AIST Transactions
Vol. 4, No. 3

Report on the Longitudinal Charpy V-Notch Model

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ABSTRACT

A linear regression model predicting whether a carbon steel plate would pass a Charpy impact test has been developed. This was done to prevent testing material that would not pass the required Charpy test, without having to sample the plate for grain size. Avoiding testing plates that would not pass would preclude loss of material and time, resulting in savings for the company. The model does not require metallographic sampling to preclude lost material and delays in processing of orders.

The Charpy LCVN model is statistically robust for ASTM A36, A516 Gr70 and A572 Gr50. The model agrees with metallurgical theory. C and Mo show a strong influence on Charpy impact properties. When impurities (sulfur and phosphorus) are too high, the chance of obtaining satisfactory test results would diminish. This is more evident when testing at lower temperatures. To account for grain size, the ratio of yield strength (YS) to ultimate tensile strength (UTS), and the percent elongation were incorporated into the model.

This paper records the development process and theory for the LCVN model. The first part of the paper describes the Charpy impact test and the metallurgical theory involved. The second part of the paper discusses the regression analysis used to develop the model.

INTRODUCTION

Charpy impact tests are used to evaluate whether a steel plate would behave in a brittle fashion or ductile fashion at the proposed operating temperatures. Steel, which has a body-centered cubic (BCC) structure, will undergo a ductile-to-brittle transition temperature (DBTT). The toughness of steel is an indication of steel's ability to absorb energy, and toughness is dependent upon the strength as well as ductility.[1]

A ductile fracture would show a large amount of energy absorbed by the sample upon fracturing. The broken Charpy sample for a ductile material shows a great deal of deformation. Conversely, a brittle fracture would have a small amount of energy absorbed during the Charpy test, and the broken specimen would show little or no deformation (Figure 1).

Different alloy contents will result in different transition curves for steel, as shown in Figure 2.[2] Figure 2 shows the effect of C content on the transition curve. Note how the maximum impact energy decreases with C, as well as the increase in transition temperature.

The fracture mode would be different for differing portions of the transition curves shown in Figure 2. Along the upper shelf, the fracture mode is ductile, with more deformation resulting during the Charpy impact test. Along the lower shelf, the fracture mode is brittle, with little or no deformation. Note the differences in deformation visible in the broken Charpy samples in Figure 1.

Steels that will be used in a lower-temperature regime would require low-temperature Charpy impact tests. This would place more stringent requirements on the producers of the steel.

When an order is entered for processing with a Charpy requirement, the plate would be sampled, and the sample coupon would be sent to a machine shop for sample preparation. The prepared samples would then go to the test lab. If microstructural analysis was required for determining whether a steel plate would pass the required Charpy impact test, then the order would be delayed longer. The goal of this model was to determine whether a particular steel plate would pass the required Charpy impact test, without having to sample the plate, for microstructural analysis, prior to

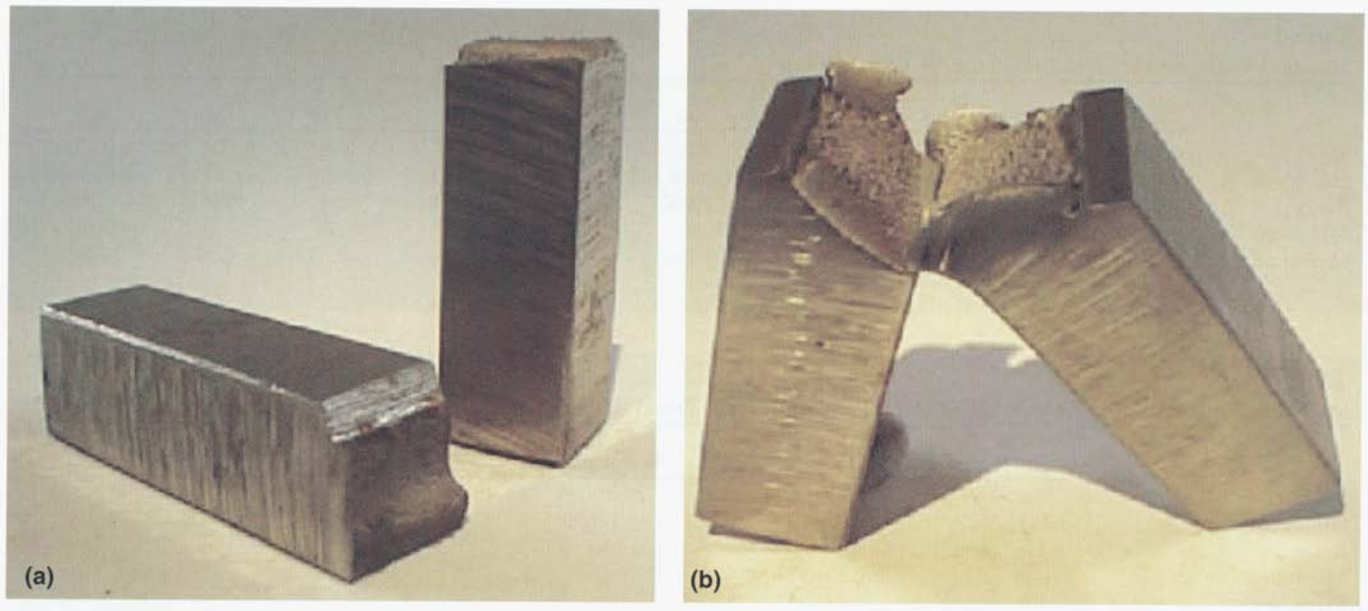


Figure 1
Broken Charpy impact samples showing the deformation associated with different fracture modes: (a) brittle fracture and (b) ductile fracture.

testing. Saving the micro sample would save material and shorten order processing time. The model will not preclude testing, but only help in selecting the best candidate plate for the test.

MODEL DEVELOPMENT

Regression analysis is a method of relating one variable with another variable. This discussion will relate the statistics involved with multiple linear regression.

The goal of regression analysis is to find the best-fit model. One important aspect of analyzing the fitness of a model is to perform an analysis of variance (ANOVA).[3] ANOVA is used to determine the statistical significance of a regression model.

There are various steps in developing a model:[4]

- Collect data, check quality of data, plot data.
- Consult experts and literature.
- Examine some fitted regression equations.
- Are goals met?
- Are parameters stable over the sample space?
- Are the coefficients reasonable?
- Is the equation plausible?
- Is the equation usable?

The final aspect of model building is to test the model. Does the model adequately predict Charpy impact test results? Is the model relatively easy to use? These questions will be answered below.

All samples were machined at one source, Howlett Machine in Berkeley, Calif., and tested at one source, Testing Engineers Inc. in San Leandro, Calif. This was done to minimize variability due to sample preparation, and testing variability from different testing regimes. All samples were prepared and tested per ASTM A370.

Table 1 shows the composition for all samples analyzed. The ranges for the alloys show the limits where the model is applicable. For example, the Charpy LCVN model should not be used to evaluate whether A514 would pass a Charpy test.

Table 2 lists the statistics for the plate dimensions as rolled at the mill, and the mechanical properties reported on the mill test certification. All test temperatures were reported in °F, and mechanical properties were reported in ksi (1,000 psi).

Figure 3 shows the number of plates for each grade tested. There were more A36 plates than A516-70 or A572-50. Figure 4 shows the average Charpy impact

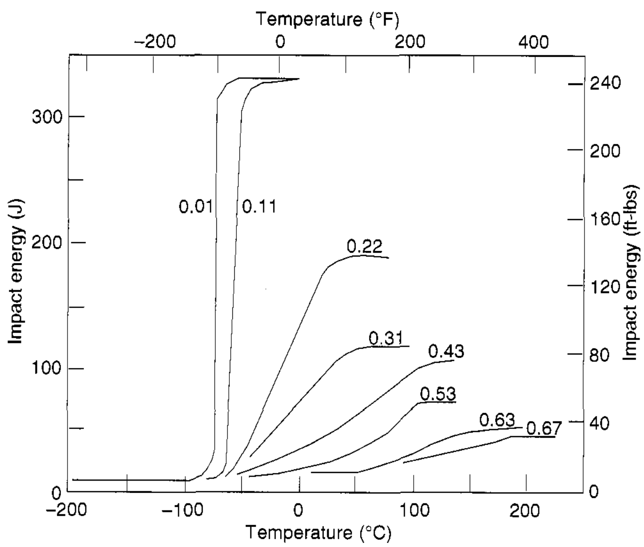


Figure 2
Change in transition curve with different C contents.[2]

Table 1
Statistical Values for the Composition for All Tested Grades

	C	Mn	S	P	Al	Si	Cu	Ni	Mo	Cr
Mean	0.162661	1.1	0.005904	0.01306	0.029404	0.224266	0.192026	0.084296	0.021738	0.077605
Std. deviation	0.040609	0.192567	0.003781	0.003134	0.008016	0.068639	0.148916	0.069902	0.017188	0.063193
Range	0.234	1	0.0292	0.016	0.052	0.37	0.51	0.47	0.094	0.58
Minimum	0.016	0.5	0.0008	0.007	0	0	0	0	0	0
Maximum	0.25	1.5	0.03	0.023	0.052	0.37	0.51	0.47	0.094	0.58

Table 2
Statistical Values for Dimensions and Mechanical Properties for All Tested Grades

	Temperature	YS/UTS	% elongation	Thickness	Width
Mean	21.20085837	0.683069	26.46695	1.70574	95.69099
Std. deviation	45.02513282	0.085791	5.78639	1.279844	10.68227
Range	128	1.19648	38	7.25	72
Minimum	−58	0.146377	16	0.25	48
Maximum	70	1.342857	54	7.5	120

Table 3
Regression Statistics and ANOVA for Aug. 22, 2006

Regression Statistics	
Multiple R	0.843114564
R square	0.710842169
Adjusted R square	0.6908543
Standard error	38.0571898
Observations	233

ANOVA

	Deg. of freedom	Sum of squares	MS	F	Significance F
Regression	15	772629.6854	51508.6457	35.56368041	4.30462E-50
Residual	217	314291.8839	1448.349696		
Total	232	1086921.569			

energy for each grade, with the average test temperature. Note that A516-70 had lower Charpy impact energy, but was also tested at lower temperatures.

Table 3 shows the output from the regression analysis. The F significance level at $\alpha = 0.05$ from Reference 3 is 1.92, while the F value from the ANOVA analysis for the LCVN model was significantly larger. Thus, the regression model was not due to chance alone. The significance of the coefficients will be addressed in the "Discussion" section to follow.

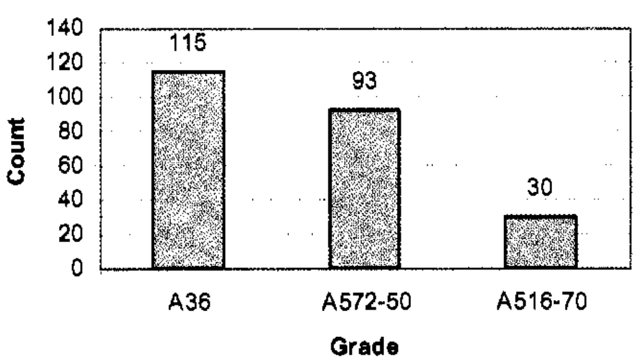


Figure 3
The number of plates sampled for each steel grade.

The degree of freedom is one less than the number of variables used in the statistical analysis. In this case, the degree of freedom was 15. The significance F is $4.305X10^{-50}$, and the measured F was 35.56; thus, the model results did not occur by chance alone. The sum of squares is a gauge of sample variance.

The R square statistic is a fraction between 0 and 1. R square is a measure of the amount of variation about the mean. The closer the measurement is to 1, the more statistically robust the model. For a multiple regression model, the statistic of importance is the adjusted R square, which is the R square divided by the degrees of freedom. Once again, this value is a fraction between 0 and 1. When increasing the variables employed in a model, the R square will increase. The

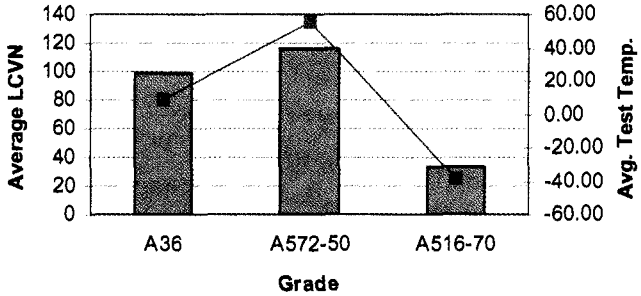


Figure 4
Average Charpy impact energy (J) for each grade, with the average test temperature (°C).

adjusted R square may become smaller as variables are added to a regression model.

As-cast plate thickness and width were added to the LCVN model to account for grain size. Plate that was air-cooled would cool slower for thicker plates than thinner plates. The slower cooling would allow more time at temperature for grains to grow. Since the actual grain size is not included in the model, the model is not applicable for steel grades utilizing normalizing for grain refinement. It was not possible to bring heat treat parameters into the model, since not all steel mills report similar data for normalizing.

The model was not able to account for inclusion content, other than through composition as reported on mill test reports There was not sufficient range in the incidental elements to account for the effect of inclusions through this method

RESULTS

The Charpy model shows good capabilities in predicting whether a specific steel plate would pass the required Charpy impact test requirements for a specified application (Figure 5) This would preclude testing plates that would not meet the test requirements, thus saving material and time

The adjusted R square was 0.691, which is reasonable, considering the model was developed using historical data rather than using a statistically designed experiment This model was not intended to preclude testing, but to avoid testing steel plate that would not pass the required Charpy impact tests

The steel composition and mechanical property data were gathered from mill test certification There were six different mills from different countries that produced the steel used for these projects Thus, there

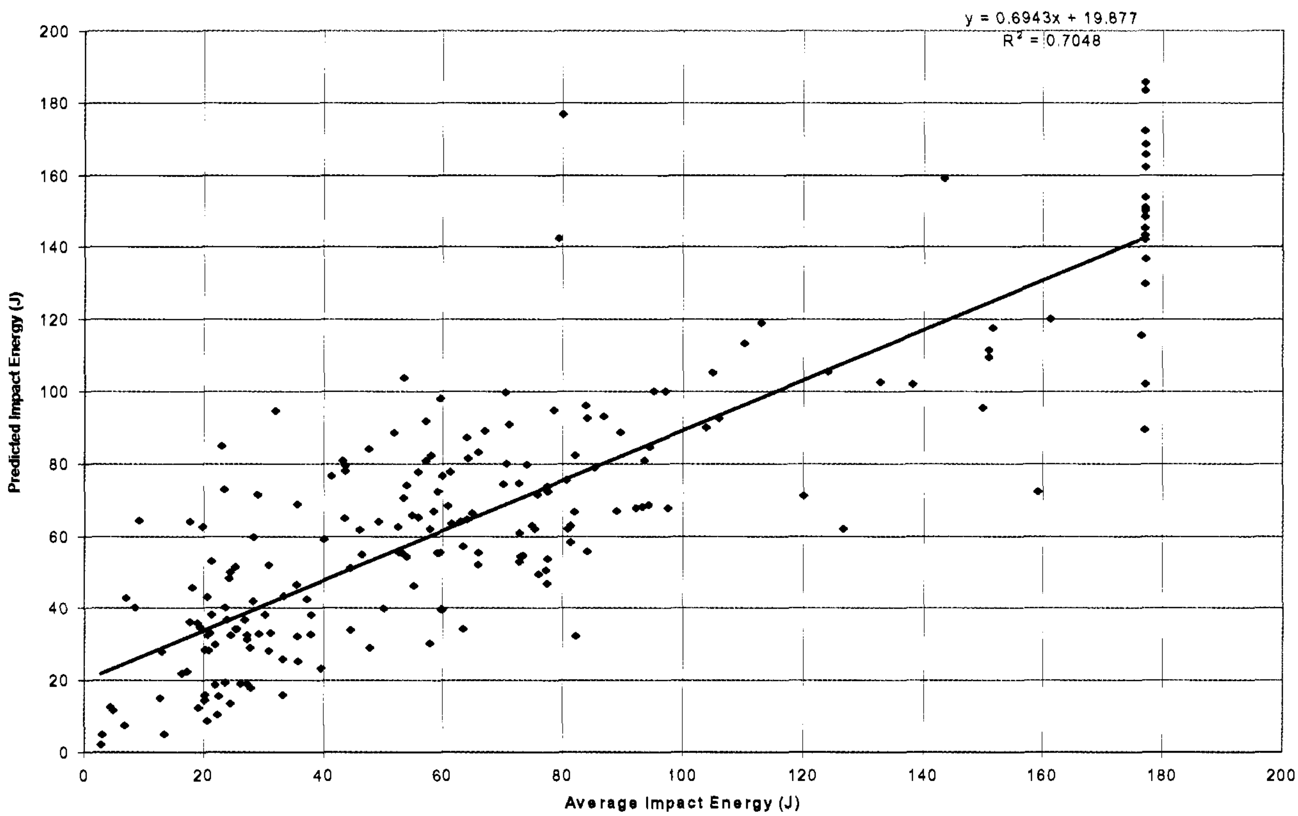


Figure 5
Average Charpy impact result versus predicted impact energy.

Table 4
Coefficients in the Model

	Coefficients	Standard error	t Stat	P-value
Intercept	135.9128152	53.10166633	2.559483056	0.011162889
C	–915.3537361	80.59426473	–11.35755428	9.14367E-24
Mn	–30.50878664	20.18790857	–1.511240579	0.132182016
S	–2862.91517	740.8283969	–3.864478173	0.000147046
P	205.285298	945.6540355	0.217082876	0.828347721
Al	979.9549636	372.645894	2.629721619	0.009157218
Si	141.1048126	49.50504452	2.850311801	0.004788621
Cu	58.457051	47.1985178	1.238535736	0.216855601
Ni	–10.90326472	81.7536875	–0.133367253	0.89402654
Mo	–831.2947422	306.6491967	–2.710898157	0.0072471
Cr	13.83310219	66.55313962	0.207850483	0.835540653
Temperature	0.901536486	0.076674174	11.75802011	5.10363E-25
YS/UTS ratio	6.0445778	41.62754463	0.145206206	0.884682849
% elongation	2.54029704	0.569056543	4.464050315	1.29247E-05
Thickness	–19.75164674	3.120350194	–6.329945521	1.38777E-09
Width	0.473624988	0.252426929	1.876285507	0.06195844

were different errors in measurements from the different mills This would introduce more potential error into the model. More error would imply that the adjusted R square would be less than optimal The model was designed to use the data from the mill test certification to determine whether a steel plate would pass a Charpy impact test

The coefficient for C was -915.354, which shows that C will drastically lower Charpy impact values The coefficient for Mo was -831.295, and Mo has been shown in the literature to raise transition temperature as rapidly as C Mn and Ni will increase impact energies measured through a Charpy test Table 4 lists the coefficients used for the model

DISCUSSION

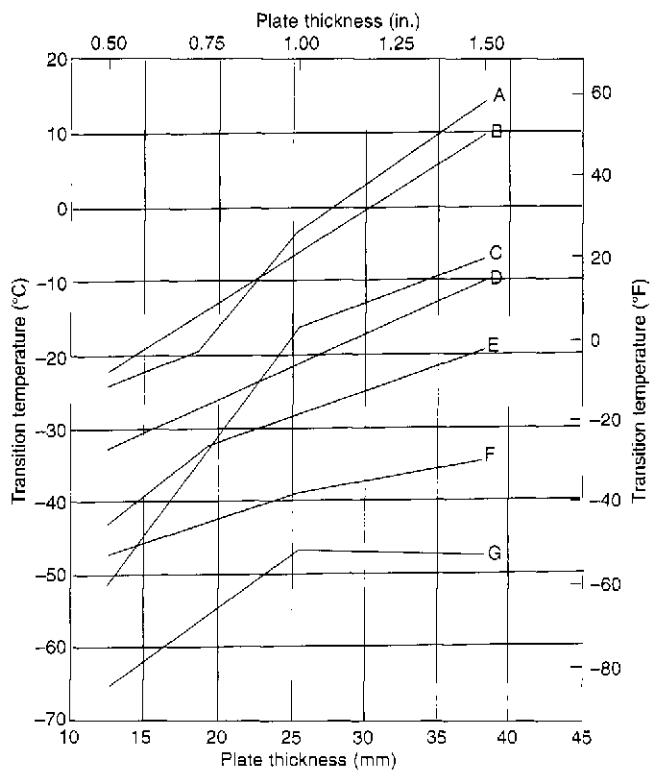
The thickness coefficient is negative, -19.752, which indicates that thicker plates would have lower C harpy impact values. This is supportive for the grain size thickness relationship The grain size of transformed ferrite (d_α) depends on the recrystallized austenite grain size (d_γ) and cooling rate from the finishing rolling temperature (FRT) [5]

$$d_\alpha = 3.75 + 0.18 d_\gamma + 1.4(dT/dt)^{-1/2} \quad \text{(Eq. 1)}$$

where

dT/dt is the average cooling rate between 750 and 550°C in °C/second,
d_α is the transformed ferrite grain size in μm and
d_γ is the recrystallized austenite grain size in μm prior to cooling.

Thicker plate would cool slower, thus allowing more time at temperature for grain growth. Microstructural analysis was not done, since the model was developed using historical data, and many of the samples were



Steel	Composition (%) C	Mn
A (semikilled)	0.23	0.45
B (aluminum killed)	0.23	0.45
C (silicon-aluminum killed)	0.16	0.45
D (silicon killed)	0.23	0.45
E (semikilled)	0.16	0.75
F (semikilled)	0.16	0.95
G (silicon-aluminum killed)	0.16	0.75

Variation in Charpy keyhole-notch transition temperature with plate thickness for seven low-carbon steels.

Figure 6
Relation of LCVN and plate thickness.[6]

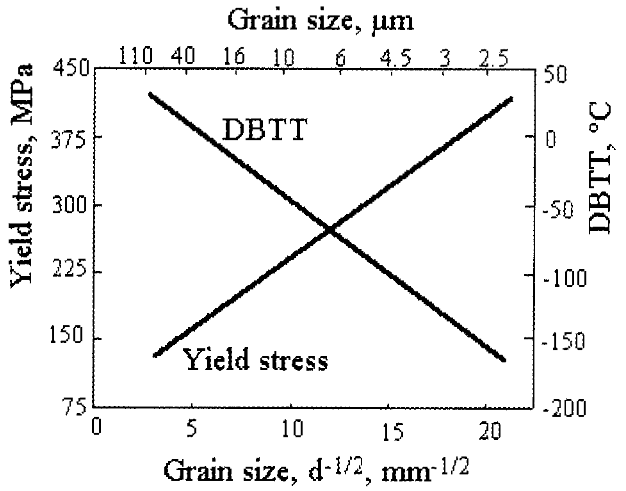


Figure 7
Relation of yield stress and transition temperature with grain size.[7]

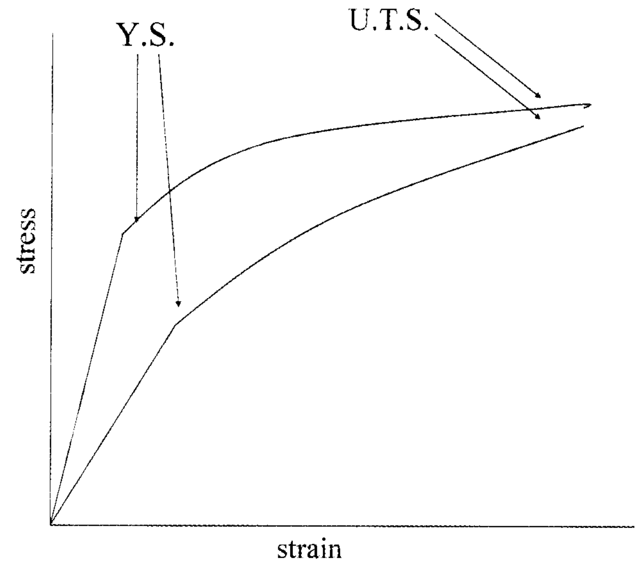


Figure 8
Theoretical stress strain curves showing the difference in area under the curve for different YS.

no longer in existence. Figure 6 shows the relationship between plate thickness and notch toughness, as reported in Metals Handbook, Desk Edition.[6]

The only thing that will increase both toughness and strength is to reduce grain size (Figure 7).[7] The model included yield strength and ultimate tensile strength. Charpy impact energy is related to toughness. Toughness is defined as the energy absorbed without fracture, and the area under the stress-strain curve can also represent it.[7] The area under the stress-strain curve would be different if the yield strength (YS) was almost the same as the ultimate tensile strength (UTS), as compared to the situation where the YS was much lower than the UTS. This can be visualized by comparing a situation with two materials having similar UTS but different YS (Figure 8). The area under the curve for the material with the greater YS would be larger than the material with the lower YS. The area under the curve would be less in the situation where the YS was much lower than UTS. This would be measurable as the YS-to-UTS ratio.

The coefficients generated for the model agree with metallurgical theory. C and Mo have similar coefficients, and metallurgical theory has shown that both alloys will lower transition temperature at similar rates. S is a deleterious impurity in low-C steel plate. The coefficient for S was -2,862.92, which indicates S has a strong negative influence on the impact energy measured through Charpy V-Notch testing.

It was not possible to model more complicated steel alloys. This was due to the different precipitation processes being utilized for other grades. A514 uses Nb, V and/or Ti to form carbides and fine grain sizes. Without bringing in the processing parameters - for example, drafting schedule through hot rolling, and normalizing and tempering practices - there was no method with the data locally available to model the more complex microstructure.

CONCLUSIONS

The model is statistically robust for A36, A516-70 (as-rolled) and A572-50. The model cannot be used for grades whose composition and/or processing falls outside the ranges listed in Table 1. Steel grades that utilize austenitizing and quenching are not suitable for this model; this includes ASTM A514 and ASTM A516 GR 70 normalized.

C and Mo will influence Charpy impact energies to a greater extent within the testing regimes. Selecting a plate that would meet the required Charpy requirements would provide a savings for a company and its customers.

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