Local Approach Treatise of High Y/T - Ratio Steels in the Ductile-to-Brittle Transition Region

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ABSTRACT. The full utilization of high strength steels, particularly modern thermomechanically processed steels (TMCPs), is usually hindered not by material properties, but rather by inadequate design procedures. In many cases the inadequacy is perceived as lack of suitable assessment methods or more commonly, their scope has not been defined with respect to high strength steels of this type. Current study focuses on these aspects with respect to fracture toughness based measures of material performance in relation to material strength.

In the current work ductile to brittle transition regime is treated by focusing on Master Curve toughness description of fracture toughness. The general effects of Y/T ratio to material toughness are modeled using local approach methods. The results of numerical simulations demonstrate that the high Y/T ratio does not need to translate to low toughness performance either with respect to the transition regime nor the upper shelf but that the toughness characteristics are more so controlled by microstructural features affecting failure micromechanisms, and that transition region criteria are not to be presented solely on the basis of indirect measures, such as tensile properties. In the current study, the transition region properties of a high Y/T ratio S460ML TMCP steel are found to be superior in comparison to conventional S355J2G3 steel, which is being used as a reference.

INTRODUCTION

High strength fine-grained low-impurity structural steels with excellent strength, ductility, formability, toughness and weldability are penalized by existing design rules due to their high yield to tensile strength (Y/T) ratio. This makes their use far less attractive and even uneconomic when compared to traditional low-strength steels with limited toughness and weldability.

Pressure vessel applications are limited when the Y/T ratio exceeds approximately 0.63, while for current thermomechanical (TM) steels the Y/T ratios are usually within 0.75 to 0.85. Works(1,2) have focused on the handicaps of current design requirements by illustrating the comparable, and in many cases superior, properties of modern TM steels in comparison to low strength C-Mn steels. These studies have presented that the Y/T ratio or tensile and impact energy properties can not be taken as general measures to which solely establish design criteria and guidelines, and that such measures only hinder the innovative and optimized use of these high strength and toughness TM steels.

EXPERIMENTAL METHODS AND RESULTS

The materials of the current study were conventional S355J2G3 grade steel and S460ML type TMCP steel. The materials were subjected to differing degrees of cold forming and artificial aging and the tensile and fracture properties were determined. The cold reduction degrees were 5%, 10% and 15% and to study embrittlement effects to fracture toughness an aging treatment (450°C for 0.5 hours) was combined to 10% cold reduction. The S355J2G3 and S460ML steels were subjected to identical treatments, and as such the S355J2G3 steel behaves as a "conventional" steel as a reference for the "modern" S460ML steel to illustrate the effects of cold reduction and thermal aging to tensile and fracture toughness properties. The results of current work are presented in more detail in [1,2].

The experimental fracture toughness results were attained by using single-edge notched bend (SENB) type specimens. The specimens were of full thickness with a cross section of 20×40 mm^2 (b_0=initial specimen ligament).

The Master Curve analysis followed in principle the ASTM Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range (E1921-97)[3].

The tensile properties and Y/T-ratios for differing mechanical and thermal treatments are presented in Table 1.

Table 1: Mechanical properties of S460ML and S355J2G3 steels at ambient temperature in as-delivered, cold worked and artificially aged conditions. Further details in [1,2].

Condition / Steel	*σ_0, $R_{p0.2}$ [MPa]*	*R_m [MPa]*	*Y/T*
S460ML	*446*	*539*	*0.83*
S460ML, 15%	*547*	*611*	*0.90*
S460ML, 10%, aged	*599*	*648*	*0.92*
S355J2G3	*353*	*542*	*0.65*
S355J2G3, 15%	*482*	*607*	*0.79*
S355J2G3, 10%, aged	*541*	*653*	*0.83*

The results of Master Curve analyses are presented in Figs. 1 and 2 for the S460ML and S355J2G3 steels, respectively. In general, both materials can be stated to possess low reference temperature values, S460ML having a value of -119°C and S355J2G3 -69°C. The upper shelf toughnesses of the two steels are seen to differ, the S460ML having approximately 30% higher initiation toughness than S355J2G3. The transition region response of the two steels differs considerably with respect to cold reduction and artificial aging. 15% reduction in S460ML brings about an increase of 19°C in reference temperature, while for S355J2G3 the increase is 79°C. Also, the aging treatment is seen to affect S355J2G3 in quite an adverse manner, the reference temperature attaining a value of 20°C, while for the S460ML TM steel the reference temperature after identical treatment is still -77°C.

NUMERICAL METHODS AND RESULTS

Numerical simulations were carried out for various Y/T ratios on the basis of determined mechanical properties to describe the transition and upper shelf behavior of the two principally differing grades. The computations were carried out to highlight the effects of differing Y/T ratios. Local approach methodologies of Beremin (m=shape parameter, σ_u=scale parameter) and modified Gurson model were utilized using the WARP3D research code. The details of the computational routines, material modeling and crack propagation analyses are presented in [4,5,6].

The cleavage crack driving stress, the Weibull stress σ_w, is presented in Figs. 3 and 4 at the lower parts of the transition region for both steels for differing values of the Weibull shape parameter as a function of crack driving force, expressed by the stress intensity factor, K.

The results of Figs 3 and 4 illustrate that as a function of crack driving force at fixed temperature the cleavage crack initiation pursuing stress is most dependent on the actual Y/T ratio, but while the higher Y/T values do increase in the values of the stress peak the absolute differences are relatively minor. For conditions involving plasticity the simultaneous decrease of strain hardening attenuates the differences further by limiting the crack driving force elevation from ductile crack initiation. These effects are given in terms of cumulative failure probability in Fig. 5.

The cumulative failure probability values with material independent scale parameters illustrate direct effects to fracture toughness due to the mechanical property and Y/T ratio differences. The relative selection of scale parameters, on the other hand, better describes material specific behavior, since the damage rates and scale parameters are strongly affected by both temperature and material microstructure. The increase in Weibull stress is seen in the failure probabilities of the higher Y/T ratio steels. This is always the case unless the loading level is so high that plasticity and lower hardening characteristics begin to decrease the failure probability for a fixed value of the scale parameter. In such cases higher Y/T ratios can produce lower failure probabilities than low Y/T simulations. The differences when comparing the S355J2G3 and S460ML sets at fixed temperatures are to great extent within the scatter of fracture toughness results and median fracture toughness differences associated to Y/T related increase in near crack tip stress fields range from 5% to 30%.

The foremost notion from the results of Fig. 5 is that for the highest Y/T ratios the near crack tip stresses are not elevated for increasing crack driving force in a similar magnitude as for those experienced by the S355J2G3 steel in different conditions. This can also be taken as a measure of steepness of the toughness transition curve, since particularly the upper parts of the regime are affected. Selecting the Weibull scale parameter relative to flow properties implies that the underlying failure mechanisms would not be affected by the mechanical or thermal treatments, which forthcoming raise the Y/T ratio.

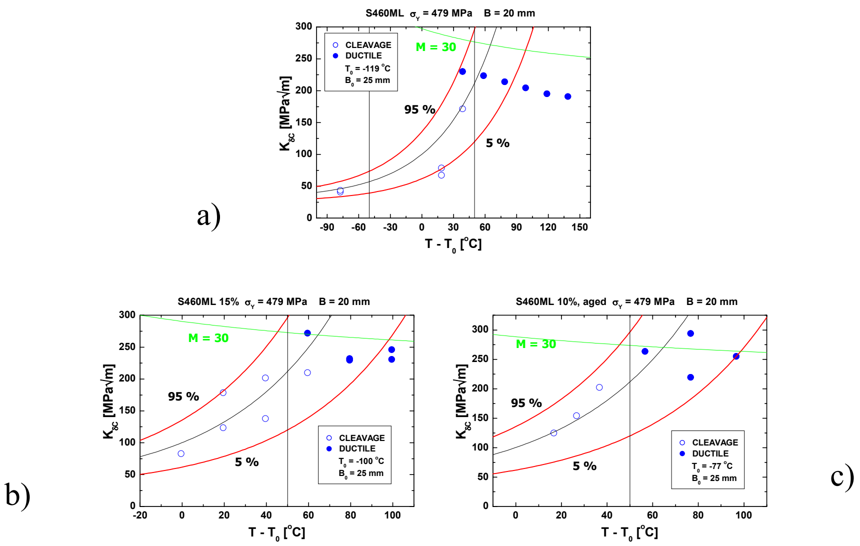


Figure 1: Results of Master Curve analyses of transition region fracture behavior for S460ML TM steel. a) As-delivered, b) 15% cold reduction and c) 10% cold reduction and artificial aging at 450°C.

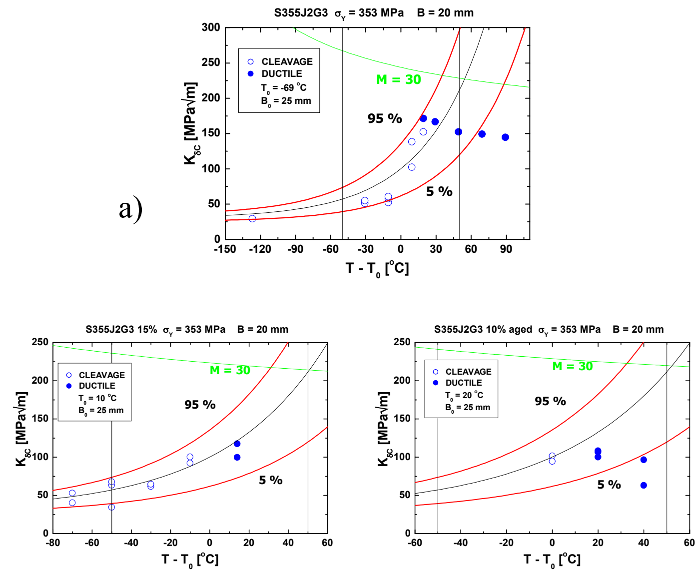
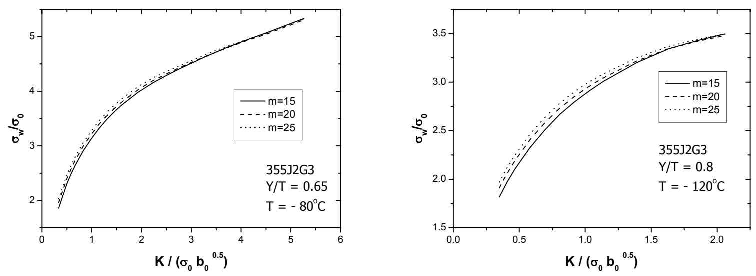
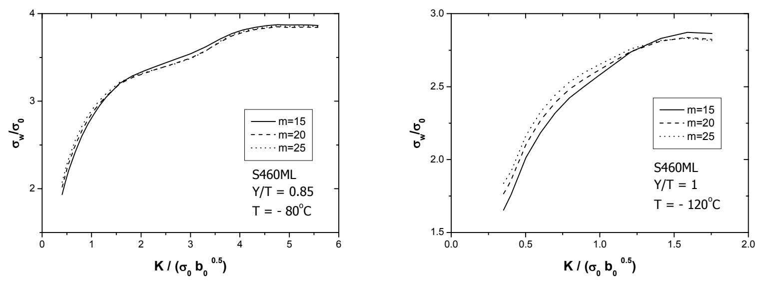


Figure 2: Results of Master Curve analyses for S355J2G3 steel. a) As-delivered, b) 15% cold reduction and c) 10% cold reduction and artificial aging at 450°C.

a) 

b)

Figure 3: Weibull stress for the S355J2G3 steel. a) Y/T=0.65, -80°C and b) Y/T=0.8, -120°C.

a) 

b)

Figure 4: Weibull stress for the S460ML steel.a) Y/T=0.85, -80°C and b) Y/T=1, -120°C.

The results of Fig. 5 can be used to compare the characteristics of S355J2G3 and S460ML steels, in which case different scale parameter levels can be taken as measures of material performance. Such comparisons produce values of median toughness that can be considered to lie within the ranges of experimentally noted differences between the two different steels, since the rate of damage and as such the shape parameter of the toughness distributions are expected to be quite close to each other for both steels. The results of Fig. 5 also indicate the obvious, that deterioration of microstructural properties resulting from e.g. cold reduction, can be inferred for the toughness decreases observed experimentally. Likewise, it also states that the Y/T ratio per se is not responsible for the toughness decrease and the mechanical property changes do not lead to near crack tip stress fields that would impede the attainment of decent fracture toughness values in the ductile to brittle transition region.

DISCUSSION

The experimental results presented the superior properties of S460ML type TM steel in various conditions when compared to a conventional relatively high strength S355J2G3 type steel. The as-delivered materials had both low transition temperatures, but any form of treatment lead to a drastic increase of transition temperature in the S355J2G3 in relation to the S460ML steel.

The numerical simulation results indicated that the sole increase of Y/T ratio would be able to introduce toughness decreases of the order of 5 to 30 percent, as originating from increase of near crack tip Weibull stress. This, however, was not in accordance with the experimental findings. As such, the features responsible for material performance for the current type of TM steel in the transition region that rank first are micromechanical features affected by microstructural properties of the steel in question, which are then reflected in its behavior under different thermal treatments and degrees of cold reduction. As such, the use of Y/T ratio to imply lowest operational temperatures or other measures of performance does not bear any direct insight into failure behavior of a certain steel, and Y/T ratio based design regulations or deterrents to use such modern steels, provide only crude guidelines rather than estimates based on quantitative material properties.

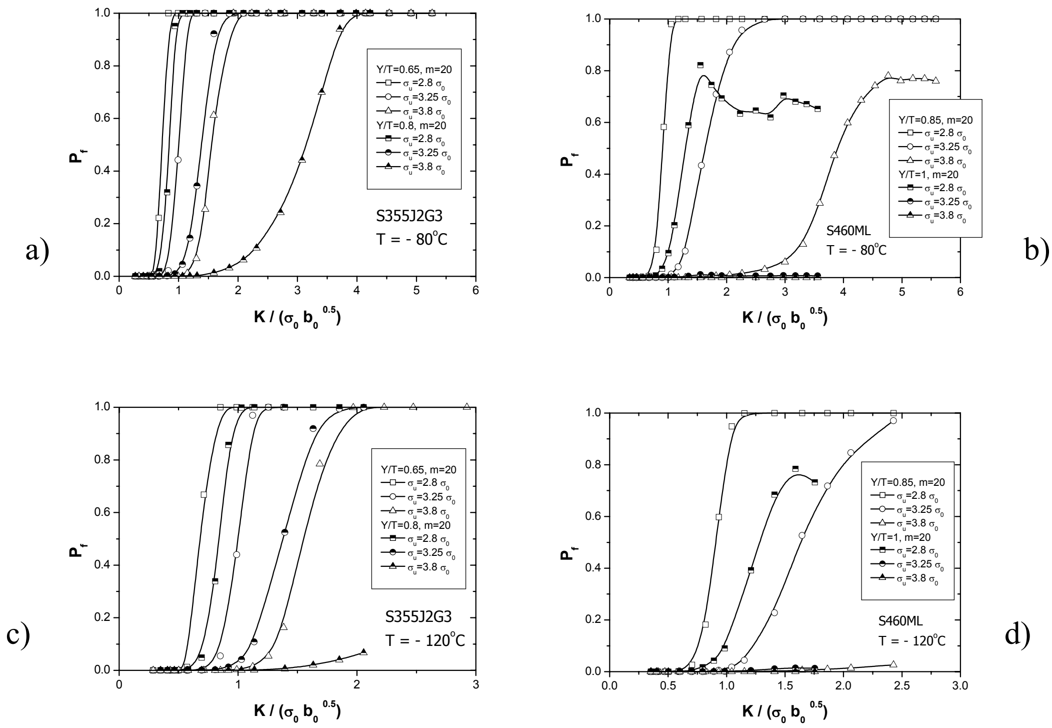


Figure 5: Failure probabilities for yield strength tied Weibull scale parameter values. a) S355J2G3, -80°C, b) S460ML, -80°C, c) S355J2G3, -120°C and d) S460ML -120°C.

When considering the use of relative and different values of the Weibull scale parameter within the numerical simulations, the differences in the fracture toughness behavior can be interpreted quantitatively. Since this is related to the probability distribution and its underlying properties, one is considering material microstructure related effects to cleavage initiation rather than consequences of high Y/T ratio.

The failure mechanism in which the behavior of steels characterized by a high Y/T ratio can be deficient is ductile crack propagation. Such lower fracture resistance conditions can occur if the increase of Y/T ratio is attained in such a fashion that the loss in strain hardening capabilities is not compensated by improved microstructural properties, such as impurity content, that can counter the adverse effects of decreased strain hardening to ductile fracture resistance.

CONCLUSIONS

The results of the work can be concluded as follows:

- ✓ The as-delivered reference temperature of the S460ML steel was lower than that of S355J2G3 by approximately 50°C. The effects of cold forming and artificial aging were far graver for the S355J2G3 steel than S460ML, and increases of reference temperature approximately 90°C were found, while in the S460ML the increase was approximately 42°C.
- ✓ The mechanism able to produce lower fracture resistances in high Y/T ratio modern steels than in steels with lower Y/T ratio is ductile rupture due to decreases in strain hardening capabilities, if effects such as improved impurity content are not considered.
- ✓ The increases of local near crack tip cleavage driving stresses from Y/T ratio were not in agreement with experimental findings. A comparison to experimental results indicated that the increase in near crack tip stress state due solely from elevated yield strength is not by far the measure to be used in judging material performance for the current TM steel, but rather micromechanical basis must be sought for the local approach parameters to attain consistent results. This implies that features of these types of modern steels exceed those of conventional steels by far, even though they possess higher Y/T ratios.
- ✓ The Y/T ratio and related design measures are only secondary in presenting limitations for use of modern high strength steels at temperatures where cleavage can pose integrity threats, and correlate only in a second order sense with fracture toughness.

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