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CORRELATION BETWEEN FRACTURE TOUGHNESS, CHARPY V-NOTCH IMPACT ENERGY, AND YIELD STRENGTH FOR ASTM A723 STEEL

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13. ABSTRACT *(Maximum 200 words)*
A large quantity of data for ASTM A723 steel correlating yield strength, Charpy impact energy, and fracture toughness has been compared with the Rolfe-Novak-Barsom correlation. The general conclusion is that this correlation is conservative, because if we estimate fracture toughness from Charpy impact energy measurements, the estimated toughness is less than the measured value. The data may be somewhat questionable, however, because the fracture toughness and Charpy impact energy measurements were taken at different temperatures. The results indicate that for correlation purposes, the Rolfe-Novak-Barsom relationship is an adequate estimate of fracture toughness based on Charpy impact energy and yield strength measurements.

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INTRODUCTION

The Special Working Group on High Pressure Vessels of the Pressure Vessel and Piping Division of ASME is writing a design code for high pressure vessels. Many of the design methods to be codified rely on a fracture mechanics analysis and fracture toughness properties. It is often difficult and expensive to obtain valid fracture toughness properties from vessel forgings. The historical approach to fracture toughness measurement has been to conduct Charpy impact energy tests. There have been many empirical correlations developed over the years to determine fracture toughness from Charpy impact energy. The most famous is the upper shelf correlation of Rolfe, Novak, and Barsom (refs 1,2).

The Rolfe-Novak-Barsom correlation was developed based on the analysis of numerous experimental measurements of fracture toughness and Charpy impact energy for many steels of different composition and strength. It was found that there is a linear relationship between the square of the toughness-to-yield strength ratio and the impact energy-to-yield strength ratio. This means that if the yield strength and upper shelf Charpy V-notch impact energy are known, then the fracture toughness can be determined.

The equation of the straight line that fits the data was determined from the data available to the developers of the correlation. At that time, there was no significant data base for the toughness of ASTM A723 steel--the steel most commonly used to manufacture high pressure vessels. The purpose of this report is to determine if the Rolfe-Novak-Barsom correlation can be used to estimate the fracture toughness of ASTM A723 steel from upper shelf impact energy and yield strength measurements.

PROCEDURE

The Rolfe-Novak-Barsom upper shelf correlation is given mathematically as

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 5\left[\frac{CVN}{\sigma_y} - 0.05\right] \qquad (1)$$

where σ_y is the yield strength in Ksi, CVN is the Charpy impact energy in ft-lbs, and K_{Ic} is the fracture toughness in Ksi$\sqrt{in}$.

Equation (1) shows that there is a linear relationship between the square of the fracture toughness-to-yield strength ratio and the Charpy impact energy-to-yield strength ratio. To determine the adequacy of Eq. (1) for estimating fracture toughness from impact energy for any material, both the fracture toughness and the Charpy impact energy at various strength levels must be known. From these data, the correlation parameters (ratios) can be determined and then plotted. The measured results are then compared with the values obtained from Eq. (1). An analysis of this comparison will determine whether Eq. (1) is adequate to predict fracture toughness from Charpy impact energy.

Fracture toughness and Charpy impact energy data for ASTM A723 steel were presented in graphical form by Underwood (ref 3). That data, along with additional unpublished results by Thornton (ref 4), are given in tabular form in Table I. The composition of the steels in the table is generally that of ASTM A723. However, the steels consist of various grades of ASTM A723 and have been melted from various refining practices, although there is no bias towards any particular grade or refining practice. The strength range of the data does not encompass the entire range of the strength classes in ASTM A723. Class 1 (100 Ksi minimum yield strength) and Class 2 (120 Ksi minimum yield strength) are not represented, but Classes 2a through 5 are well-covered in the table. There is one thing that biases the results here: fracture toughness and Charpy impact energy measurements were not made at the same temperature. The Charpy impact energy was measured at -40°F, and the fracture toughness was measured at +70°F. The room temperature impact energy could be significantly higher than the low temperature impact energy if the low testing temperature is below the upper shelf minimum temperature. However, experience with this alloy (ref 5) suggests that for the data reported here, the minimum upper shelf temperature should be lower than -40°F.

To determine the adequacy of the Rolfe-Novak-Barsom correlation, the data from Table I are normalized to the appropriate parameters for the correlation and compared with the predicted relationship from Eq. (1). The normalized parameters are the final two columns in the table and the comparison is depicted graphically in Figure 1.

An analysis of the plot shown in Figure 1 shows that Eq. (1) provides an excellent lower bound of the measured data. Virtually all of the data fall above and to the left of the Rolfe-Novak-Barsom correlation. Essentially, none of the data fall below the line described by Eq. (1). Bounding the measured data in this manner means that the Rolfe-Novak-Barsom correlation is conservative. For a given yield strength and Charpy impact energy, the Rolfe-Novak-Barsom correlation predicts a fracture toughness less than that actually measured. This underestimation could be the result of the different testing temperatures.

SUMMARY AND CONCLUSION

A large quantity of data for ASTM A723 steel correlating yield strength, impact energy, and fracture toughness has been compared with the Rolfe-Novak-Barsom correlation. The general conclusion is that this correlation is conservative, because if fracture toughness is estimated from Charpy impact energy measurements, the estimated toughness is less than the actual measured value. The data may be somewhat questionable, however, because the fracture toughness and Charpy impact energy were measured at different temperatures. However, experience with the alloy suggests that both toughness and Charpy impact energy were upper shelf values. Therefore, it is our conclusion that for correlation purposes, the Rolfe-Novak-Barsom relationship is adequate for estimating fracture toughness from Charpy V-notch impact energy and yield strength measurements.

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2. S.T. Rolfe and S.R. Novak, "Review of Developments in Plane-Strain Fracture Toughness Testing," ASTM STP 463, The American Society for Testing and Materials, Philadelphia, PA, 1970, pp. 124-159.
3. J.H. Underwood, Experimental Mechanics. Vol. 18, No. 9, September 1978, pp. 350-355.
4. P.A. Thornton, Private Communication, U.S. Army ARDEC, Benet Laboratories, Watervliet, NY, July 1990.
5. D.P. Kendall, Materials Research and Standards, Vol. 10, No. 12, December 1970.

TABLE I. COMPILATION OF STRENGTH AND TOUGHNESS DATA FOR ASTM A723 PRESSURE VESSEL STEEL*

YS (MPa)	K_{Ic} (MPa$\sqrt{m}$)	CVN (J)	YS (Ksi)	K_{Ic} (Ksi$\sqrt{in.}$)	CVN (ft-lbs)	CVN/YS (ft-lbs/Ksi)	$(K_{Ic}/YS)^2$ (in.)
1090	184	61	158.1	167.5	44.9	0.28	1.12
1090	202	67	158.1	183.8	49.3	0.31	1.35
1090	202	69	158.1	183.8	50.7	0.32	1.35
1110	190	57	161.0	172.9	41.9	0.26	1.15
1110	190	60	161.0	172.9	44.1	0.27	1.15
1110	187	56	161.0	170.2	41.2	0.26	1.12
1110	187	53	161.0	170.2	39.0	0.24	1.12
1170	157	41	169.7	142.9	30.1	0.18	0.71
1170	157	42	169.7	142.9	30.9	0.18	0.71
1170	157	44	169.7	142.9	32.4	0.19	0.71
1170	165	41	169.7	150.2	30.1	0.18	0.78
1170	165	42	169.7	150.2	30.9	0.18	0.78
1170	165	37	169.7	150.2	27.2	0.16	0.78
1170	165	37	169.7	150.2	27.2	0.16	0.78
1210	140	24	175.5	127.4	17.6	0.10	0.53
1210	140	25	175.5	127.4	18.4	0.10	0.53
1210	140	26	175.5	127.4	19.1	0.11	0.53
1210	140	27	175.5	127.4	19.9	0.11	0.53
1210	140	28	175.5	127.4	20.6	0.12	0.53
1210	140	29	175.5	127.4	21.3	0.12	0.53
1210	166	31	175.5	151.1	22.8	0.13	0.74
1210	166	32	175.5	151.1	23.5	0.13	0.74
1210	166	33	175.5	151.1	24.3	0.14	0.74
1210	166	35	175.5	151.1	25.7	0.15	0.74
1210	166	37	175.5	151.1	27.2	0.16	0.74
1280	126	25	185.7	114.7	18.4	0.10	0.38
1280	126	30	185.7	114.7	22.1	0.12	0.38
1280	126	34	185.7	114.7	25.0	0.13	0.38
1280	126	24	185.7	114.7	17.6	0.10	0.38
1280	126	33	185.7	114.7	24.3	0.13	0.38
1280	126	29	185.7	114.7	21.3	0.11	0.38
1280	146	25	185.7	132.9	18.4	0.10	0.51
1280	146	30	185.7	132.9	22.1	0.12	0.51
1280	146	34	185.7	132.9	25.0	0.13	0.51
1280	146	24	185.7	132.9	17.6	0.10	0.51
1280	146	33	185.7	132.9	24.3	0.13	0.51
1280	146	29	185.7	132.9	21.3	0.11	0.51
1340	122	23	194.4	111.0	16.9	0.09	0.33
1340	122	25	194.4	111.0	18.4	0.09	0.33
1340	122	27	194.4	111.0	19.9	0.10	0.33
1340	122	28	194.4	111.0	20.6	0.11	0.33
1340	131	23	194.4	119.2	16.9	0.09	0.38
1340	131	25	194.4	119.2	18.4	0.09	0.38

*References 3 and 4

TABLE I. CONT'D

YS (MPa)	K_{Ic} (MPa$\sqrt{m}$)	CVN (J)	YS (Ksi)	K_{Ic} (Ksi$\sqrt{in.}$)	CVN (ft-lbs)	CVN/YS (ft-lbs/Ksi)	$(K_{Ic}/YS)^2$ (in.)
1340	131	27	194.4	119.2	19.9	0.10	0.38
1340	131	28	194.4	119.2	20.6	0.11	0.38
1198	160	29	173.8	146.0	21.1	0.12	0.71
1190	163	29	172.6	148.0	21.5	0.12	0.74
1198	166	28	173.8	151.0	20.5	0.12	0.75
1033	231	80	149.8	210.0	58.8	0.39	1.97
1033	229	83	149.8	208.0	61.2	0.41	1.93
1033	237	82	149.8	216.0	60.0	0.40	2.08
896	275	106	130.0	250.0	78.0	0.60	3.70
898	275	107	130.3	250.0	78.8	0.60	3.68
898	266	106	130.3	242.0	78.0	0.60	3.45

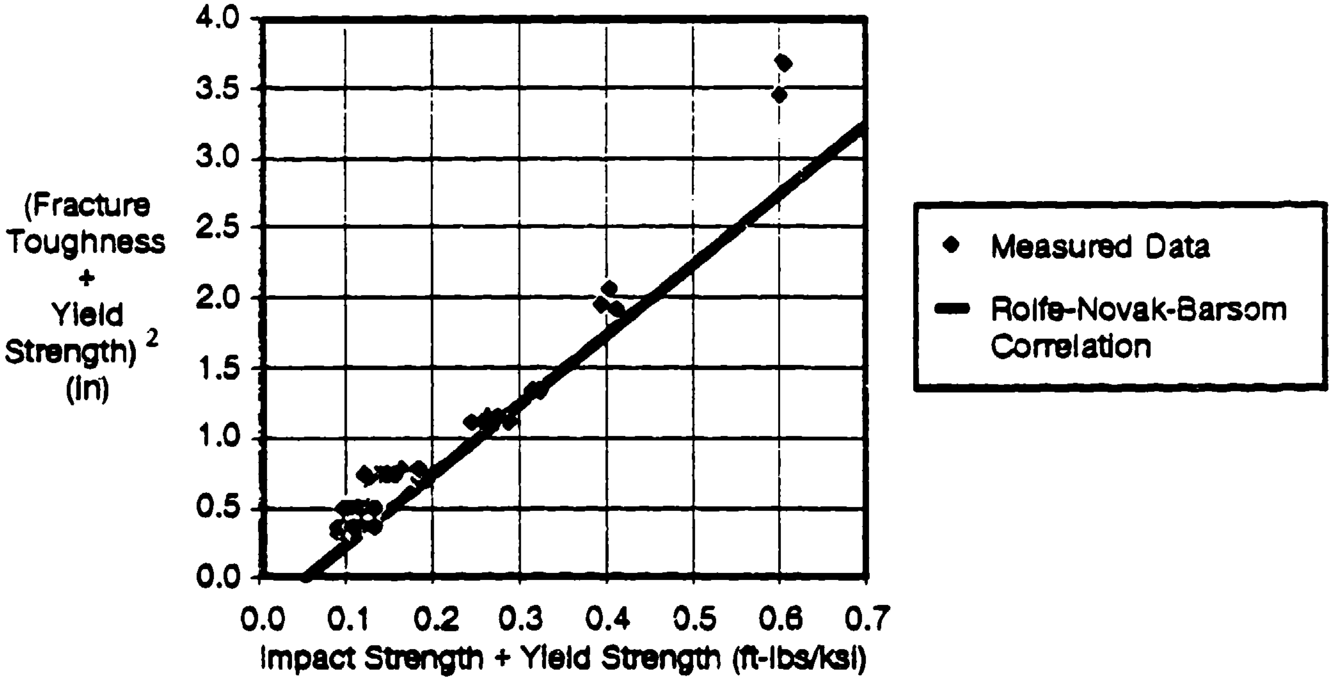

Figure 1. Comparison of measured Charpy impact and fracture toughness correlation with the Rolfe-Novak-Barsom correlation for ASTM A723 pressure vessel steel.

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