CHAPTER 3

The notch toughness of welded 3CR12

3.1 Introduction

Steels with 11% to 12%Cr conventionally have predominantly martensitic structures, and require preheating in order to prevent hydrogen cracking during welding. The welded joints may also require post-weld heat treatment in order to temper the transformed weld area and to improve the toughness of the joints[1].

During welding, the high temperature heat affected zone (as discussed in Chapter 2) in 3CR12 is heated into the delta ferrite phase region on the iron-chromium phase diagram[2]. The structure consequently transforms to δ -ferrite and massive ferrite grain growth occurs (even at low heat inputs), which can cause a major loss of toughness in the weld area[1].

In spite of the above-mentioned problems, in-service brittle failures have been infrequent in welded 3CR12 components. There are a number of possible explanations as to why brittle failure in welded 3CR12 is not experienced regularly. In the first place, most commercial applications for 3CR12 employ section thicknesses of 5mm or less[3], and therefore the through-thickness constraint is low. In the second instance, the grain growth region is narrow and is surrounded by 3CR12 parent plate and austenitic (usually 309L) weld metal. Both the 3CR12 and the 309L have relatively high toughness. Furthermore, the austenitic 309L does not exhibit a ductile-to-brittle transition temperature. In addition, the applied stress is often low. The service temperature is also of significant importance, and under South African conditions the service temperature may be higher than the ductile-to-brittle transition temperature of the heat affected zone, so that fracture would not occur unless severe impact loading is involved[3].

3.2 The low occurrence of in service brittle failure

As stated above, few occurrences of in-service brittle failure of welded 3CR12 components have been reported. The main reasons for the lack of brittle failure, namely the low through-thickness constraint and the protection offered to the high temperature heat affected zone by the weld metal and parent metal will be discussed in the subsequent chapters.

3.2.1 Low through-thickness constraint

Through-thickness plastic constraint is one of the most important factors that may lead to brittle failure. In some cases a full sized Charpy specimen may not be a realistic model of the actual situation that would exist in thicker sections in practice[4]. The difference in through-thickness constraint causes a phenomenon that is illustrated in figure 3.1. The relatively small Charpy specimen does not provide the same constraint as present in a larger specimen, and at a specific service temperature the sub-thickness Charpy specimen may show high impact energy, while the same material in a standard section would have a low toughness[4].

The dependence of the fracture toughness on the plate thickness can also seen in figure 3.2. In the diagram, B_1 denotes a plate thickness at which the plane strain, or normal fracture, dominates sufficiently so that the fracture toughness effectively equals K_{Ic}. At this thickness, the central normal fracture is large enough so that the shear fractures at the ends of the crack do not influence the fracture toughness[5]. For any thickness less than B_1, the shear fractures at the front and the back of the plate become significant factors in determining the magnitude of the fracture toughness K_c. Consequently, K_c rises at thickness values below B_1 as the size of the central region undergoing plane strain decreases relative to that of the two shear lips, since the shear lip size tend to be independent of the plate thickness[5]. A maximum in the fracture toughness is shown at B_0, and the corresponding fracture toughness value is often used as the plane stress fracture toughness[5]. Below B_0, thin plates tend to exhibit simple shear fractures[5] . The influence of plate thickness on the fracture toughness is well understood, and is probably one of the most important reasons for the low occurrence of brittle fractures in 3CR12 welds in practice, as 3CR12 is mostly used in plate thicknesses of 5mm or less. The fact that 3CR12 welds exhibit a low occurrence of brittle failure in practice is an important factor determining the application of the steel in the automobile industry[6].

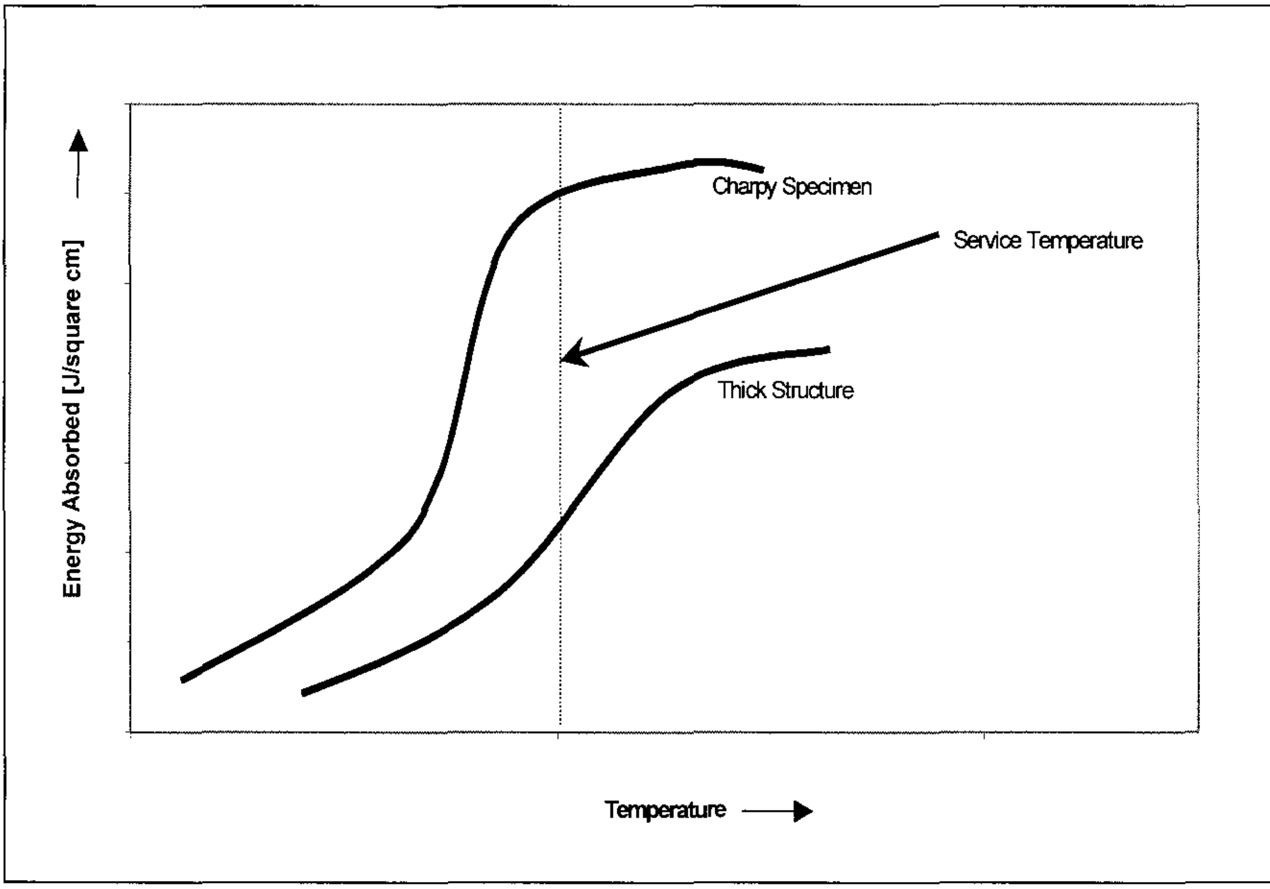

Figure 3.1: The effect of section thickness on transition temperature curves[4].

3.2.2 The protection of the HAZ by the weld metal and the parent metal.

The use of 309L weld metal is recommended for welding 3CR12 (E316L or other austenitic consumables are sometimes also recommended) as a result of the protection offered by the relatively soft weld metal to the coarse and brittle high temperature heat affected zone. In bead-on-plate bend tests performed by Grobler[7], the tendency for brittle failure in the high temperature heat affected zone increased with increasing weld metal hardness. The highest maximum bend angles were obtained when an

E309L or an E316L filler metal was used[7]. 180° bend angles could be obtained because almost all of the plastic deformation occurred in the relatively soft weld metal and parent metal, and consequently the fracture stress of the brittle, coarse grained high temperature heat affected zone was not exceeded[7]. The untempered martensite on the delta ferrite grain boundaries in the high temperature heat affected zone causes it to be harder than the surrounding parent metal and weld metal, and as a result plastic deformation tends to occur in those areas instead of in the high temperature heat affected zone during bending[7]. The conclusion can be drawn that an increase in the relative hardness of the heat-affected zone could have a positive effect on the impact properties of the joint.

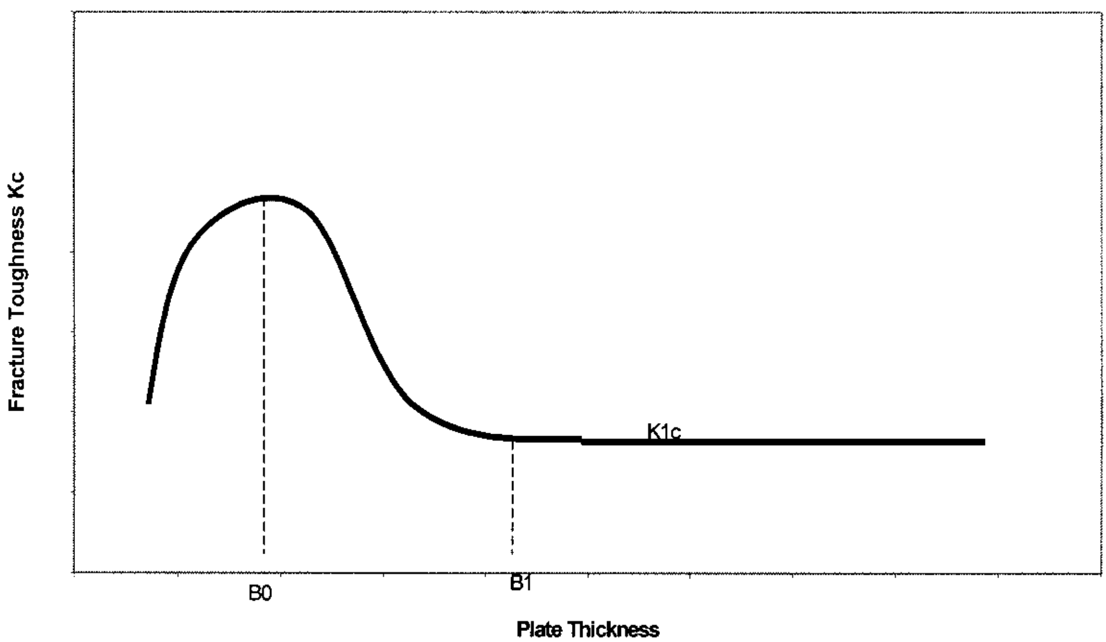

Figure 3.2: The dependence of the fracture toughness on the plate thickness[5].

3.2.3 The orientation of the heat affected zone relative to the applied impact load.

The orientation and shape of the HAZ relative to the applied impact load have a major influence on the energy absorbed during the Charpy test. The narrow width of the grain growth zone (200 μm max) makes it very difficult to place the tip of a Charpy notch directly into the grain growth zone. The contour which the fusion line and the high temperature heat affected zone follows through the thickness of the plate is also important. If the grain growth zone has a curved or a K-type form (see figure 3.3), the placement of the notch tip directly into the grain growth zone becomes even more difficult. In order to obtain a grain growth zone that runs straight through the thickness of the Charpy specimen, a butter layer was welded on the flat side of a K-type weld preparation for the purpose of the experiments (see figure 3.3). If this type of preparation is not used, the crack will propagate into the parent metal or the weld metal, and the true properties of the grain growth zone will not be determined in the Charpy test. Even with this preparation, the precise placement of the notch tip into the grain growth zone is still difficult, and a large number of weld metal and parent metal failures occur[2]. Properly prepared (such as a double V-type or a K-type without a butter layer) welded structures in practice would render straight crack propagation through the grain growth zone difficult if not impossible, and would contribute to the fact that brittle failure in the heat affected zone of 3CR12 rarely occurs in service. The difference between a prepared butter layer K-type joint for the Charpy impact test and a practical double V-type preparation is shown in figure 3.3.

3.3 The heat affected zone toughness in welded 3CR12

As mentioned earlier, excessive δ-ferrite grain growth occurs in the high temperature heat affected zone in welded 3CR12. The grain growth is detrimental to the impact strength of the heat-affected zone. Although few brittle failures of 3CR12 welds have been reported, the observed ferrite grain growth nevertheless causes concern about the impact properties of welds in 3CR12, as the effect of grain size on impact resistance is well known and well documented. The theoretical influence of grain size is discussed in the following paragraphs.

Cottrell discussed the important variables that play a role in brittle fracture[4] and derived an equation that provides the limiting condition for a crack to form and propagate:

$$(\tau_i d^{1/2} + k')k' = G\gamma_s\beta \quad .... (3.1)$$

where τ_i = the resistance of the lattice to dislocation movement

k' = a parameter related to the release of dislocations from a pile up

γ_s = the effective surface energy + the energy of plastic deformation

d = grain diameter

β = a term which expresses the ratio of shear stress to normal stress. For torsion $\beta = 1$; for tension $\beta = 1/2$; for a notch $\beta = 1/3$.

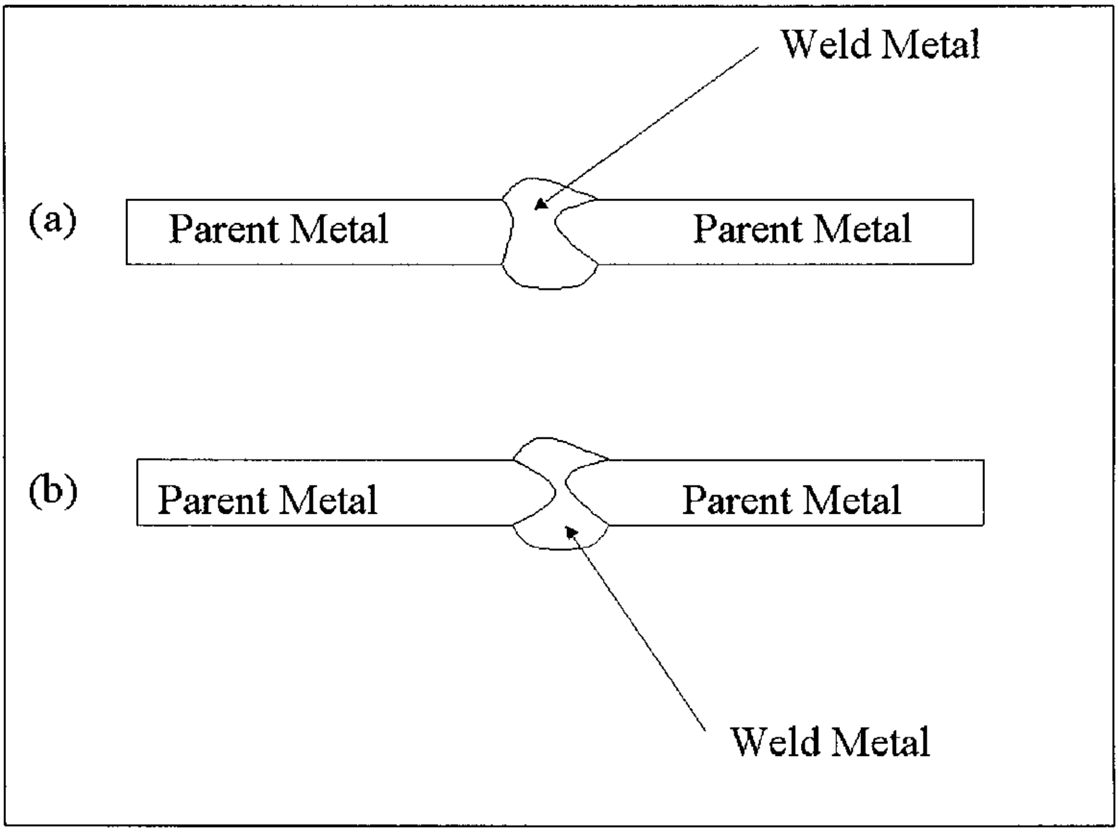

Figure 3.3: a) A butter layer K-type preparation b) A double V-type preparation.

If the left side of equation (3.1) is smaller than the right side, microcracks can form, but cannot propagate. If the left side is greater than the right side, a propagating brittle fracture can occur at a shear stress equal to the yield stress. In effect, this equation describes a ductile-to-brittle transition.

The parameter k' determines the number of dislocations that are released from a pile-up at an obstacle to dislocation movement (such as a grain boundary) when a dislocation source is unlocked[4]. Materials with high values of k' (like iron and molybdenum) are prone to brittle fracture. Strengthening mechanisms that depend on dislocation locking usually cause embrittlement. The grain size should be interpreted as the slip-band length, or the distance that the first dislocation loop created by a Frank-Read source can move outwards before it is stopped by the grain boundary[4]. A fine grain size results in a short slip distance and a low transition temperature[4]. A coarse grain results in a long slip distance and a high transition temperature[4].

A high value of frictional resistance (τ_i) promotes brittle fracture, since high stresses are required before yielding occurs. The highly directional bonding in ceramics, for instance, leads to a high τ_i value and high inherent hardness and brittleness[4]. In body centered cubic (BCC) metals, the frictional resistance decreases rapidly with decreasing temperature and this leads to a ductile-to-brittle transition[4]. In equation (2.1), $d^{1/2}$ enters as the product of τ_i, so that a fine-grain material can withstand a higher value of τ_i (or lower temperatures) before becoming brittle. The term β is related to the negative effects of a notch, and the γ_s term increases with the number of available slip systems and the size of the plastic region at the crack tip[4]. Plumtree and Gullberg applied equation (3.1) to ferritic stainless steels, and suggested the following modification[1]

$$\sigma_y k_y d^{1/2} = k_y^2 + \sigma_0 k_y d^{1/2} \geq C\mu\gamma \quad .... (3.2)$$

where σ_y = the flow stress or the fracture stress (coincident at the DBTT)

k_y = the Hall-Petch slope

d = the grain diameter

σ_0 = the lattice friction stress

γ = the effective crack surface energy

C = a constant related to the stress state

Taking σ_0 as the major temperature dependent term in equation (3.2), Petch derived a relationship between transition temperature and critical grain size of the form[1]:

$$DBTT = F + G \ln(d^{1/2}) \quad \text{..........(3.3)}$$

where F and G are constants.

Ductile-brittle-transition-temperature (DBTT) results obtained by Gooch and Ginn[1] for 12% chromium steels welded with an austenitic filler metal, represent a fair fit to the straight line suggested by equation (3.3), if the temperature for an absorbed impact energy of 30J from a standard Charpy specimen is plotted against $\ln(d^{1/2})$. These results (figure 3.4) clearly indicate that ferrite grain growth in the HAZ has a major influence on the impact properties of the welded joint.

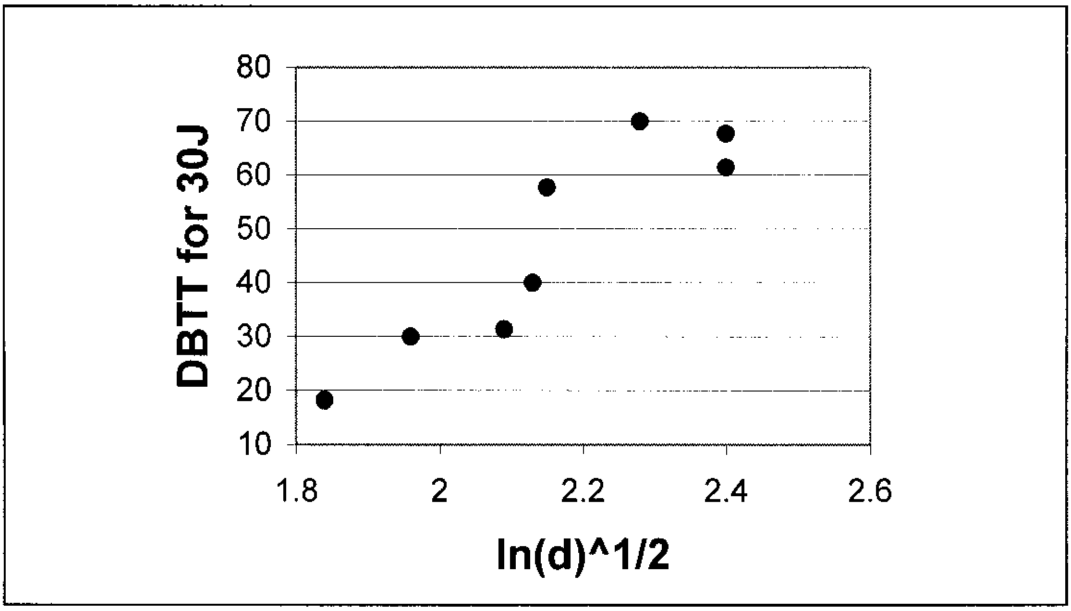

Figure 3.4: The effect of HAZ ferrite grain size on toughness of 12%Cr martensitic-ferritic steels[1].

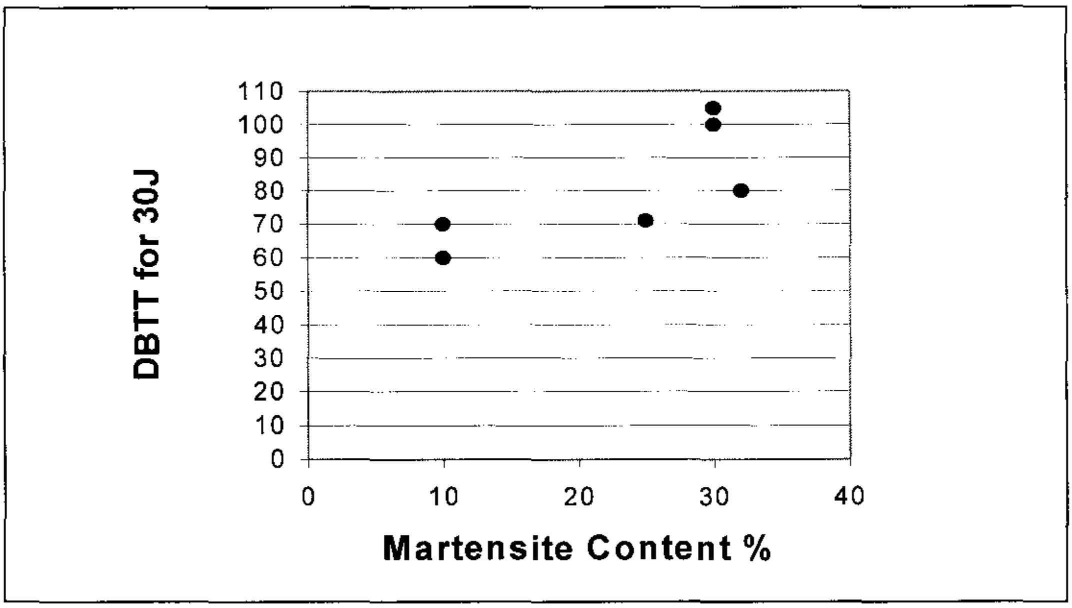

Figure 3.5: The effect of HAZ martensite on the toughness of 12% Cr martensitic-ferritic steels[1].

The phase composition of the HTHAZ also influences the impact properties. The influence of martensite on toughness was studied by Gooch and Ginn[1]. Their results are shown in figure 3.5. The influence of martensite is not clear from the figure, but there is a trend for the DBTT's to increase at higher martensite contents. However, fractographic examination by Gooch and Ginn[1] indicated that some cleavage fractures originated at martensite colonies, and it seems that martensite in a predominantly ferritic structure facilitates cleavage initiation. Intergranular martensite would inhibit the transmission of slip from one grain to another, effectively raising the k_y term in equation (3.2) and acting as an internal stress raiser[1]. These effects would be more severe with increasing martensite hardness.

The comments made by Gooch and Ginn[1] assume that fracture occurs in a predominantly ferritic matrix. If the major phase is martensite, the situation would be different[1,2,7,8]. Metallographic examination by Gooch and Ginn[1] also showed subsidiary cleavage to be arrested at martensite colonies, and with increased martensite, this effect would increase the total amount of energy absorbed during fracture[1]. Furthermore, ferrite grain growth would be minimized by the increased austenitic range at high temperatures. This suggests that improved toughness would be obtained at high martensite fractions[1].

3.4 Summary

Although substantial δ-ferrite grain growth occurs in the high temperature heat affected zone, brittle failure of welded joints in 3CR12 rarely happens during service. A number of explanations may be offered to account for this apparent contradiction.

In the first place, the fracture toughness is dependent on the plate thickness, and a weld in a thinner section may exhibit a lower DBTT than a weld in a thicker section. Furthermore, it appears as if the coarse grained zone is protected from brittle failure by plastic deformation of the relatively soft parent metal and weld metal. The alignment of the fusion line relative to the direction of the force is also of importance. If the heat-affected zone is not aligned properly with the notch (crack tip) during testing, the crack may simply propagate into another region of the weld.

Grain growth in the heat-affected zone (HAZ) does however cause concern. Work performed by Gooch and Ginn[1] clearly shows the detrimental influence of grain growth in the welded joint. Their comments are valid for a predominantly ferritic structure, and suggest that the presence of martensite colonies may have an adverse effect on the toughness of the heat-affected zone. Their results also show an increase in DBTT at higher martensite contents. However, they also found cleavage to be arrested by martensite colonies. In a predominantly martensitic structure this effect would be more significant, and the total energy absorbed by the joint during fracture may increase. If the high temperature heat affected zone can be prevented from entirely transforming to δ-ferrite during welding, grain growth may be inhibited. The structure may also be predominantly martensitic after cooling, causing the impact energy of the heat affected zone to increase.

3.5 References

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