CHAPTER 1

AN INTRODUCTION TO THE WELDABILITY OF 3CR12

1. INTRODUCTION

The main purpose of this first chapter is to outline three important aspects of the weldability of a 12 percent chromium steel, designated 3CR12, on which little information is available yet. This thesis is a report on a detailed study of these aspects.

3CR12 is a low carbon (0.03%), titanium stabilised, 12 percent chromium, duplex ferritic-martensitic steel which was developed by Southern Cross Steel, the stainless steel producing division of Middelburg Steel and Alloys (Pty), Ltd. The steel was developed from the ferritic stainless steel AISI 409 by careful balancing of the ferrite (Cr, Si, Ti) and austenite (Ni, Mn, C, N) stabilising elements using Kaltenhauser's(1) relationship:

$$\text{Ferrite Factor (F.F.)} = Cr + 6Si + 8Ti - 2Mn - 4Ni - 40(C+N)$$

where F.F. = 11.5 for 3CR12.

The microstructure of the steel consists of slightly elongated to equiaxed ferrite and highly tempered martensite grains (grain size ASTM 7) with large blocky cubic titanium carbonitrides. This structure is obtained by tempering (750-770°C) of hot rolled plate of which the temperature during the final pass was within the dual-phase ferrite-austenite phase field. This results in a banded microstructure consisting of pancake shaped ferrite and martensite grains.

Two basic varieties of 3CR12, one containing 0.6 percent nickel (3CR12) and one containing 1.2 percent nickel (3CR12Ni), are being marketed by Southern Cross Steel. (See table 1.1 for chemical compositions.) The lower nickel variety is intended for general applications, while the higher nickel variety is produced for high strength applications.

3CR12 has been developed as a relatively inexpensive corrosion resisting steel and replacement for mild and structural steels for application in mildly corrosive environments where the corrosion resistance of these

Table 1.1: Chemical composition limits (wt-%) for AISI 409 and 3CR12.

Steel	C	S	P	Mn	Si	Cr	Ni	Ti	N
409 Limits	0.08 max	0.045 max	0.045 max	1.00 max	1.0 max	10.5-11.75	0.5 max	6 x C 0.75max	-
3CR12 Limits	0.03 max	0.030 max	0.030 max	1.50 max	1.0 max	11-12	1.5 max	4(C+N)min 0.6max	0.03 max
3CR12 Typical	0.025	0.012	0.020	1.2	0.5	11.2	0.6	0.3	0.015
3CR12Ni Typical	0.025	0.012	0.020	1.2	0.5	11.2	1.2	0.3	0.015

steels are inadequate. Sheet and plate are presently being marketed respectively within the thickness ranges 0.55 to 3.0 mm and 3.5 to 30 mm. The steel is presently finding application in the South African gold and coal mines for construction of transport wagons, coal bunkers, railway masts, storage tanks, containers, etc. It is also increasingly being used in structural applications for petro-chemical, metallurgical, pulp and paper, and sugar industries.

The mechanical properties, i.e. toughness, formability and weldability of 3CR12 are superior to that of AISI 409. This is due to the fine grained microstructure which contains large fractions of low carbon, highly tempered martensite. Typical mechanical properties of 3CR12 and 409 are(2):

		3CR12	AISI 409
Tensile strength, Rm (MPa)	:	530	450
0.2% Proof Stress, Rp (MPa)	:	380	250
Elongation, A (% in 50mm)	:	26	27
Brinell hardness (HB)	:	165	150

Typical Charpy V-notch values for 10 mm plate are(2):

		3CR12	AISI 409
Temperature (20°C)	:	85J	20J
Temperature (0°C)	:	65J	10J
D.B.T.T. (30J)	:	-20°C	40-100°C

2. WELDABILITY

The standard ferritic stainless steels exhibit a poor weldability due to undesirable heat-affected zone (HAZ) microstructural changes, i.e.

a. Excessive HAZ grain growth with a loss of both ductility and toughness.
b. Formation of chromium carbonitrides which lowers the corrosion resistance and toughness(3).
c. Loss in ductility and corrosion resistance due to the formation of small amounts martensite on the grain boundaries(4).

The poor weldabiltiy is the major constraining factor in using ferritic stainless steels in thicknesses exceeding 3 mm, which is generally the maximum recommended thickness, if adequate weldment toughness is to be maintained(5,6). The improvement of the weld HAZ toughness of 11.5 percent chromium ferritic stainless steels, e.g. AISI 409, is the critical factor in extending the applications of these steels to thicker plate material.

Since 3CR12 was developed from AISI 409, it is of some significance to consider attempts by Thomas and Apps(7) to improve the weldability of 6 mm AISI 409 plate by compositional variations within the AISI 409 specification. Table 1.2 shows the compositional range of their experimental steels together with the composition of one of the steels (steel A) which contained up to 20 percent martensite in the high temperature (HT) HAZ.

The weld HAZ toughness of TIG welds on 6 mm plate was determined with thermal simulated substandard (10 mm x 5 mm x 55 mm) Charpy V-notch specimens. Depending on the peak temperature during thermal simulation, steel A (table 1.2) contained up to 20 percent low carbon martensite in the HT HAZ. Ductile-brittle transition temperatures (30J) of 76°C and 86°C were

Table 1.2: Chemical compositional range (wt-%) of AISI 409 steels studied by Thomas and Apps(7).

-	C	N	Mn	Si	S	Cr	Ni	Ti	Al
Range	0.020-0.027	0.012-0.015	0.72-0.98	0.39-0.51	0.015-0.023	11.42-11.57	0.32-0.60	0.17-0.30	0.09-0.028
Steel A	0.025	0.015	0.74	0.39	0.017	0.6	0.6	0.3	0.09

obtained respectively for specimens with 5-10% and 15-20% martensite in the HT HAZ. It should be remembered that higher transition temperatures will be obtained with standard size Charpy V-notch specimens. Thomas and Apps also found that the transition temperatures and therefore the weld HAZ toughness were not significantly influenced by subsequent low peak temperature thermal cycles which simulated the thermal effects of multipass welding. It was therefore concluded that, due to the very low weld HAZ toughness values of the experimental steels (high transition temperatures), compositional variations in the AISI 409 specification were unlikely to give any significant improvement in the weldability of these steels. Finally, it was suggested that attemps to improve the weldability of AISI 409 should concentrate on reducing both grain growth and martensite formation in the HAZ.

Although the HAZ toughness of the low carbon, titanium stabilised steel A in table 1.2 was not improved to any significant extent by up to 20 percent martensite, the superior weldability of 3CR12 (which was developed from AISI 409) is in fact partly attributed to the formation of about 40 percent of this low carbon lath martensite (2,4,8,9,10). The composition of 3CR12 falls within the AISI 409 limits (table 1.1), although certain elements such as Mn, Ni, and Ti may fall outside these limits. A comparison between the typical composition for 3CR12 in table 1.1 and the composition of steel A in table 1.2 reveals that 3CR12 exhibits a slightly higher manganese content which will result in the formation of a higher fraction martensite in the weld HAZ. Figure 1.1 shows such a weld HAZ of a bead-on-plate MIG welded weld on 6 mm tempered 3CR12 plate. The HT coarse

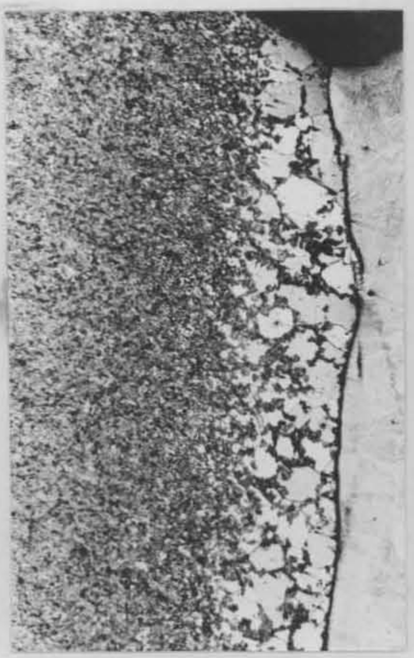


Figure 1.1: Weld HAZ of 3CR12 with 35 percent grain boundary martensite in the coarse grained, duplex ferrite-martensite high temperature HAZ adjacent to the fusion line (35X).

grained HAZ adjacent to the fusion line contains 35 percent grain boundary martensite with the balance ferrite. The HT HAZ of the high nickel 3CR12Ni contains up to 90 percent martensite, with even better toughness properties.

3CR12 has been developed to overcome the three major problems which limit the weld HAZ toughness and therefore the weldability of AISI 409:

a. The excessive grain growth which usually occurs in the HT HAZ is limited by the formation of about 40 percent grain boundary martensite(7,8,9).

b. The harmful effects of carbon and nitrogen on the toughness of ferritic stainless steels is limited by a low carbon and nitrogen content and titanium stabilization(8,11).

c. Ball and Hoffman(12) concluded that, since the hardness of the martensite (HV 250) in the HT HAZ is equivalent to the hardness of martensite containing less than 0.05 percent carbon, the average toughness of the weld HAZ should not be less than the parent metal.

In summary, it appears therefore that the superior weld HAZ toughness of 3CR12, over AISI 409, results from the synergistic effect of the tough low carbon lath martensite and the restricted grain growth. The steel is claimed to be weldable in thicknesses up to 32 mm without any pre- or post weld heat treatments(8).

Hoffman(8) published a comprehensive summary of research, down to September 1984, done on the weldability of 3CR12. Satisfactory results were obtained with reference to the following factors determining the weldability: joint strength, ductility, toughness, fatigue strength, corrosion resistance, ease of welding and susceptability to hot cracking. Of particular interest is the half size Charpy V-notch ductile-brittle (10.2 Joule) transition temperature of less than room temperature which was obtained for the weld HAZ of 3CR12 and a ductile-brittle transition temperature of below 0°C which was obtained for the weld HAZ of 3CR12Ni. Melville et al.(2) reported average standard Charpy V-notch impact energy values of 49J and 35J, obtained at room temperature and 0°C, respectively.

Before discussing the excellent HAZ toughness values reported for 3CR12 in comparison to the poor HAZ toughness values obtained, respectively by Thomas and Apps(7) for AISI 409, and Gooch and Davey(13) for 3CR12, it is necessary to take a closer look at the weld HAZ microstructure of 3CR12 in figure 1.1. The HAZ may be divided into at least three zones; each with a different microstructure, phase composition and therefore mechanical properties. The microstructural changes which occurred in the three zones during welding may be described by means of the pseudo-binary phase diagram for 11.5% chromium steels in figure 1.2 and the microhardness transverse across the fusion line of the weld in figure 1.1 (fig. 1.3).

The three zones in the HAZ are:

1. A narrow coarse grained zone adjacent to the fusion line (figs. 1.1 and 1.3). The phase composition (δ-ferrite and granular blocky and

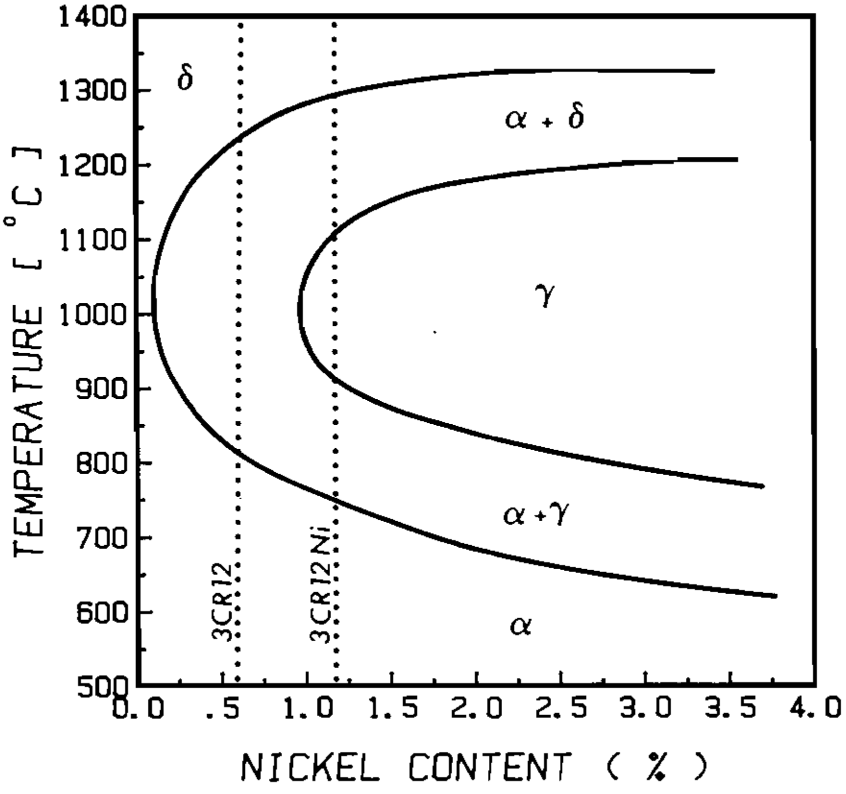
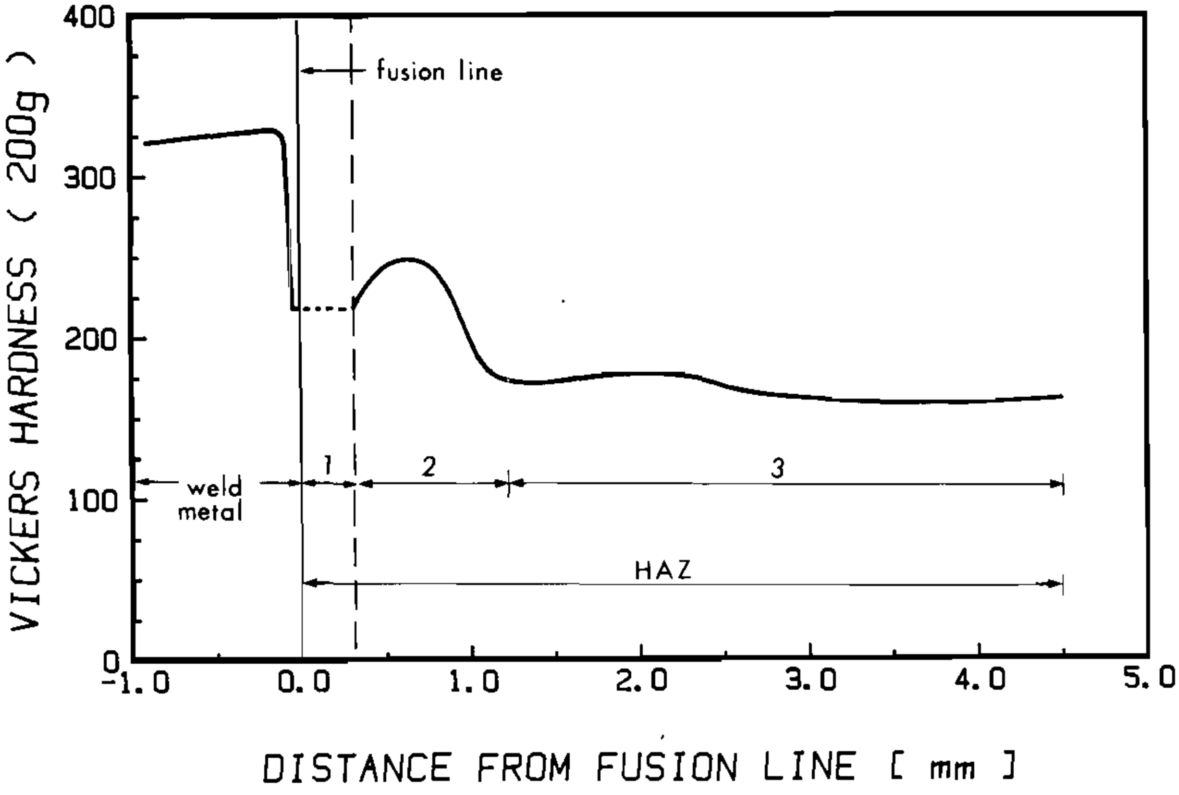


Figure 1.2: Pseudo-binary phase diagram for 11.5% chromium steels. (After Protopappas(14)). Typical compositions for 3CR12 and 3CR12Ni are also indicated.

angular Widmanstätten intergranular martensite(7)) of the zone is determined by the relative amount of ferrite and austenite stabilizing elements, while the width depends on the weld heat input. (For a very low heat input of 0.46 kJ/mm this zone has a typical thickness of 0.2 - 0.3 mm). During welding this zone was heated within the δ -ferrite phase field (above about 1250°C) in figure 1.2. Due to the very high peak temperatures in this zone, excessive δ-ferrite grain growth occurred, with subsequent transformation of some of the δ-ferrite to angular Widmanstätten austenite during subsequent cooling cycle. Grain refining actually occurred therefore during the δ-ferrite to austenite transformation. Any δ-ferrite that transforms to austenite will subsequently transform to martensite upon further cooling. The weighed average hardness of the ferrite and martensite in this zone is indicated in figure 1.3.



1: HT HAZ, 2: Fine grained HAZ, 3: Low temperature HAZ

Figure 1.3: Microhardness transverse across the fusion line of a bead-on-plate weld on 6.3 mm 3CR12 plate.

The only differences between this high temperature (HT) HAZ in 3CR12 and steel A in table 1.2 are the lower martensite content and coarser grain size of this zone in steel A.

2. A much wider duplex zone with fine grained ferrite and untempered inter- and intragranular martensite(7), right next to the coarse grained zone (figs. 1.1 and 1.3). This wider duplex zone originated when the material was heated to temperatures (900-1300°C) within the dual phase ferrite and austenite phase field in figure 1.2. The width of this zone depends on the weld heat input and the composition of the steel. The phase composition of this zone varies across the width of this zone. The maximum amount of martensite formed at the point in this zone at which the longest time was spent during welding, and at the temperature (1050°C in fig. 1.2) at which the maximum amount of austenite will form in 3CR12. The high

hardness of this zone in figure 1.3 results from the presence of the large amount of untempered martensite.

3. A third zone (low temperature HAZ) more distant from the fusion line that was heated to temperatures below the A_1 temperature (800°C in fig. 1.2) during welding. The hardness of the material in this zone is unchanged (fig. 1.2) since the plate was previously, subsequent to hot rolling, tempered at 750-770°C.

It is therefore clear that the weld HAZ of 3CR12 consists of at least three different zones with different microstructures and mechanical properties. For a proper comparison of the weld HAZ toughness of 3CR12 and AISI 409, it will therefore be necessary to compare the toughness of the various corresponding zones in the HAZ with each other. In the literature reference is made only to the weld HAZ toughness of 3CR12 and toughness values are only therefore being reported for the weld HAZ. In general it is actually not clear to which of the three zones in the weld HAZ these excellent toughness values apply.

The narrow high temperature (HT) zone in the HAZ adjacent to the fusion line, is considered to be the critical zone. The toughness of this zone is expected to be much lower than the toughness of the other two zones in the HAZ due to the relatively much larger grain size (fig. 1.1) and the possibility of high temperature embrittlement in this zone. The toughness of both the fine grained and low temperature zones in the HAZ of 3CR12 is expected to be superior to the toughness of the corresponding zones in AISI 409 as a result of the effective grain refining which occurred in the fine grained HAZ during welding and the superior original toughness of 3CR12 in the low temperature HAZ prior to welding. It is not clear whether the toughness of the HT HAZ of 3CR12 is superior to that of AISI 409. If the size of this zone is considered, it is doubtful whether the toughness of this zone, in actual welds, has ever been determined, since only the Charpy V-notch test has been used in the past. As far as the Charpy V-notch test is concerned it is questionable whether it is possible accurately to position the notch tip of the V-notch in this narrow HT HAZ, and guarantee that fracture will be limited exclusively to this zone.

The very low HT HAZ toughness which was obtained by Thomas and Apps for steel A (table 1.2), with 20 percent martensite in the HT HAZ, seems to indicate that the toughness of this zone in 3CR12 is much lower than the reported values. This possibility is further strengthened by the Charpy V-notch weld HAZ toughness results which have been reported by Gooch and Davey(13) for 10 mm 3CR12 plate. Although Gooch and Davey have not been very successful in determining the toughness of the HT HAZ, their variable results, which are summarized in table 1.3, also seem to indicate that the actual toughness of the HT HAZ is much lower than that which is generally reported. The low toughness values in table 1.3 were obtained when

Table 1.3: Summary of weld HAZ Charpy values which was obtained by Gooch and Davey(13) for 10 mm 3CR12 plate.

Test Temperature (°C)	Absorbed energy (J)
-20	4 - 9
0	8 - 61
20	11 - 65
40	9 - 68

cleavage fracture occurred within three to four ferrite grain diameters of the fusion boundary. The high toughness values were obtained when ductile fracture occurred in the fine grained and low temperature HAZ.

It may therefore be concluded that there is an uncertainty as far as the actual toughness of the HT HAZ of welds on 3CR12 is concerned. If the actual toughness of this zone is much lower than the values reported by, e.g. Hoffman(8) and Melvill et al.(2), their values appear to apply to the fine grained zone in the HAZ, rather than the HT HAZ. The superior weldability of 3CR12 over the ferritic stainless steel AISI 409, from which it was developed, can therefore be seriously questioned.

3. WELDING CONSUMABLES FOR 3CR12

Although some ferritic filler metals are available for welding ferritic stainless steels, the resultant weld deposits are low in ductility. Austenitic steel fillers are therefore generally recommended for welding ferritic stainless steels(7). Hoffman investigated the influence of different MMA and MIG filler metals on the weldment properties of 3CR12 and recommended that any austenitic filler metal may be used for welding 3CR12. The use of AISI 308L, 309L and 309LMo is, however, preferred(8). Gooch and Davey also reported no significant differences in the weldment properties of welds on 3CR12, welded with AISI 308L, 309 and 310 electrodes(13). A high strength matching (composition) electrode, E3CR12, has also recently been developed by Pagani for welding 3CR12(15).

The evaluation of the mechanical properties of weldments, welded with the abovementioned filler metals, has been based on bend test and tensile test results only. These tests only evaluate the plane stress fracture behaviour of welds. With the toughness of the HT HAZ lower than the toughness of the rest of the HAZ, the suitability of a filler metal for welding 3CR12 should also be evaluated on the basis of its influence on the fusion line fracture behaviour of welds in the presence of a triaxial stress field. The HT HAZ is expected to have a significant effect on the fusion line fracture behaviour of welds on the presence of a triaxial stress field.

4. LAMELLAR TEARING

Mechanical tests on 3CR12 often reveal splitting or tearing in the rolling plane. Figure 1.4 shows such parallel splits on the fracture surface of a transverse 3CR12 Charpy specimen. These splits form in the rolling plane and is usually associated with a low through thickness fracture stress and the development of high through-thickness stresses during mechanical testing. Various mechanisms have already been suggested for the formation of these splits which are also common to hot rolled duplex steels.

Although Hoffman(8) do not consider these splits to be detrimental to the properties of 3CR12, the possibility of a correlation between splitting and the susceptability of 3CR12 to lamellar tearing during and after welding in the rolling plane, has not yet been investigated. With 3CR12 being used in more and more higher strength structural applications, this aspect of the weldability of 3CR12 becomes even more important.

Figure 1.4: Parallel splits on the fracture surface of a transverse 3CR12 Charpy V-notch impact specimen. These splits developed in the rolling plane during impact testing.

5. EXPERIMENTAL

3CR12 is presently finding application as a replacement for mild steel, galvanized steel and coated structural steel. It finds use in more and more higher stress structural applications in the petro-chemical, metallurgical, pulp, paper and sugar industries due to its superior corrosion resistance and mechanical properties. There is therefore a growing concern about the actual weldability of 3CR12 over AISI 409 and the steels it is replacing due to the uncertainty concerning the true weld HAZ toughness and the higher constraint levels to which weldments are being subjected to.

A better understanding of the weld HAZ fracture behaviour, the effects of weld and base metal mechanical properties on the fusion line fracture toughness, and the susceptibility of welded 3CR12 to lamellar tearing, may greatly contribute towards confidence in the integrety of welded 3CR12 structures and the development of higher chromium duplex steels, e.g. 14 percent chromium steels (3CR14), with superior weldability.

The principal aims of this thesis may therefore, with reference to the various aspects of the weldability of 3CR12, be summarised as follows:

a. A study of the fusion line (HT HAZ) fracture behaviour of welds on 6 mm duplex 12 percent chromium (3CR12) and 14 percent chromium (3CR14) steel plate, in the presence of a triaxial stress field. A new test method was developed for measuring the fracture toughness of the HT HAZ of actual welds and to determine respectively the effects of factors such as chemical composition, phase composition, stabilising elements, loading rate, etc. on the fracture toughness of the HT HAZ (Chapters 3 and 4).

b. A study of both the effects of weld metal and base metal mechanical properties on the fusion line fracture behaviour of highly restrained welds. The suitability of different filler metals for welding of 10 mm 3CR12 plate is evaluated with another newly developed test method devised for measuring the fusion line fracture toughness of fillet welds (Chapter 5).

c. A study of the mechanism of splitting in the rolling plane of 10 mm 3CR12 plate and the correlation between splitting and the phenomenon of lamellar tearing which sometimes manifest during and after welding (Chapter 6).

The major results and conclusions on the different aspects of the weldability of 3CR12 and 3CR14 are discussed in Chapter 7.