Program for Reducing the Variability of Gray Iron Tensile Tests

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ABSTRACT

This paper shows that a system using recursive, multiple regression can produce a statistically significant reduction in the variability of the tensile strength of gray iron. By analyzing three years of a foundry's gray iron tensile tests, a periodic shift in results was found. In order to compensate for those shifts, a computer program was written that calculated a copper addition based on the results of a multiple regression analysis of the residual elements of the most recent tensile tests.

Comparison of the tensile results from one year using the system to the previous years' results showed significant reduction in tensile strength variability, but not to the degree desired. Future modifications to the program are included.

INTRODUCTION

Controlling the variability of tensile properties has always been very important to gray iron foundries, and it promises to become more so in the future. Historically, most gray iron castings have been sold on the basis of meeting minimum tensile property requirements. Now, many customers are beginning to require suppliers to meet minimum capability indexes for these tensile requirements. Since the machinability of iron is usually adversely effected by increasing tensile strength, the iron metallurgist is faced with the task of making sure the tensile properties are sufficient to meet specifications, but not so high as to hurt machinability. With the variability inherent in tensile testing, it becomes even more important to control the processes that lead to achieving desired tensile properties.

Seneca Foundry in Webster City, Iowa decided to try to prevent the occasional tensile test failure they experienced, as well as the occasional machinability complaint they received from customers, by investigating the tensile test control procedures in their gray iron production. While neither of these problems happened with any degree of frequency, Seneca decided that, if it were to maintain its reputation for quality, *any* occurrence was not satisfactory.

THE OPERATION

Seneca currently produces class 30 and class 40 gray iron, as well as 60-40-18, 65-45-12, 80-55-06 and 100-70-03 grades of ductile iron castings on a two-shift basis, with iron melted in medium-frequency, coreless induction furnaces. For the work being reported in this paper, only the gray iron portion of the operation is being considered. While the operation is currently two shifts, some of the data taken before the improvement program came from a one-shift operation.

Their two furnaces each hold 4000 pounds. Melting is accomplished using a tap and charge technique, where 500 pounds of metal is tapped from a full furnace and 500 pounds of "cold" charge is immediately put back in the furnace. Preheating is limited to making sure material is moisture-free. The gray iron metallic charge components consist of returns, prompt industrial steel scrap and a small amount of pig iron. Carbon and silicon additions are based on the thermal analysis results from prior charges. All materials going into the furnace and all iron taken from the furnace is weighed.

As the iron is transferred to the pouring ladle, it is inoculated with inoculating grade 75% ferrosilicon in the case of class 30 iron. The same base iron and inoculation is used for the class 40. The additional strength for the class 40 comes from the addition of copper and molybdenum.

Beside the thermal analysis, a full chemistry is obtained from a sample taken from the furnaces after every fourth charge. This analysis, performed on a vacuum spectrometer, consists of carbon, magnesium, aluminum, silicon, phosphorus, sulfur, titanium, chromium, manganese, nickel, copper, molybdenum, tin and lead. Prior to this program to reduce variability, the function of this base furnace analysis was to verify the thermal analysis, to make sure no elements were drastically changing, and to provide information to control sulfur and manganese. (Sulfur and manganese were consistent enough that changes of additions were made very infrequently.)

In addition, after inoculation, a spectrometer sample is taken from every ladle of iron produced. Actual spectrometer analysis of these samples is limited to a random number per shift and any ladle from which a tensile test is performed. The remaining samples are stored for a period of time, to be used in case any problems arise.

Tensile tests are poured for each grade of iron produced during a shift. If there is more than one ladle of a grade produced during a shift, an alternate set of bars is also poured. The test bar molds are made in accordance to ASTM A-48 and, except when required in rare cases, produce "B" size test bars. Beside having the chemical analysis from the spectrometer sample, the temperature of the iron in the ladle, the time between inoculation and pouring the test, the time between pouring and shaking out the test bars, and the information from the thermal analysis at the furnace is recorded for each tensile specimen.

The tensile testing of the specimens is done at commercial laboratories. A primary lab is chosen and is used for all regular tests until there is a significant reason for changing. Reasons for changing usually center around the time required to obtain results; however, in one case, a change was made because the quality of results obtained from a lab had deteriorated. All of the data concerning each test is entered into a computer program that not only stores all of the information but also checks each of the variables for being in statistical control.

Considering the purity of the charge and the control procedures described above, one would expect excellent control of tensile properties. The control of the chemistry did appear to be very good. Table 1 shows standard deviation of the elements in the class 30 tensile tests. The control of the elements for the class 40 is very similar.

THE PROBLEM

Even with this degree of control, the variability of the tensile results was considered too high. Table 2 shows the standard deviations of the two grades of the gray iron for the years 1992 through 1994. In the AFS Research Report produced in September of 1991, Bates[1] reported the standard deviations of the test results obtained by 11

Table 1.
Standard Deviations of Elements (Class 30)

	1992	1993	1994
C	0.028	0.029	0.027
Al	0.0007	0.0007	0.0007
Si	0.075	0.050	0.063
P	0.0052	0.0032	0.0033
S	0.0091	0.0056	0.0056
Ti	0.0036	0.0033	0.0018
Cr	0.0090	0.0097	0.0078
Mn	0.0289	0.0300	0.0257
Ni	0.0097	0.0082	0.0136
Cu	0.0387	0.0320	0.0341
Mo	0.0183	0.0174	0.0189
Sn	0.0007	0.0007	0.0007

Table 2.
Standard Deviation of Tensile Strength by Year

Year	Standard Deviation Class 30	Standard Deviation Class 40
1992	2.43	3.24
1993	2.41	3.03
1994	2.88	2.23

laboratories testing gray iron samples designed to be consistent were between 0.371 and 1.149 ksi (thousand pounds per square inch). During the period of 1992 through 1994, the standard deviation for Seneca tensile tests was 2.63 and 2.98 ksi for the class 30 and class 40 tests, respectively.

The logical assumption was that standard deviations larger than those found strictly in the tensile testing were caused by variability in the processes used to produce the iron.

THE SOLUTION

Numerous theories were developed regarding the cause of the variation. Most of these theories centered around observations made with the chemistry of the iron. Change in chemistry is a logical explanation for changes in tensile properties. The alloying effect of elements has long been recognized; however, prior to the ready availability of computers, accounting for small changes in the numerous chemical elements analyzed was practically impossible. Typically, foundries either keyed decisions on changes in one or two elements, or had a standard practice that was believed to have enough safety factor in it to allow for the changes typically experienced.

The computer and multiple regression analysis now makes it possible to assess the effect of numerous changes at one time. It was decided to use the information from 1992 through 1994 to perform a multiple regression analysis, using the chemical elements as the independent variables and the tensile strength as the dependent variable. The elements used for the analysis are seen in Table 1, except for lead. (It should also be pointed out that, because of the author's prejudice against carbon analyses from spectrometers, the carbon results used in the analysis came from the thermal analysis taken of the base iron in the furnace.)

The multiple regression analysis for the class 30 results provided an equation with a coefficient of multiple correlation of 0.52 (considered acceptable for production data); however, the standard error of estimate was still 2.30 ksi. Results for class 40 was an equation with coefficient of multiple correlation of 0.5133, and the standard error of estimate was 2.628 ksi.

Further analysis of this data was made by applying the equation to each of the sets of data, in order to calculate a predicted tensile strength, and then deriving the difference between the actual results and predicted results. Because of a perception that there was a difference between summer and winter results, the differences were averaged by month, and plotted. The results are seen in Figs. 1 and 2. Examination of those figures does give credibility to a perception of a difference related to the season of the year.

A great deal of thought went into the possible causes of the seasonal changes. In particular, nitrogen has been given a great deal of consideration. It does appear that nitrogen goes up in the summer months, but not consistently. Because of the difficulty with nitrogen analysis (cost and accuracy), no correlation with tensile variation has been found. None of the other theories have been proven, either. What was evident was that, if variability of tensile properties was to be minimized, a control procedure would be needed that would allow compensation for such changes not caused by the chemistry.

Because of previous successes with the technique in other areas of the operation, it was decided that a recursive multiple regression analysis program would be developed in which the regression analysis would be performed using, as the independent variables, the base residual elements (sulfur, chromium, nickel, aluminum, titanium, tin, copper, molybdenum and phosphorus) and the desired tensile strength. The dependent variable would be the copper addition required to be made to each ladle of iron.

The data used for the prediction would be saved in a file until the actual test results were obtained. Then the desired tensile strength would be replaced with the actual results achieved, and that information would then be part of the data base used in the next regression analysis.

The desired tensile strength was set as being two standard deviations above the minimum specified. Carbon and silicon were not incorporated into the regression analysis because control procedures were in place that compensated for any changes that would occur in them. Because of the slowness of the computer being used at that time, the data base on which the regression analysis was performed was allowed to grow from 25 to 35 data sets. Once the data base grew to the point of having 35 data sets, the ten oldest were automatically purged from the file.

In actual practice, the program is used only once per shift. The technician runs it early in the shift using one of the first base chemistries obtained. The resulting copper addition is used throughout the shift. The technicians are instructed to rerun the program whenever they see significant changes in the base chemistries. During the initial period, such reruns were common; however, as the technicians developed a feel for how big a change was necessary to result in a change in the copper addition prediction, reruns became less frequent. Now reruns during a shift are rare, except when the metal grade being produced is changed.

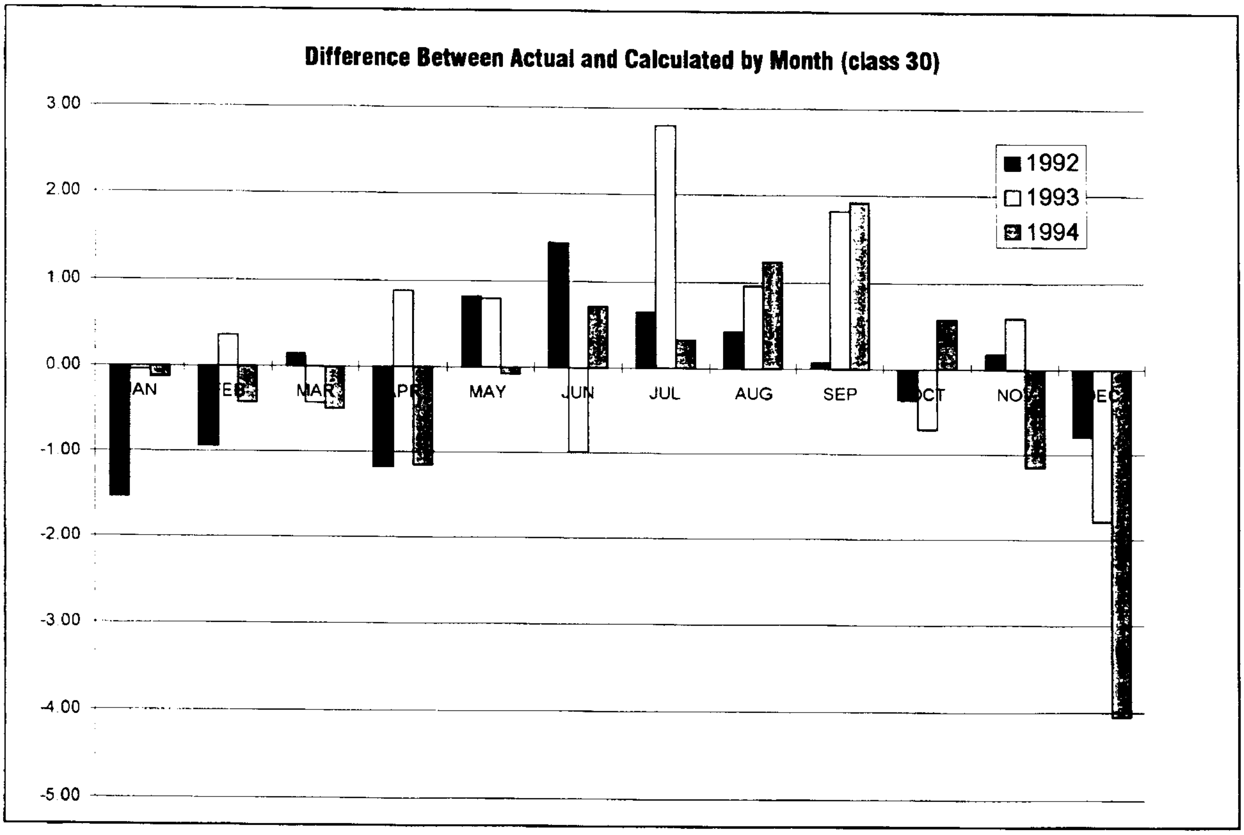

Fig. 1. Class 30 difference from prediction by month.

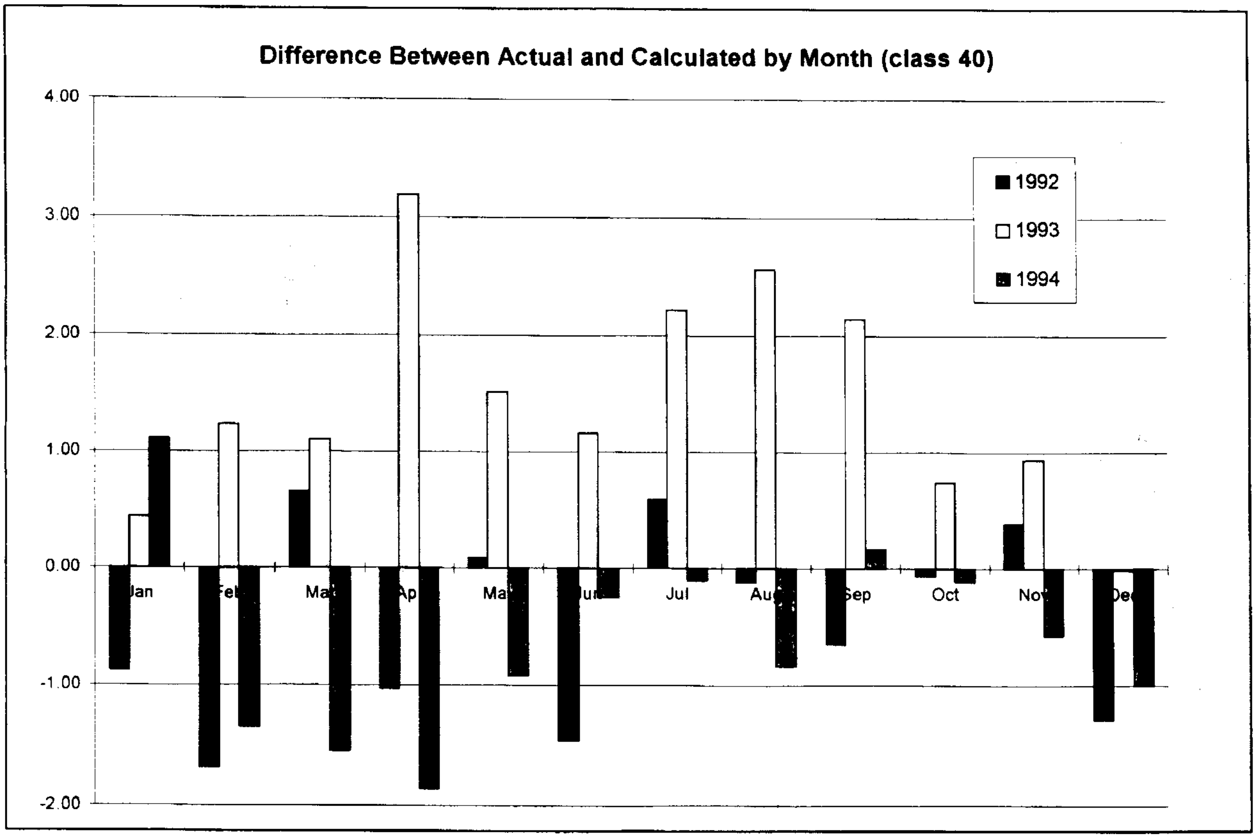

Fig. 2. Class 40 difference from prediction by month.

RESULTS

Seneca began using this program for calculating copper additions in April 1994. By May, the program had collected enough data to actually make predictions; therefore, for the sake of this report, data coming from tests taken before April 1, 1994 were considered to be prior to using the program, and tests taken after April 30, 1994 were considered as being taken after the program was in use.

The class 30 results were particularly spectacular, initially. The standard deviation of the tensile strength for the test results taken in May, 1995 was the lowest it had ever been, and June was even lower. However, as time passed and the normal variations in an operating foundry came to pass, the improvement was not as dramatic.

Tables 3 and 4 show the progress of the standard deviation comparison as the number of tests increased. At each of the comparison levels, using the "F" test for comparing the differences in variability, the new procedure showed a statistically significant improvement at the 99% confidence level. It is readily apparent that the improvement in the class 30 results were far more dramatic than in the class 40.

Table 3.
Comparison of Class 30 Tensile Variation Before and After Program

Number of Tests	Standard Deviation Before Regression Procedure	Standard Deviation After Regression Procedure	Percent Reduction of Standard Deviation	F	Confidence of Improvement (%)
50	2.09	1.89	9.43	1.22	75.6
75	2.93	2.11	27.95	1.93	99.7
100	2.82	2.08	26.12	1.83	99.9
125	2.70	2.15	20.57	1.58	99.4
1 year	2.70	2.16	20.20	1.57	99.7
	n = 165	n = 142			

Table 4.
Comparison of Class 40 Tensile Variation Before and After Program

Number of Tests	Standard Deviation Before Regression Procedure	Standard Deviation After Regression Procedure	Percent Reduction of Standard Deviation	F	Confidence of Improvement (%)
50	2.33	1.5	35.65	2.41	99.8
75	2.26	1.66	26.63	1.86	99.6
100	2.23	2.09	6.18	1.14	74.2
1 year	2.19	2.1	4.4	1.09	67.0
	n = 106	n = 107			

DISCUSSION OF RESULTS

The reduction in the class 30 variability leaves no doubt that this is a viable system to improve control; however, the reduction of the variability only to the approximate level of the class 40 results before the system, and the minimal improvement in the class 40 after the program was in use, leads to the question of why there wasn't more improvement. Several possible and/or contributing causes for the limited degree of improvement have been developed.

One likely possibility is that the changing copper additions are compensating for the changes in residual elements affecting the amount of pearlite in the matrix. With the amount of copper going into the class 40 iron before this system, the structure was already completely pearlitic; therefore, significant improvement could not be expected.

On the class 40, with the amount of copper being added, the total copper is raised to a point where it is on the flatter part of the alloy factor curve.[2] Thus, large changes in copper would have to be made, in order to make significant changes in the tensile results.

Another weakness in the plan was that there was no opportunity to compensate when the class 30 iron was giving higher tensile results than expected. By adding the copper, we could compensate for the times when the iron was weaker than normal; however, once all the copper had been removed, no further compensation could be made if the iron was stronger than desired.

FUTURE WORK

As of the writing of this paper, three modifications to this program are being tested to see if further reductions in variability can be obtained. They are:

1. For the class 40 iron, the controlling variable is being changed from copper to molybdenum.
2. For the class 30 iron, when the iron is stronger than desired and no copper addition is being made, a partial replacement of the 75% inoculating-grade ferrosilicon with a titanium-bearing inoculant is being calculated.
3. The number of data sets used in the regression analysis is being reduced from 25 to 15, and replacement of data will now take place with each new data point instead of dropping ten points at a time.

CONCLUSION

It can be concluded that a system involving recursive multiple regression analysis can be an effective tool in reducing variability. The effectiveness of the tool is controlled by the accuracy of the data, the degree to which the variables selected for analysis control the variable being controlled, and the completeness of the design of the control system.

ACKNOWLEDGMENT

While this paper could not have been prepared without the help of many people, the author would like to specially acknowledge the help of K. McCollough of Seneca Foundry. Without his willingness to allow this untried system to be used in his foundry, the system would never have been more than an untested theory.

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2. Bates, C.E.; "Alloying Elements Effects on Gray Iron Properties: Part II," *AFS Transactions,* 1986, pp 889-912.