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$T_0 - T_{28J}$ correlation of low-carbon ultra-high-strength quenched steels

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Abstract

Direct-quenched structural steels are a cost-effective ultra-high-strength solution for demanding applications. These untempered, mainly S900 and S960 grade steels can possess good impact toughness and weldability when they contain low carbon contents and have low carbon equivalents. However, it is reported that as regards brittle fracture toughness these steels do not follow the commonly used correlation between the Charpy-V impact toughness transition temperature T_{28J} and the fracture toughness reference temperature T_0, i.e. $T_0 = T_{28J}$ - 18 °C. These T_0 estimates are on the unconservative side, so there is a risk of overestimating the brittle fracture toughness of these steels in structural design when relying solely on impact toughness transition temperature values. In this study, the correlation between T_0 and T_{28J} temperatures of low-carbon ultra-high-strength martensitic and martensitic-bainitic steels in the quenched state is analyzed. In total, 78 new and re-analyzed data sets are reported i.e. data for 39 steels tested in both longitudinal and transverse orientations. These data sets are then evaluated using the procedures found in the literature. A recently updated $T_0 - T_{28J}$ correlation is tested and it is shown that it gives less unconservative estimates of T_0 by including the effects of yield strength and upper shelf energy. Finally a new correlation between T_0 and T_{28J} for as-quenched low-carbon steels is proposed, i.e. $T_0 = 0.8*T_{28J} + 14$ °C.

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Keywords: quenched martensite; fracture toughness; DBTT; T_0; T_{28J}

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1. Introduction

Low-carbon, low-alloyed direct-quenched steels can possess a good combination of strength, toughness and formability without tempering (Hemmilä et al. (2005), Kaijalainen et al. (2013)). The aforementioned type of steels is typically used in lightweight mobile structures like containers as well as booms, arms and other structural members of mobile lifting equipment. It is expected that the importance of direct quenching as a production method and direct-quenched steels in structural applications will increase in the future.

For safe structural design of the steel against the brittle fracture, a knowledge of fracture toughness behaviour is essential. To promote this and to reduce the number of needed fracture toughness tests, empirical correlations have been established to indirectly estimate fracture toughness from impact toughness tests results. Wallin (1989) has introduced a well established correlation, Eq. (1), between the Charpy-V impact toughness transition temperature T_{28J} and the fracture toughness reference temperature T_0, for ferritic steels, defined in ASTM E1921 (1997) This is now used in the European standard EN 1993-1-10 (2005) and in the structural integrity procedures of FITNET (2008) and SINTAP (1999).

However, it has been reported by Nevasmaa et al. (2010) and Kaijalainen et al. (2013) that some ultra-high-strength, low-carbon steels, produced by TMCP-DQ do not follow the above-mentioned correlation. One logical reason for this could be that the correlation of Eq. (1) was based on nuclear pressure vessel steels of lower yield strength and different microstructure compared to these relatively new direct-quenched steels. Therefore it is perhaps not surprising that the Eq. (1) is not suitable for estimating the T_0 of as-quenched steels. Wallin (2011) has proposed an updated correlation, which also includes the factors yield strength (YS) and upper shelf energy (US). For SE(B) specimens, it has a form of Eq. (2) and its applicability to the steels studied has been tested. This paper will show that a new correlation is required in the case of ultra-high-strength as-quenched steels.

$$T_{0-Est.1} = T_{28J} - 18°C,\ \sigma \pm 15°C \tag{1}$$

$$T_{0-Est.2} = T_{28J} - 87°\mathrm{C} + \frac{YS}{12MPa \cdot {}^{\circ}C^{-1}} + \frac{1000J \cdot {}^{\circ}C}{US},\ \sigma \pm 18 \tag{2}$$

2. Experimental

39 steels from six different alloy grades, covering the chemical composition range shown in Table 1, have been studied. Tested materials included samples from pilot scale direct quenching trials, normal direct quenching production as well as laboratory cast, rolled and quenched materials. Of the 39 steels, 10 were S900, 26 were S960 and 3 were S1100 grade steels. 29 were direct quenched and 10 reheated and quenched. The microstructures of the steels consist of mainly auto-tempered and untempered lath martensite and in some cases bainite was also present. All the steels are tested in the as-quenched (untempered) state. Both longitudinal (LT) and transverse (TL) samples were studied giving a total of 78 different data sets.

Table 1. Range of chemical compositions studied.

Weight %	C	Si	Mn	Cr	Mo	Ti	B	Ni	P	S	N
Min	0.08	0.18	0.7	0.7	0	0	0	0	0.001	0.000	0.000
Max	0.15	0.26	1.2	1.2	0.2	0.03	0.003	4.1	0.011	0.005	0.009

Charpy-V notch impact testing according to EN 10045-1 (1990) and EN ISO 148-1 (2010) has been used to determine the transition temperature T_{28J} and the upper shelf energy. Tests have been performed at various temperatures, typically between +20 °C and -100 °C, using LT and TL oriented sub-sized and full-sized specimens with thicknesses from 3.5 to 10 mm. Tanh-fitting of Eq. (3), introduced by Oldfield (1975) and the procedure described by e.g. EricksonKirk et al. (2009) has been used to obtain the transition curves of all the tested steels. Sub-size 35 J/cm^2 transition temperatures were converted to their equivalent full-size T_{28J} values using the procedure of Wallin (1986). Sub-size US values are converted to their full-size equivalents (US_{10mm}) using Eq. (4), which is the conservative form of the equation given by Wallin (2001) with the factor 1.09 (B is specimen thickness).

Fracture toughness tests have been performed in two different laboratories according to the standard ASTM E1921 (2005) in order to determine the reference temperature T_0 (thickness corrected to 1T results where K_{Jc} = 100 MPa√m) using 4 - 10 mm thick SE(B) specimens. Four of the steels were tested with side grooves of 10 % reduction in thickness in one of the laboratories.

Tensile tests have been performed in accordance with standards EN 10002-1 (2002) and EN ISO 6892-1 (2009) at room temperature using rectangular 6 - 12,5 mm thick specimens in longitudinal and transverse directions relative to the rolling direction.

$$Y = A + B \cdot \tanh\left\{\frac{T - T_0}{C}\right\} \tag{3}$$

$$\frac{US_B \cdot 10}{US_{10mm} \cdot B} = 1.09 - \frac{0.5 \cdot \exp\left(\frac{2 \cdot (US_{10mm} / B - 44.7)}{17.3}\right)}{1 + \exp\left(\frac{2 \cdot (US_{10mm} / B - 44.7)}{17.3}\right)} \tag{4}$$

3. Results & Discussion

3.1. Mechanical test results

Test results are summarized in Table 2. The values of T_{28J} are always lower than T_0, on average by 28 °C. US_{10mm} values have the widest scatter, but the majority of the values are in the range 50 - 250 J. US_{10mm} values calculated by Eq. (4) are on average 18 J higher than values calculated simply on the basis of the ligament area. Overall, calculated US_{10mm} values show good agreement with the results of Wallin (2001). From the selected metrics, no conclusions could be made that a steel with lower yield strength would be tougher or have lower transition temperature values.

T_0 estimates based on Eqs (1) and (2), i.e. $T_{0\text{-Est.1}}$ and $T_{0\text{-Est.2}}$, are presented in Fig. 1. The data does not follow the correlation of Eq. (1); slopes differ, measured temperature values are on the unconservative side and $T_{0\text{-Est.1}}$ clearly overestimates the fracture toughness reference temperature T_0, even when conservative upper bound estimate of Eq. (1) is used. It is apparent, however, that there is a linear trend between the measured transition temperatures T_0 and T_{28J}. Values of $T_{0\text{-Est.2}}$ do come closer to the measured values of T_0 but they still remain unconservative. Slopes differ less than with $T_{0\text{-Est.1}}$ and the 6 % difference in slopes must be due to the effects of yield strength and upper shelf energy.

Figure 2 shows how much of the difference between T_0 and T_{28J} can be explained with yield strength or upper shelf energy. There is a slight trend between yield strength and the difference between the transition temperatures and coefficient is approximately the same $^1/_{12}$ as that of Eq. (2). No connection between yield strength and transition temperature T_0 itself was found. As regards upper shelf energy, no conclusions about its effect on T_0-T_{28J} or T_0 can be made with this data.

Table 2. Mechanical test results.

N = 78	T_{28J} [°C]	T_0 [°C]	US_{10mm} [J]	YS [MPa]
Average	-61	-33	156	1028
Median	-52	-27	127	1008
[min, max]	[-175, 0]	[-132, 21]	[48, 600]	[893, 1250]
Standard deviation	32.6	27.8	105.2	74

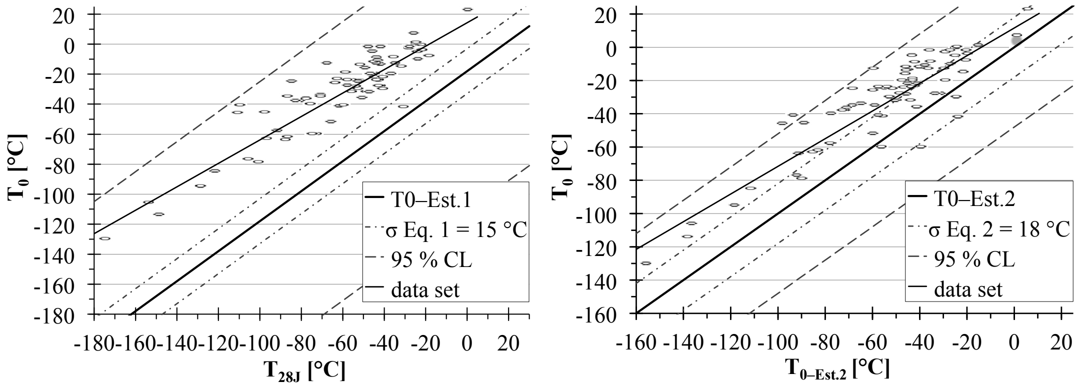

Fig. 1. (a) $T_0 - T_{28J}$ correlation; (b) $T_0 - T_{0\text{–Est.2}}$ correlation.

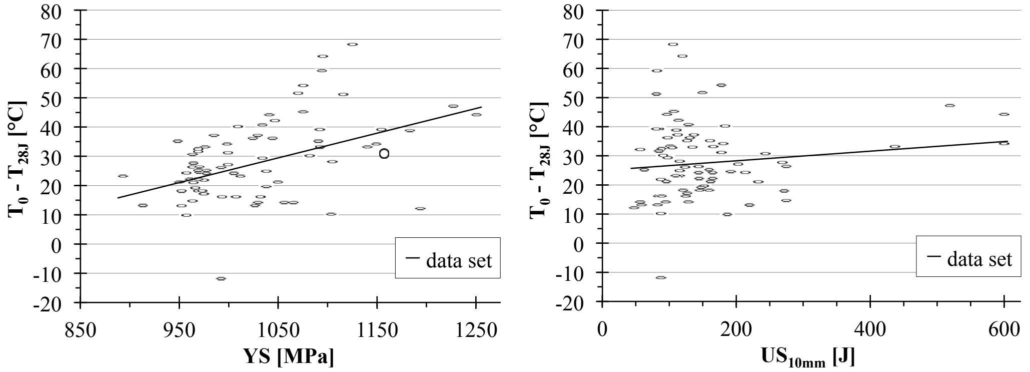

Fig. 2. The effect of (a) yield strength and (b) upper shelf toughness to the difference between the T_0 and the T_{28J} temperatures.

3.2. Statistical Analysis

As the two presented empirical correlations overestimate the level of T_0 of low-carbon as-quenched steels, further analysis was needed. A linear trend was noted in Fig. 1. (a), so a simple linear regression analysis was utilized and the results are presented in Table 3. The significance of strength class, specimen orientation, specimen thickness and side grooves was also tested, but apart from side grooves, they showed no correlation with T_0. Side grooves and/or inter-laboratory differences increase T_0 by 16 °C on average. Because of the uncertainty regarding how much of the difference is due to side grooves and how much to inter-laboratory differences, this effect was not considered in the following analysis.

Adjusted R^2 values of $T_{0\text{-Est.1}}$ and $T_{0\text{-Est.2}}$ indicate, that the data does not fit with the estimates. $T_{0\text{-Est.1}}$ has also substantial root-mean-square error (RMSE) of 47.5 °C. That error is halved by using $T_{0\text{-Est.2}}$. Both estimates have significantly larger scatter than that associated with equations (1) and (2).

Table 3. Comparison of the regression models.

Regression [°C]	Adjusted R^2	RMSE [°C]	Confidence limit [°C]
T0-Est.1	0.00	47.5	± 93
T0-Est.2	0.21	24.4	± 48
#1 0.8 * T_{28J} + 14	0.83	11.3	± 22
#2 0.8 * T_{28J} + 0.04 * YS - 23	0.84	11.2	± 22
#3 0.8 * T_{28J} + 0.04 * YS - 0.02 * US_{10mm} - 19	0.84	11.1	± 22

Regression models #1 to #3 are calculated with the whole data set (N = 78); #1 has the simplest form with predictor T_{28J}, while #2 also includes the effect of yield strength and #3 the effects of yield strength and upper shelf energy. Again the error is halved when the regressions are made in this way.

Comparing the three new regression models, it is seen that adding predictors YS and US does not raise adj. R^2 nor reduce the error significantly. Equally importantly, T_{28J} is the only predictor that maintains its t-test significance at p = 0.000 while its 95 % confidence limits vary between 0.7 and 0.9. Yield strength has confidence interval [0.00, 0.08] and p = 0.083 in regression equation #2 and 0.104 in #3. The confidence interval for upper shelf energy confidence interval is [-0.05, 0.10] and p = 0.163. The constant, or intercept, significance drops from p = 0.000 in #1 to 0.290 in #2 and 0.373 in #3. A bit surprisingly, the simplest model fits the data as well as the extended versions and turned out to be the most valid. The addition of YS or YS and US is questionable (at $\alpha = 0.05$), as it produced more outliers and did not improve the estimates of T_0 within this data set.

It was of interest to find out if the regression model #1 gives statistically significant equal estimates of the reference temperature T_0. The non-parametric Mann-Whitney 2-sample rank test, or Mann-Whitney U-test, developed by Mann and Whitney (1947) was chosen as the data set was proven to have a non-normal distribution using the Anderson-Darling normality test (Table 4). The Mann-Whitney test is a non-parametric alternative to the 2-sample t-test of normal distributions, that performs a hypothesis test of the equality of two populations, i.e. that does a particular population tend to have larger values than the other. It assumes equal variances, so that was tested with Levene's test. $T_{0\text{-Est.2}}$ and regression model #1 fulfil this condition with p = 0.283 and 0.771, respectively. The median of model #1 comes closest to the median of T_0 results with only 4 % difference.

The test result of equality of the population medians with T_0 was that the null hypothesis was rejected with $T_{0\text{-Est.1}}$ and $T_{0\text{-Est.2}}$ (p = 0.000) but model #1 had very significant p = 0.660, indicating that it produces equal estimates of with the measured T_0 values. Thus, for low-carbon ultra-high-strength quenched steels, a correlation between the Charpy-V impact toughness transition temperature T_{28J} and the fracture toughness reference temperature T_0 that has a form of Eq. (5) with a RMSE of 11 °C is proposed. Results calculated with Eq. (5) and comparison between the T_0 estimates error terms are presented in Fig. 3.

Further studies are still needed to identify the metallurgical factors affecting the relationship between the T_0 and T_{28J} in as-quenched steels. One possible explanation can be the much higher minimum stress-intensity factor K_{min} values obtained by Zhang and Knott (2000) for homogeneous autotempered or untempered lath martensite compared to the used standard value $K_{min} = 20\ \text{MPa}\sqrt{\text{m}}$. This would need a correction to the standard Master Curve procedure. Also Neimitz et al. (2012) have verified that the fracture toughness behaviour of a untempered quenched steel can be anomalous. They proposed a higher critical level of 167 MPa√m without a thickness correction for defining the reference temperature T_0.

Table 4. Statistical comparison of models.

	Normality, p-value	Equal variances with T0, p-value	Median	Mann-Whitney point estimate	Equal populations with T0, p-value
T0-Est.1	< 0.005	0.004	-70	8463.5	0.000
T0-Est.2	< 0.005	0.283	-46	7527.0	0.000
0.8 * T28J + 14	< 0.005	0.771	-28	6247.5	0.660
T28J	< 0.005	0.004	-52	7822.5	0.000
T0	< 0.005	-	-27	-	-

$$T_0 \approx 0.8 \cdot T_{28J} + 14°C,\ \ \sigma \pm 11°C \tag{5}$$

4. Conclusions

The correlation between the impact and fracture toughness transition temperatures of low-carbon ultra-high-strength quenched steels has been studied. Reported empirical correlations between the transition temperatures T_0 and T_{28J}, have been demonstrated to be inadequate for these as-quenched steels. This is not unreasonable, as they were not established on the basis of this type of steel. A simple new correlation of Eq. (5) for the studied kind of as-quenched steels is proposed.

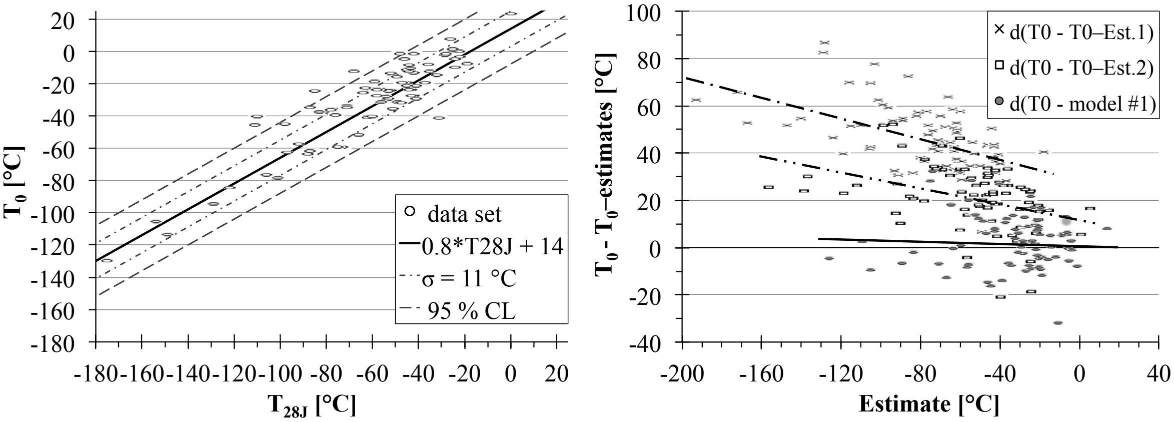

Fig. 3. (a) Correlation between T0 and T28J for the low-carbon as-quenched steels; (b) Error terms of the three studied estimates studied.

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