

# The Effect of Anisotropy on the Fatigue and Fracture of a 12 per cent Chromium Steel

M. B. CORTIE\*, C. J. FLETCHER\*, and W. VELDSMAN†

\* *Mintek, Randburg, South Africa*

† *MS&A Stainless, Sandton, South Africa*

The manufacturing process for 3CR12, a dual-phase steel containing 11 per cent chromium, produces a material with a directional microstructure, a relatively well-developed crystallographic texture, and anisotropic tensile properties. This paper examines the toughness and fatigue resistance of this alloy and, in particular, the effects of its microstructure.

It was found that there is little variation with direction in the fatigue properties of 3CR12 in all except the short-transverse direction, and the alloy exhibits excellent resistance to the growth of fatigue cracks at elevated temperatures. There is a significant difference in impact toughness between the short-transverse, crack-arrestor, and crack-divider orientations, as well as between the longitudinal and the transverse directions. It is shown that the delamination that occurs in these alloys has an effect on the mechanical properties, and prevents the correct measurement of the standard fracture-toughness parameters. The causes and mechanisms of the delaminations are discussed.

## Introduction

The concept of a tough, weldable version of type 409 ferritic stainless steel was mooted at Middelburg Steel & Alloys (MS&A) during the 1970s, and an alloy denoted 3CR12\* was patented in 1978<sup>1</sup>. Since its introduction, the alloy has undergone a number of small changes in composition. There were originally two versions: 3CR12Ni containing about 1,3 per cent nickel, 0,03 per cent carbon, and 0,3 per cent titanium; and 3CR12 with a nickel content reduced to 0,6 per cent. The former material was found to exhibit superplasticity under laboratory conditions<sup>2</sup>, but was not commercialized<sup>2,3</sup>. A considerable tonnage of the second composition (3CR12) has been manufactured, and the present work relates to that alloy.

The physical metallurgy and microstructure of 3CR12 have already been described by others<sup>3-8</sup>. Although 3CR12 is similar to the better-known type 409 ferritic stainless steel, it has a composition with a greater 'nickel equivalent'. The alloy thus contains a greater percentage of austenite at elevated temperatures than type 409. This austenite is transformed to low-carbon martensite when the material is cooled to room temperature (the  $M_s$  temperature is typically<sup>3</sup> about 550 °C), yielding a dual-phase microstructure consisting of ferrite and martensite. Usually the material is subsequently sub-critically annealed or tempered, a process that further tempers the martensite, or that can be considered to convert it to ferrite plus carbides<sup>5</sup>. The high  $M_s$  temperature also permits the possibility of eliminating a special tempering step, provided that the material is cooled sufficiently slowly from the hot-rolled condition.

\* 3CR12 is a trademark of MS&A

The final microstructure of hot-rolled and annealed plate normally consists of pancake-shaped grains of largely carbide-free ferrite, interspersed with other ferrite grains containing a profusion of small carbide particles. The grains measure about 30 by 25 by 15  $\mu\text{m}$  in a typical plate<sup>9</sup>, yielding an ASTM grain size number of between 7 and 9. Under normal conditions, 3CR12 is not, therefore, a dual-phase alloy, although it can be prepared as one by rapid cooling after hot rolling.

This paper addresses fatigue and fracture in 3CR12 plate, and the interaction of these two cracking mechanisms with the anisotropy of the material. The anisotropy of 3CR12 leads to the occurrence of delamination, and the mechanisms and significance of that phenomenon are discussed. The effect of plate anisotropy on the impact toughness, the effect (or lack of effect) of heat treatment on the fatigue endurance, and the effect of temperature on the propagation of fatigue cracks are discussed. The behaviour of weldments in 3CR12 is not considered, since these have received attention elsewhere<sup>10-12</sup>. The authors wish to point out that the anisotropy and delamination that occur in 3CR12 and other dual-phase steels is rarely of any practical significance. The examination of these phenomena is therefore the consequence of intellectual curiosity, rather than in response to any perceived practical need.

## Experimental

The tests described in this paper were carried out on specimens machined from 3CR12 plates manufactured in 1987. A 25 mm plate was used for the fatigue and fracture-toughness specimens, and a 10 mm plate was used for the impact

toughness specimens. The compositions of the plates are given in Table I.

TABLE I  
COMPOSITION OF MATERIALS USED, WEIGHT %

Plate	C	N	Si	Mn	Cr	Ni	Ti
25 mm	0,025	0,021	0,46	1,18	11,1	0,51	0,24
10 mm	0,030	0,008	0,33	1,27	11,6	0,55	0,48

All the fatigue specimens were machined from the 25 mm plate. The fatigue-endurance specimens were machined at 0, 45, and 90° to the rolling direction. Compact-tension specimens used for the propagation of fatigue cracks and the fracture-toughness tests were machined in the X-Y orientation, as detailed in BS 5447<sup>13</sup>. The notation used for describing the specimen orientations is shown in Figure 1. Microstructural examination was undertaken after potentiostatic etching in sodium hydroxide, or after etching in Modified Kallings solutions. The techniques used have been described previously<sup>14</sup>.

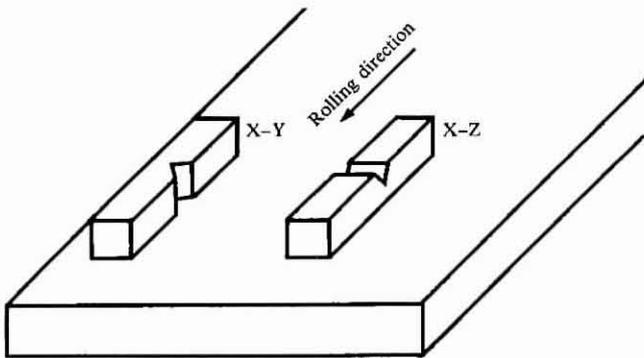


FIGURE 1. Notation used to describe the orientation of impact-toughness and compact-tension specimens (see British Standard BS 5447 for more details<sup>13</sup>)

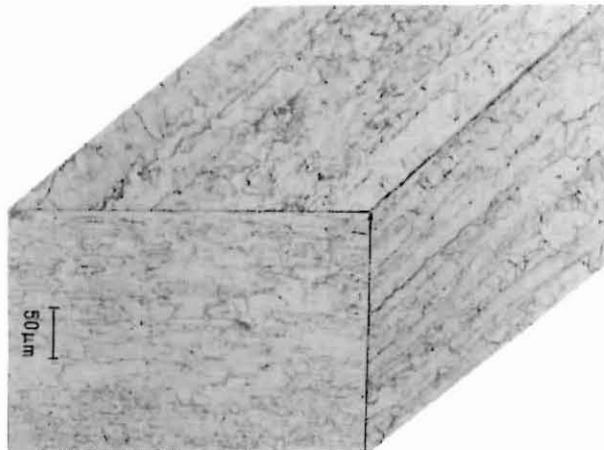


FIGURE 2. Microstructure of as-received 10 mm 3CR12 plate in transverse, longitudinal, and normal directions (micrographs assembled in a pseudo three-dimensional representation, etched in Modified Kallings solution)

The microstructure of the as-received plate is shown in Figure 2 for all three orientations. The pronounced anisotropy of the microstructure is clearly visible. Some of the fatigue-endurance specimens were heat-treated to yield a ferrite-plus-martensite microstructure. This was accomplished by immersion in a neutral salt bath at 1000 °C for 1 hour, followed by water quenching. Quantitative image analysis indicated that such specimens consisted of about 80 per cent martensite, with the balance ferrite (Figure 3).

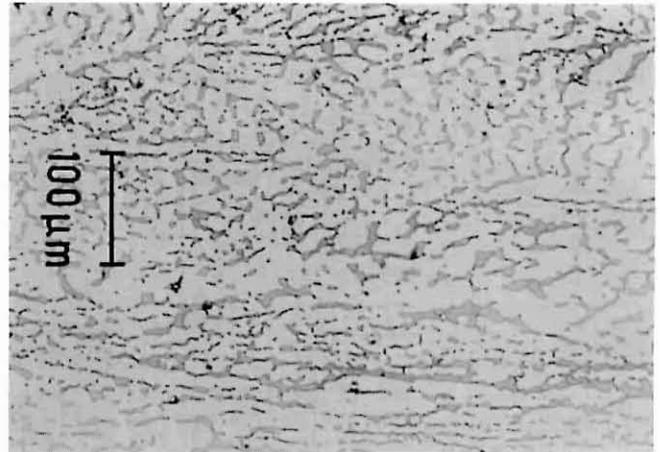


FIGURE 3. Microstructure of 25 mm 3CR12 plate quenched from 1000 °C (potentiostatically etched in sodium hydroxide)

The fatigue testing of smooth specimens was carried out in a 250 kN servohydraulic test machine using hydraulic grips to ensure a constant grip pressure and no slippage. A frequency of 20 Hz, an R-ratio of 0,1, and a sinusoidal waveform were used. The crack-propagation and fracture-toughness experiments were carried out on a computer-controlled servoelectric test machine. The fatigue cracking employed a frequency of 1 Hz, an R-ratio of 0,1, and a triangular waveform. All the tests were carried out in air. The Charpy specimens were machined from the 10 mm 3CR12 plate in the conventional X-Y orientation, as well as in the less-common X-Z orientation.

## Fracture and Fracture Toughness of 3CR12

### Effect of Orientation on Charpy Impact Toughness

It is known<sup>9,15,16</sup> that 3CR12 exhibits anisotropy with regard to its impact toughness. Grobler and Van Rooyen<sup>15</sup>, for example, investigated the difference in toughness between conventional transverse and short-transverse specimens, and they found that the impact toughness in the short-transverse (Z-X) direction was low, with a high ductile-to-brittle transition temperature (DBTT). Weiss and his co-workers<sup>16</sup> found, as expected, a difference in impact toughness between the longitudinal and the transverse directions. However, there does not seem to have been a systematic study of the 'crack arrestor'<sup>17</sup> (X-Z or Y-Z) orientation in 3CR12.

Figure 4 illustrates Charpy impact energies in 3CR12 specimens as a function of temperature for longitudinally orientated crack-arrestor, Figure 4(a), and crack-divider, Figure 4(b), specimens. Also shown on Figure 4 are the

trendlines for the impact data measured by Grobler and Van Rooyen<sup>15</sup> for the short-transverse direction. It can be seen that the 150 J DBTT (a DBTT corresponding to about half the upper-shelf energy) in the crack-arrestor orientation is about  $-15^{\circ}\text{C}$ , which is considerably lower than the corresponding  $55^{\circ}\text{C}$  in the conventional crack-divider orientation. The upper-shelf energy of the crack-arrestor orientation is also somewhat higher than that of the crack-divider specimens. However, the excellent impact properties of 3CR12 in the X-Y or X-Z directions should be compared with the poor toughness of Z-X (short-transverse) specimens.

The toughness of 3CR12 plate is known to vary, like that of most other steels, with the angle of the Charpy specimen to the rolling direction. Figure 5, taken from the work of Matthews and his co-workers<sup>9</sup>, shows the toughness at room temperature of conventional crack-dividing Charpy specimens at angles of 0, 45, and 90° to the rolling direction. It can be seen that, at 22 °C, the toughness of the particular plate tested varied from 90 J in the transverse orientation to 120 J in the longitudinal orientation.

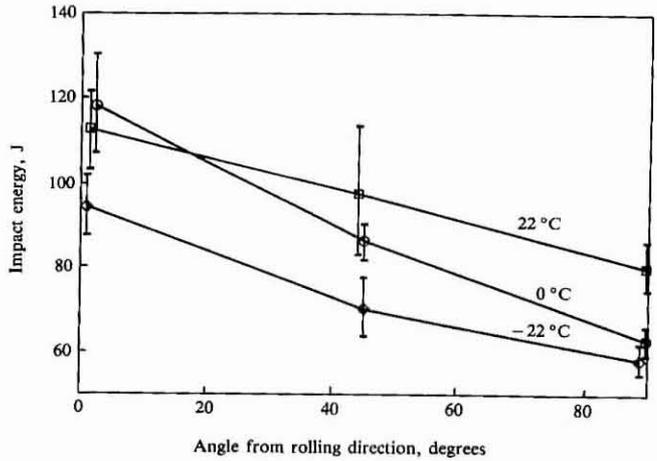


FIGURE 5. Room-temperature fracture toughness as a function of the angle between the specimens and the rolling direction in 10 mm crack-divider specimens (after Matthews, Nana, and Cortie<sup>9</sup>)

### Delamination

The tendency of 3CR12 to delaminate during shearing or mechanical testing is relatively well known, although the mechanisms by which delamination occurs are not entirely clear. It is agreed, however, that the delamination in this material, like that in other susceptible materials, is associated with anisotropy of some kind<sup>9,15,18</sup>. It is also agreed that the major cause of anisotropy in 3CR12 is the fact that the material is hot-rolled in the ferrite-plus-austenite phase field, and that the elongated grains thus produced largely retain their shape after annealing or tempering. Grobler<sup>15</sup> has argued that the delamination is caused primarily by the presence of these pancake-shaped grains of ferrite and martensite, whereas Knutsen<sup>18</sup> has suggested that sheets of manganese sulphide inclusions play the most important role. Matthews *et al.*<sup>9</sup>, on the other hand, have contended that the tendency towards delamination in this material is the result of its crystallographic texture, which in the 25 mm plate consisted of a strong  $\{100\}\langle 110\rangle$  texture intermingled with bands of  $\{111\}\langle uvw\rangle$  texture. The first component of this texture has the effect of aligning the  $\{100\}$  brittle cleavage planes in the rolling plane, as well as at  $45^{\circ}$  to the rolling direction. In addition, the two kinds of band develop strains differently on being stressed, causing separation stresses at their boundaries.

Each of the above mechanisms is known to cause delamination in specific steel alloys, and it is likely that they all play at least some role in the delamination of 3CR12.

The extent of the delamination that occurs depends on the type of metal-working operation and the orientation of the material. The characteristic crack-arrestor fracture mentioned previously is obtained when the direction of crack growth within the material is perpendicular to the rolling plane (X-Z or Y-Z specimens in the notation of BS 5447<sup>13</sup>). An example of a 3CR12 Charpy specimen in the crack-arrestor orientation is shown in Figure 6. The state of triaxial stress around the tip of the advancing crack pulls the banded microstructure of the material apart, resulting in blunting of the crack, a reduction in the triaxiality of stresses at the crack tip, and a significant decrease in the DBTT.

It has been said that delamination in 3CR12 is not detrimental, but this may over-simplify the situation. The much better impact toughness of 3CR12, in comparison with that of type 409, arises from the tendency of 3CR12 specimens

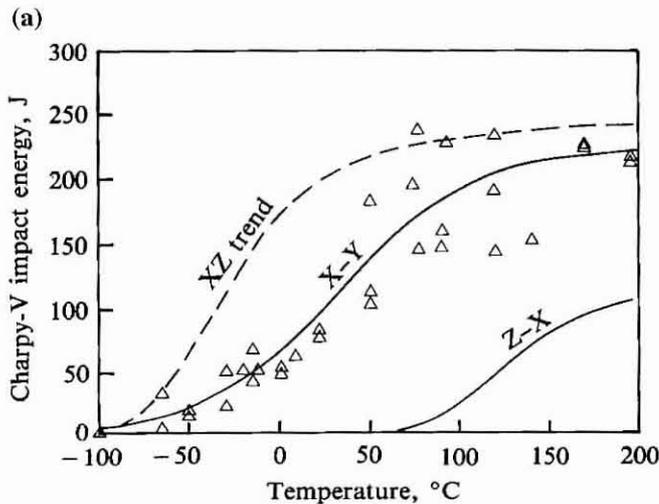
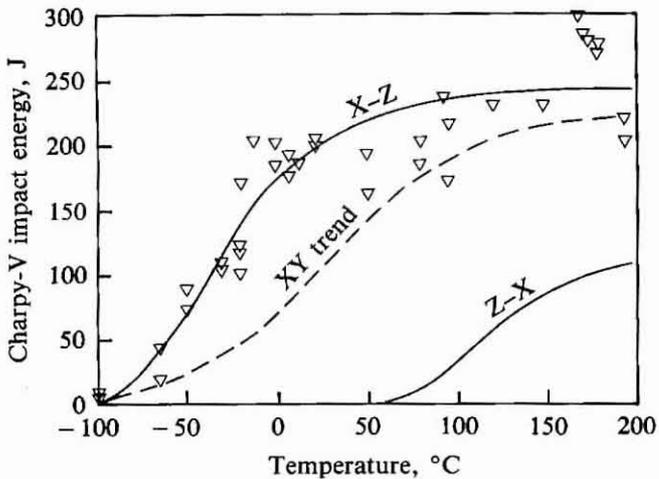


FIGURE 4. Charpy impact toughness as a function of temperature and specimen orientation for 3CR12 plates. The short-transverse line is from the work of Grobler and Van Rooyen<sup>15</sup>  
(a) crack-arrestor (X-Z) orientation  
(b) crack-divider (X-Y) orientation

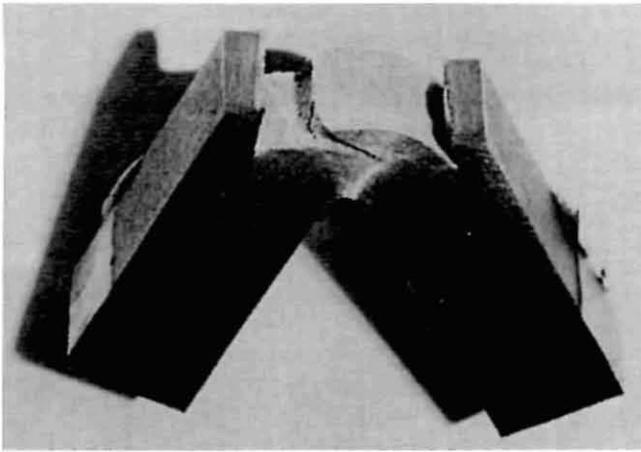


FIGURE 6. A 3CR12 Charpy specimen in the crack-arrestor orientation after impact testing

to delaminate<sup>15</sup> and not, as is sometimes claimed, from the finer grain size of 3CR12. The process of delamination blunts the crack and increases the energy required to tear the material apart. The beneficial effect of delamination on the DBTT must, however, be offset against the low toughness of these materials in the short-transverse direction, as well as a reduction that may occur in the upper-shelf energy<sup>15</sup>.

It is not possible to prepare standard-size Z-X or Z-Y fracture-toughness specimens from 3CR12 plate, and it is necessary to resort to composite specimens as prepared by, for example, Grobler and Van Rooyen<sup>15</sup>. In the present work, Z-X compact-tension specimens were prepared by TIG welding, followed by annealing. It was found, as expected, that the fracture toughness of 3CR12 was low in this orientation, of the order of  $15 \text{ MPa}\sqrt{\text{m}}$ , and that the rate of fatigue-crack propagation was high for alternating stress intensities in the range 12 to  $15 \text{ MPa}\sqrt{\text{m}}$ . The mechanism of crack propagation in these specimens was brittle, transgranular cleavage, Figure 7(a). An examination of the delamination surfaces in Charpy specimens also indicated that the mechanism of delamination in those specimens was that of brittle, transgranular cleavage, often initiated by a particle of titanium carbonitride, Figure 7(b). No evidence was found in these specimens of the intergranular decohesion reported by others<sup>15,18</sup>.

### Testing of Fracture Toughness

The tendency of 3CR12 to delaminate also causes some experimental difficulties when attempts are made to determine its fracture toughness. Since the material is ductile, the appropriate fracture-toughness test is either the COD test<sup>19</sup> or the J-integral test<sup>20</sup>. The latter test requires that the energy absorbed be plotted against the variation in the length of the crack. The length of the crack in a sample that is in the process of delaminating is, however, an indeterminate quantity. Figure 8 shows a trace of load versus clip-gauge displacement in a specimen of 3CR12 that was loaded in a J-integral test. The load-clip trace *appears* to show that extensive yielding and tearing have taken place. However, examination of the actual specimen after heat tinting and cryogenic fracturing revealed (Figure 9) that no extension of the pre-fatigue crack had taken place, although there was extensive delamination (arrowed).



(a)



(b)

FIGURE 7. Surfaces produced by delamination (a) in a fatigue specimen with a crack growing in the short-transverse direction, and (b) in a Charpy impact test with a crack-arrestor specimen

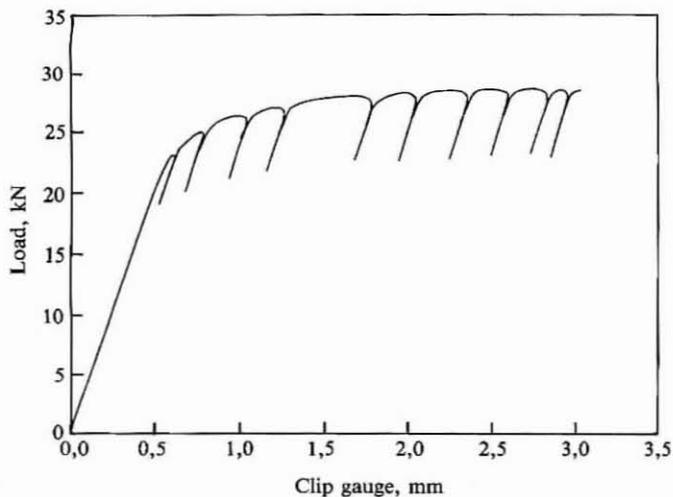


FIGURE 8. Graph of load versus clip-gauge displacement obtained during a J-integral fracture-toughness test of 3CR12. The load reversals result from the unloading compliance technique used for the measurement of crack length

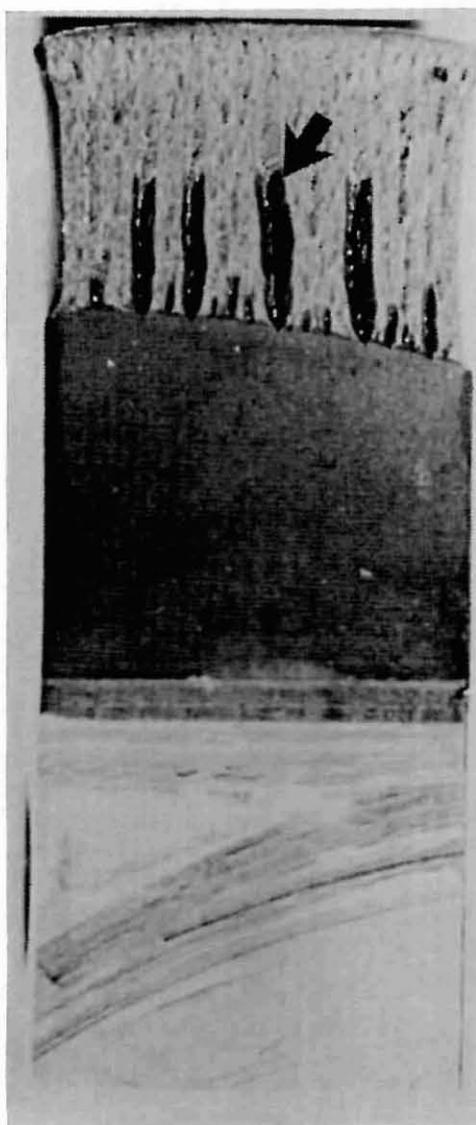


FIGURE 9. The fracture-toughness specimen shown in Figure 8 after heat-tinting and cryogenic fracture. Extensive delamination has taken place (arrowed)

Experience at Mintek has shown that the tendency towards delamination is greater in thicker specimens, an observation consistent with the known increase in triaxially induced through-stresses with greater specimen thickness. In addition, it is common to estimate crack extension during the J-integral test by means of changes in elastic compliance. However, the equations and correlations used for the estimation of crack length do not allow for extensive delamination, and the supposed crack length calculated is probably in error. It is hence problematic, and possibly incorrect, to cite  $J_{Ic}$  values for 3CR12 plate (or for any other material that exhibits significant delamination). The same objection may apply to parameters such as  $\delta_i$ , the critical COD value at which slow crack growth commences.

## Fatigue Cracking in 3CR12

### Fatigue Endurance at Room Temperature

In studies of the fatigue behaviour of weldments at The Welding Institute<sup>10,11</sup>, it was found that 3CR12 behaved in a fashion similar to that of structural steels. However, the effect, if any, of the anisotropy in 3CR12 on fatigue endurance does not seem to have been investigated previously.

In the present work, it was found that the fatigue endurance of the as-received material did not vary dramatically between the 0, 45, and 90° specimens, although there was an indication that the life of the 45° specimens *may* have been slightly shorter than the others. The fatigue lives of the heat-treated specimens lay within the scatter band of the fatigue lives of the as-received specimens, and there is no justification at this stage for supposing that any difference exists between them for this particular type of test. The results for specimens in the 0 and 90° orientations are shown in the S-N diagram of Figure 10. Overall, the results are similar to those expected for normal structural steels, confirming the findings of previous investigators<sup>10</sup>.

Although the tendency of this material to delaminate when subjected to through-thickness cyclic stresses might be expected to be deleterious, studies at The Welding Institute<sup>10,11</sup> have found that, from an engineering point-of-view, delamination has a negligible effect on the overall

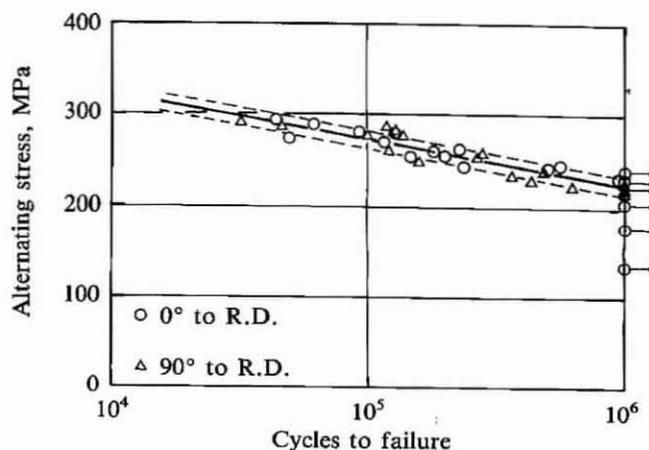


FIGURE 10. S-N diagram for the fatigue behaviour of 3CR12 specimens in air at 25 °C for specimens at 0 and 90° to the rolling direction

fatigue endurance of a variety of welded joints. However, as already noted in the section on fracture toughness, once a crack has initiated in the short-transverse plane it can be expected to propagate rapidly on account of the material's low fracture toughness in that plane.

### Propagation of Cracks at Room Temperature

The rate of fatigue-crack propagation in 3CR12 at room temperature as previously determined by MS&A was found to be similar to the rate of fatigue-crack propagation in other structural steels. In addition, MS&A reported that there is little difference in the rate of crack propagation between the T-L and L-T directions. These observations are consistent with the fact that the propagation rate of Stage II fatigue cracks is largely independent of the microstructure of a material and depends for the most part on the value of the Young's modulus<sup>17</sup>. This is in contrast to the propagation of Stage I fatigue cracks, where it is known that the microstructure has a relatively strong effect.

Despite the similarity in their fatigue lives, the as-received and the heat-treated specimens exhibited rather different fatigue-cracking mechanisms. The cracks in as-received specimens were propagated by the formation of ductile striations accompanied by delamination at right-angles to the crack. A typical region is shown in Figure 11, and contains secondary cracking and patches of striations. Figure 12 shows the delamination that occurred *ahead* of a fatigue crack propagating in a compact-tension specimen. This is indicated by the fact that the crack front has bowed at the delaminations. The alternating stress intensity over the region of cracking shown was about  $60 \text{ MPa}\sqrt{\text{m}}$ .



FIGURE 11. Surface of a fatigue crack in as-received 3CR12, showing striations and secondary cracking



FIGURE 12. Low-magnification view of an S-N specimen of as-received 3CR12, showing that the final fracture was associated with extensive delamination

The surfaces of the cracks in the heat-treated material were rather different, and showed that cracking occurred by intergranular fracture around the ferrite grains and quasi-cleavage through the martensite (Figure 13). Delamination

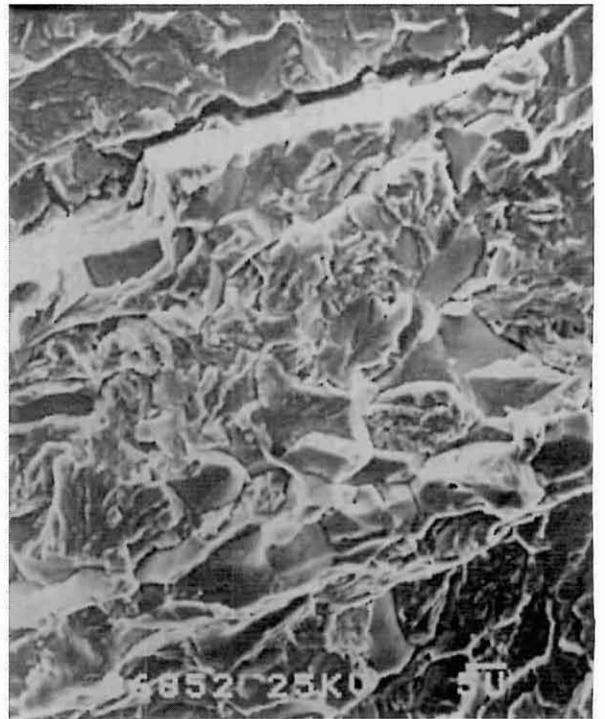


FIGURE 13. Surface of a fatigue crack in a sample of heat-treated 3CR12. The crack was propagated by a mixture of intergranular fracture and quasi-cleavage

in specimens that had been heat-treated to yield a microstructure of martensite and ferrite was not observed in this work.

### Propagation of Fatigue Cracks at Elevated Temperatures

The good oxidation resistance of 3CR12, relative to that of steel alloys that do not contain chromium, indicates that it can be used for a variety of elevated-temperature applications. Since some of these applications might involve cyclic loading, it was of interest to determine the propagation rates of fatigue cracks at elevated temperatures as a function of  $\Delta K$ .

The propagation rate of fatigue cracks at 550 °C is shown in Figure 14. The diagram also shows a scatter band encompassing the reported rates of crack growth in 3CR12 at room temperature, as well as a curve showing the behaviour measured for the alloy Fe-0,5% Cr-0,5% Mo-0,25% V (frequently known as 1/2-1/2-1/4). It is evident that the rate of fatigue-crack propagation in 3CR12 at 550 °C is comparable with that of the latter alloy, which is frequently specified for application in the steam lines of power stations.

The rate of fatigue-crack propagation in 3CR12 is about five times greater at 550 °C than at room temperature at  $\Delta K$  values of about 20 MPa $\sqrt{m}$ . The difference between the rates of fatigue-crack growth at 550 °C and room temperature decreases as  $\Delta K$  rises, and the rate of growth at 60 MPa $\sqrt{m}$  does not vary much over the temperature range 25 to 600 °C. These results indicate that there is a time-dependent component to the propagation of fatigue cracks in

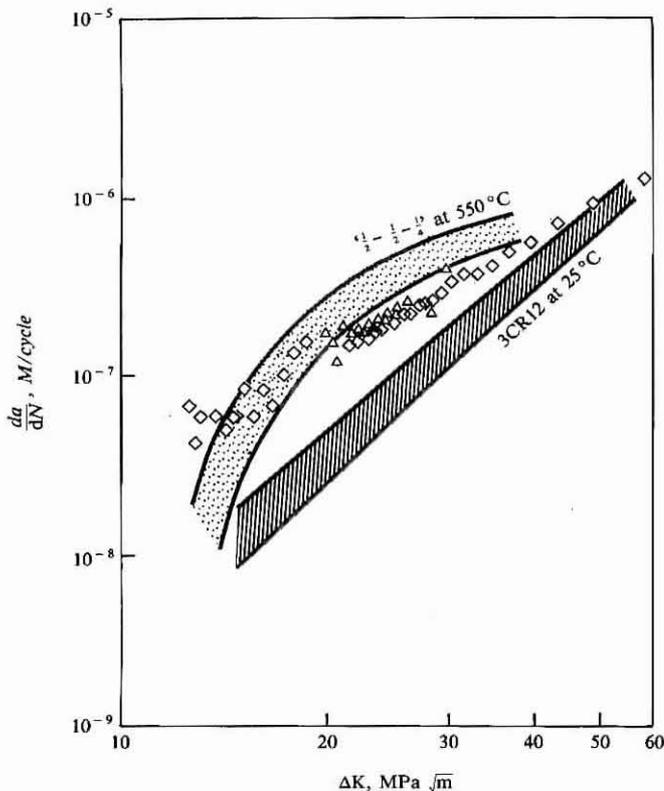


FIGURE 14. Rate of fatigue-crack propagation in 3CR12 at 550 °C and 1 Hz. The rate of fatigue-crack propagation in 3CR12 at room temperature and that of the alloy 1/2-1/2-1/4 at 550 °C are shown as scatter bands

3CR12 at elevated temperatures, just as in other ferrous materials. Although many authorities consider that creep is the applicable time-dependent phenomenon in ferrous materials<sup>21</sup>, work carried out at Mintek has indicated that the mechanism may involve gas adsorption or oxidation<sup>22</sup>. The visible mechanism of crack propagation remains that of the formation of ductile striations.

## Discussion

### Comparison of 3CR12 with Other Dual-phase Steels

It is known that the microstructure of a material can exert considerable influence on the growth of fatigue cracks at low values of  $\Delta K$ . This is especially true of dual-phase steels, where it has been found that the amount and morphology of the martensite can exert a marked effect on the fatigue threshold<sup>23-26</sup>. This effect has been explained in terms of the roughness-induced crack closure<sup>24</sup> or, in a nearly equivalent view, in terms of the tortuousness of the crack paths<sup>25</sup>. The real differences between the growth rates of Stage I cracks for the various possible ferrite-martensite microstructures are, however, masked during endurance (S-N) testing, and such materials have very similar fatigue lives<sup>25,27</sup>. This phenomenon results from the fact that the life of smooth endurance specimens is largely determined by the time taken for the initiation of a fatigue crack, which depends mostly on the quality of the surface of the material and on the presence of any sizeable flaws. It is therefore not surprising that, although 3CR12 has a fairly different composition and microstructure, its fatigue-endurance properties are similar to those of carbon-manganese structural steels.

### Delamination

A small amount of delamination, or splitting, commonly occurs in structural steels, but it occurs to a greater extent on suitably oriented fracture surfaces in 3CR12. It was shown earlier that delamination in the crack-arrestor orientation can lower the DBTT and increase the amount of energy absorbed during the fracture of 3CR12. Delamination can occur whenever there are parallel planes with slightly different mechanical properties. In structural steels, for example, the planes may be regions of slightly higher manganese and carbon content formed by interdendritic segregation<sup>28</sup>, or the planes may be defined by sheets of inclusions. These inclusions may be rare-earth oxides or sulphides, manganese sulphide stringers, or any of a variety of metal carbides.

It is probable that each of the mechanisms proposed for the occurrence of delamination in 3CR12 plays some role. However, it can be argued that the real cause of delamination is the layered microstructure, and that the role of the inclusions is, firstly, to hinder the development of equiaxed ferrite grains, and, secondly, to provide convenient sites for decohesion. The known effect of the titanium, sulphur, carbon, and nitrogen contents<sup>18</sup> on the tendency towards delamination in 3CR12 plate can be explained in terms of the different morphology of the manganese sulphide and titanium sulphide inclusions, and the consequent effects that these inclusions have on the development of the ferrite-martensite microstructure during subcritical annealing. This opinion is supported by observations that delamination is less common, or absent altogether, in specimens

that have been heat-treated at 1000 °C to produce roughly equi-axed grains of ferrite and austenite. This treatment does not greatly alter the distribution of the inclusions<sup>6</sup>, but it does change the microstructure from layered to equi-axed. It is difficult to evaluate the contribution of the crystallographic texture in 3CR12, although it has been proposed as a sufficient cause of delamination in some other alloys<sup>29,30</sup>. The observation that delamination usually occurs in 3CR12 by way of transgranular cleavage parallel to the plane of splitting indicates that the role of texture is not insignificant, and it can be concluded that the delamination would be less evident if the material possessed, for example, a {111}-type texture.

### Conclusions

- (1) Although rarely seen in the field, specimens of 3CR12 may delaminate when they are subjected to various laboratory mechanical tests.
- (2) The delamination properties of the material result in large variations in the impact toughness with direction, as determined by laboratory testing.
- (3) Excellent impact-toughness properties can be obtained with crack-arrestor orientations, but these may be offset against weaker properties in the short-transverse direction.
- (4) The tendency of mechanical test specimens to delaminate during fracture precludes the application of the J-integral fracture-toughness test to these materials.
- (5) The fatigue-endurance properties of specimens aligned within the X-Y plane show little or no variation with orientation, and are similar to those of structural steels.
- (6) The propagation of fatigue cracks in 3CR12 is accompanied by delamination but, for all directions except the short-transverse direction, this does not affect the rate of crack growth significantly.
- (7) The growth of fatigue cracks is rapid in the short-transverse direction, and the fracture toughness of the material in that direction is of the order of  $15 \text{ MPa}\sqrt{\text{m}}$ .
- (8) The fatigue-crack propagation properties at elevated temperatures in the longitudinal and transverse planes of 3CR12 are excellent, and are similar to those of existing steels intended for high-temperature applications.

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