 of 0.64 and standard errors of 6.32, 6.34 and 6.35 ksi. For the V-data, the standard error of CE_{fp100y}, CE_{x2}, CE_{Br}, and CE_{my} was 9.99, 10.37, 9.83 and 10.46 ksi. When the TT adjustment was made to these factors the standard error was 9.75, 10.08, 9.07 and 9.99 ksi. So for CE factors, $CE_{Br}+T_T$ gave the best estimate of UTS.

THE FORMULAS THAT GAVE THE LOWEST

Standard error to estimate the UTS for normalized and tempered steel casting heats are given in Table 5. For the estimate of UTS from YS, the standard error is 4.88 ksi. The estimates from the factors had a standard error of less than 10 ksi, with the best factor at 8.51 ksi and the SFSATT regression equation at 7.69 ksi. Note that the formula was calculated with tempering temperature originally, so can- not have TT added in the final column of Table 5.

CONCLUSION

This project was directed at identifying the best reported equation based on steel composition to estimate the UTS of QT and NT cast steel non-standard alloy compositions. This was completed using the newly developed SFSA data set, which contains over 9,500 entries. Highly correlated equations were assessed for over 100 formulas. Based on mill product reported properties for common steel alloys, a TT adjustment was proposed and was included with the developed formulas. These formulas were compared to additional data, not used for initially fitting (V-data) to verify the formulas' accuracy without having to perform a new study. The conclusions of this effort are listed below.

QT CONCLUSIONS:

1. UTS was determined to be the most useful standard property available to characterize the mechanical capacity of the steel heat in the QT condition.
2. A tempering temperature adjustment, based on a temperature and a weighting factor, improved the estimate of the UTS from composition, to allow standard errors of less than 10 ksi.
3. The linear regression, SFSA R^2+T_T in Table 4, from the SFSA compositional data plus the tempering temperature adjustment gave the best estimate of UTS, with a standard error of 7.63 ksi in the V-data, included in Table 3.
4. Hardness estimates, HRC_{jE}+ T_T in Table 4, for Jominy testing positions, based on composition plus T_T, gave best the estimate of the UTS for V-data, with a standard error of 8.07 ksi.
5. Carbon equivalent, CE_{x2}+ T_T in Table 4, plus T_T, gave a good estimate of UTS for the V-data, with a standard error of 8.19 ksi.

NT CONCLUSIONS:

1. The regression of the SFSA data with T_T, SFSA T_T in Table 5 gave the best estimate of UTS with a standard error of 7.69 ksi.
2. An adjustment for T_T for other published formu- las that were used to estimate UTS was developed from the SFSA regression; T_T adjustment was -0.05*TT?57.5. This adjustment reduced the standard error of formulas based on composition alone by 0.6 to over 1 ksi.
3. The best factor identified from literature was Di_p+ T_T in Table 5, which gave a standard error of 8.71 ksi.

REFERENCES

1. SECO/Warwick. *Heat Treating Data Book: Tenth Edition*; 2011.
2. ASTM 01.18. ASTM A148/148-M Steel Castings, High Strength, for Structural Purposes. ASTM International 2019.
3. ISO TC17 SC11. ISO 9477 High Strength Cast Steel for General Engineering and Structural Purposes. ISO 2015.
4. Grossmann, M. A. Hardenability Calculated from Chemical Composition. 29.
5. Wang, W. The Great Minds of Carbon Equivalent. 6.
6. Monroe, Raymond, and Jianyu Liang. Predicting Cast Steel Alloy Properties Based on Composition and Heat Treatment . Steel Founders' Society of America, 2020.
7. ASTM International. ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials.
8. E28 Committee. *ASTM E10 Test Method for Brinell Hardness of Metallic Materials*; ASTM International. https://doi.org/10.1520/E0010-15.
9. Gabauer, W. The Determination of Uncertainties in Tensile Testing. **2000**, 35.
10. Loveday, M. S. Room Temperature Tensile Testing: A Method for Estimating Uncertainty of Measurement. *Draft EN 10002Part 1 Met. Mater. Test. Ambient Temp.* **1999**, *CMMT* (MN)048, 16.
11. L.R.O. Silva, Evaluation of the Uncertainty of Measurement of Mechanical Properties on Tensile Testing. In Simposio de Metrologia **2004**, 5 (2004)
12. ASTM. ASTM A255 Determining the Hardenability of Steel. ASTM International.
13. A01 Committee. ASTM A216 Steel Castings, Carbon, Suitable for Fusion Welding, for High-Temperature Service. ASTM International. https://doi.org/10.1520/ A0216_A0216M-14E01.
14. E. Just, New Formulas for Calculating Hardenability Curves. Met. Prog. 96(5), 87–88 (1969)