CHAPTER 7

GENERAL CONCLUSION

1. WELD HEAT AFFECTED ZONE TOUGHNESS OF 3CR12 AND 3CR14

The important results, concerning the HAZ toughness of 3CR12 and 3CR14, may be summarized as follows:

a. The weld HAZ of 3CR12 and 3CR14 consists of at least three different zones, i.e. the HT HAZ adjacent to the fusion line, the fine grained HAZ adjacent to the HT HAZ and the low temperature HAZ more distant from the fusion line. These different zones in the HAZ exhibit different microstructures, mechanical and toughness properties. For a valid comparison of the HAZ toughness of 3CR12 with that of AISI 409 it will be necessary to compare the respective zones in the HAZ.

b. The fracture toughness of the HT HAZ of 3CR12 is not superior to that of the HT HAZ of the ferritic stainless steel AISI 409 from which 3CR12 was developed.

c. The fracture toughness of the HT HAZ of both 3CR12 and 3CR14 was not significantly improved by the grain refining which resulted from the increase in the low carbon martensite content from 15 percent to 98 percent(35). It is therefore possibly determined by other phenomena which have not yet been identified.

1.1 High temperature heat affected zone

3CR12 was developed by Middelburg Steel and Alloys (Pty), Ltd inter alia in an attempt to improve on the poor weldability of AISI 409. The weld HAZ toughness was evaluated, without differentiating between the different zones in the HAZ, using only the Charpy V-notch test. Although excellent toughness values were reported for the HT HAZ of 3CR12 by Hoffman and others (2,4,8,9,11), no fractographic or metallographic evidence was ever provided to show that the fracture path was limited exclusively to the narrow HT zone in the HAZ during impact testing. The very low toughness values which were obtained (Chapter 4) in this study for the HT HAZ of

3CR12, with the newly developed bead-on-plate bend test, strongly suggests that the high toughness values reported in literature for the HT HAZ of 3CR12 apply rather to the adjacent tough, fine grained zone in the HAZ. It may therefore be concluded that the Charpy V-notch test cannot be used reliably to evaluate the fracture toughness of the narrow HT zone in the HAZ of 3CR12. This is conceivable when the Charpy notch tip radius (0.25 mm) is compared with the size of the HT HAZ which ranges from 0.3 mm to 1 mm. In practice it is very difficult accurately to position the Charpy notch tip in the HT HAZ and guarantee that fracture will occur exclusively in this zone. Another practical limitation as far as the Charpy test is concerned, is the difficulty in producing a welded specimen, especially from 6 mm plate, with a planar HT HAZ oriented normal to the plate surface.

The toughness of both the fine grained and low temperature zones in the HAZ of 3CR12 is higher than that of the corresponding zones in AISI 409. This is due to the grain refining effect which occurs during welding in the fine grained zone in the HAZ of 3CR12, the relatively high HAZ toughness values which were reported in the literature for 3CR12, and the much higher base metal toughness of the dual phase ferritic-tempered-martensite structure of 3CR12, compared to that of the ferritic structure of AISI 409. This does not qualify 3CR12 as a structural steel with a superior weldability over that of AISI 409 since the weldability of AISI 409 is still limited by the low fracture toughness of the HT HAZ. This is especially important when 3CR12 is used in higher strength applications than what is customary for AISI 409, due to its higher yield and tensile strength. Although 3CR12 is specified by Middelburg Steel and Alloys, in some of the most recent technical publications(36) as a weldable structural steel for application in the petro-chemical, metallurgical, pulp and paper, and sugar industries, it is not recommended for critical application in plate thicknesses above 3 mm if adequate as-welded joint toughness is to be maintained.

Although Thomas(10) was actively involved in the developement of 3CR12, he did not realise apparently that the poor HAZ toughness or weldability of 3CR12 could be predicted (as discussed in chapter 1) by using the results of a study of his on the improvement of the weldability of AISI 409 with compositional variations within the specification.

Colt Crucible (USA) has also developed a tough, weldable 11.5 percent chromium ferritic stainless steel from AISI 409, known as Crucible E-4. For plate applications this steel contains 0.06 percent carbon, about 0.2 percent titanium and 0.85 percent nickel(36). Since a predominantly martensitic microstructure develops in the HT HAZ of E-4, this steel may be compared with 3CR12Ni. The major differences between the chemical compositions of E-4 and 3CR12Ni are the higher carbon content (0.06%C) and lower titanium:carbon ratio of 2.5 for E-4. The as-welded HT HAZ toughness of E-4 is expected to be lower than that of 3CR12Ni due to the formation of a higher carbon martensite in the HT HAZ. The HT HAZ ductile-brittle transition temperature of E-4 should therefore be much higher than 100°C. The bead-on-plate bend test described in chapter 4 for 3CR12Ni indicates an HT HAZ ductile-brittle transition temperature higher than 100°C. This is contrary to the weld HAZ Charpy transition temperature of below 0°C which was reported by Eckenrod and Kovach(37) for E-4. This controversy may also be accounted for by the fact that Eckenrod and Kovach failed to differentiate between the different zones in the HAZ. With the edge of the V-notch of their Charpy test specimen located on the fusion line of a welded specimen with a reasonably planar fusion line, the notch tip was positioned at a distance of about 0.8 mm from the fusion line in the tough, fine grained zone in the HAZ. The toughness of the fine grained zone was therefore measured and reported as the toughness of the narrow HT HAZ. The HT HAZ toughness of E-4 is therefore also much lower than the reported values.

1.2 High-temperature embrittlement

The low HT HAZ toughness of 3CR12 and 3CR14, which is nearly independent of the grain size and low carbon martensite content, may be explained by considering the high-temperature embrittlement phenomenon which manifests in high-chromium ferritic stainless steels. After heating commercial high-chromium ferritic stainless steels, containing 16 to 30 percent chromium and moderate-to-high martensite levels, above about 950°C, the steels show an abnormal loss in toughness and ductility at room temperature(38). It is generally agreed that this embrittlement is caused by the precipitation of chromium rich carbides and nitrides on grain boundaries and/or dislocations. The HT HAZ toughness therefore depends on the carbon and nitrogen levels of the steels.

Baerlecken et al. studied the effect of heat treatment on the toughness of vacuum melted 16 to 30 percent chromium ferritic stainless steels(39). They reported a reduction in the transition temperature of an annealed 30 percent chromium steel from 150°C to -30°C by a water quenching treatment from 1050°C and attributed it to a reduction in the amount of chromium-rich carbides and nitrides. Another important conclusion from their work is that grain size has little effect on the toughness of vacuum-melted high-chromium ferritic stainless steels because even with a grain size of ASTM 1-3 a transition temperature of -40°C was obtained. Semchyshen et al. studied the effects of chromium, carbon and nitrogen levels on the toughness of Cr-Fe alloys containing 14 to 28 percent chromium(40). They reported an increase in the ductile-brittle Charpy transition temperature of a 17%Cr-0.01%N steel from -50°C to 130°C with a corresponding increase in the carbon content from 0.002 percent to 0.061 percent. The transition temperature of a 17%Cr-0.004%C steel increased from -50°C to 50°C with a corresponding increase in nitrogen content from 0.010 percent to 0.032 percent.

The general poor weldability of ferritic stainless steels arises from the loss in ductility, corrosion resistance and toughness in the HAZ as a result of chromium-rich carbide and nitride precipitation and excessive grain growth. The as-welded ductility and corrosion resistance is improved tremendously with the addition of stabilizers such as titanium and niobium. Semchyshen et al. and Wright studied the effects of stabilizing additions on the impact properties of ferritic stainless steel plate and found that acceptable room temperature HAZ impact resistance may not be obtained with stabilizing additions(41). For section thicknesses greater than 3.2 mm excellent as-welded HAZ corrosion resistance, ductility as well as toughness can only be obtained with high-purity steel containing extremely low carbon and nitrogen levels. Wright, e.g., reported a decrease in the Charpy transition temperature of 11 mm 26%Cr-1%Mo steel plate from 149°C to -57°C with a corresponding decrease in total carbon and nitrogen content from 0.03 percent to 0.0065 percent.

The high-temperature embrittlement phenomenon which is associated with high-chromium ferritic stainless steels may also be responsible for the low HT HAZ toughness of 3CR12 and 3CR14. Although Rowlands reported that this phenomenon was suppressed successfully in 3CR12, no conclusive experimental evidence was provided(11). If high-temperature embrittlement is responsible for the poor HT HAZ toughness of 3CR12 and 3CR14 it could not be suppressed using high titanium additions but only by a reduction in the total carbon and nitrogen levels. This high-temperature embrittlement phenomenon should therefore be considered in future research attempts to improve the weldability of 3CR12 and 3CR14. Attention should also be given to the residual elements like P, S and Cu. Wright, for example, found that the HAZ toughness of 26%Cr-1%Mo steels was improved with one or more of these residual elements below the levels normally found in electric furnace processed conventional stainless steels.

1.3 Fine grained heat affected zone

Transverse Charpy 30J ductile-brittle transition temperatures which ranged from -57°C to -68°C were obtained for 12 mm 3CR12 plate in chapter 6. These transition temperatures increased to room temperature after a normalising (after 1h at 1000°C) and tempering (1h at 750°C) heat treatment. It was also found that the excellent toughness of 3CR12 arises, apart from its fine grain size, from the phenomenon of splitting or delamination which releases the triaxial stress field at the Charpy notch tip during testing. This tendency towards splitting is determined by the degree of dimensional anisotropy of the grain structure. The loss in toughness after a normalising and tempering treatment was characterized by a reduction of the degree of dimensional anisotropy of the grain structure. This loss in toughness cannot be restored by a heat treatment since it is not possible to increase the degree of dimensional anisotropy of the grain structure by a heat treatment.

An irreversible loss in toughness will therefore also occur in the fine grained zone in the HAZ of 3CR12 and 3CR14. The transition temperature of 3CR12 was found to increase to about room temperature in this zone as a result of the formation of some untempered martensite and the reduction in the degree of dimensional anisotropy of the grain structure(8). The toughness of the fine grained HAZ can therefore not be improved significantly by a post-weld heat treatment. It may therefore be argued that the as-welded toughness of the fine grained and low temperature HAZ phenomenon was suppressed successfully in 3CR12, no conclusive experimental evidence was provided(11). If high-temperature embrittlement is responsible for the poor HT HAZ toughness of 3CR12 and 3CR14 it could not be suppressed using high titanium additions but only by a reduction in the total carbon and nitrogen levels. This high-temperature embrittlement phenomenon should therefore be considered in future research attempts to improve the weldability of 3CR12 and 3CR14. Attention should also be given to the residual elements like P, S and Cu. Wright, for example, found that the HAZ toughness of 26%Cr-1%Mo steels was improved with one or more of these residual elements below the levels normally found in electric furnace processed conventional stainless steels.

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2. LAMELLAR TEARING

In chapter 6 the through-thickness tensile test, which was also used by De Ardo(27), was used to establish whether splitting in transverse 3CR12 Charpy specimens is related to the phenomenon of lamellar tearing which sometimes attends welding. Satisfactory through-thickness tensile ductilities were obtained and it was therefore concluded that the phenomenon of splitting is not expected to result in lamellar tearing during welding. However, the validity of the through-thickness tensile test, which evaluates the plane stress fracture behaviour, for this purpose is questioned since it was also shown that splitting is dependent on plane strain, rather than plane stress conditions(42,43). The high through-thickness ductile-brittle transition temperatures (112-116°C) and relatively low through-thickness fracture stress of 12 mm 3CR12 plate (chapter 6) strongly suggests that highly restrained welded 3CR12 plate may be susceptible to lamellar tearing initiating from planar defects.

Although the cruciform test is considered as a test with a large degree of restraint in which high through-thickness stresses develop, delamination cracks per se were not found in any of the specimens welded with the different filler metals (chapter 5). Brittle cleavage delamination type fractures did in fact occur in the rolling plane of FLNFT test specimens (chapter 5) welded with AISI 316L, 309L and E3CR12 filler metals, respectively (figure 7.1). In each instance the delamination crack

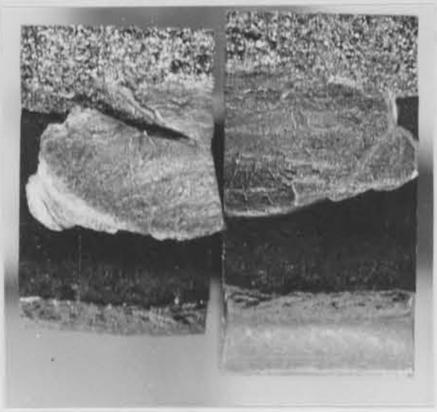

Figure 7.1: Brittle cleavage delamination fracture in a fractured 308L welded FLNFT specimen. The delamination fracture was initiated by the cleavage fracture (bright fracture surface) in the coarse grained HT HAZ.

initiated from a brittle cleavage fracture in the coarse grained HT HAZ. This indicates that the susceptibility of 3CR12 welds to delamination fractures is dictated, apart from TiCN stringers, by the fusion line notch fracture toughness which is usually lower than that associated with delamination. The choice of a filler metal for welding 3CR12 will therefore also influence the susceptibility of welds to subsequent delamination type fractures in the rolling plane.

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