UPPER SHELF FRACTURE TOUGHNESS OF AS-WELDED MANUAL METAL ARC WELD METAL

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Abstract

Structural integrity assessment procedures such as R6 use fracture toughness as one of the input parameters for considering flaws that are associated with welds. In this paper, results of fracture toughness testing performed on manual metal arc weld metal in the as-welded and stress relieved conditions are compared. Tests were performed on standard 25mm thick compact tension specimens machined from nominally 100mm thick weldments manufactured using basic coated Fortrex 35A consumables and C-Mn steel parent plate. The baseline for the dependence of fracture toughness on temperature was established by performing tests on stress relieved weld metal as a function of temperature. A comparison between the fracture toughness of as-welded and stress relieved weld metals was made by testing specimens from the same weld at 200°C. To assess the temperature dependence of as-welded weld metal, further tests were performed at 300ºC.

Introduction

Manual metal arc welding is used frequently in the manufacture of structural components. In general, manual metal arc weldments are subjected to a stress relief heat treatment. When the thickness of welded components is below 25mm and it is subjected to moderate stresses, it is often deemed acceptable to use them in the as-welded condition. Welds are judged to be most likely to contain any potential defects and are designed to be tolerant of flaws and defects. A fracture mechanics based approach which employs the R6 assessment procedure [1] is used to assess margins against failure avoidance. The main inputs in this assessment procedure are (i) depth, shape and position of a potential defect, (ii) tensile and fracture toughness properties, (iii) loading conditions, and (iv) geometry and dimensions of the plant component. In a previous investigation, upper shelf fracture toughness properties of manual metal arc weld metal in a stress relieved condition were established by Windle and Moskovic [2,3]. In this paper, results of fracture toughness tests in the upper shelf temperature region performed on the as-welded and stress relieved manual metal arc weld metal are described. The fracture toughness test programme has two aims. First, to establish a baseline for the temperature dependence of fracture toughness. These tests were principally carried out on stress relieved weld metal. Secondly, to compare the fracture toughness properties of as-welded and stress relieved weld metal by performing tests at the same temperature of 200°C on specimens manufactured from the same weld.

Material

Double V butt welds was used for this investigation. Typical macrostructure of the weldment and hardness measurements are shown in Figure 1. The macrostructure of the welds reveals beads consisting of cast columnar grains and heat treated fine grained microstructures. The microstructure of the columnar grains, shown in Figure 1b, comprises proeutectoid allotriomorphic ferrite at the grain boundaries and acicular ferrite within the grains.

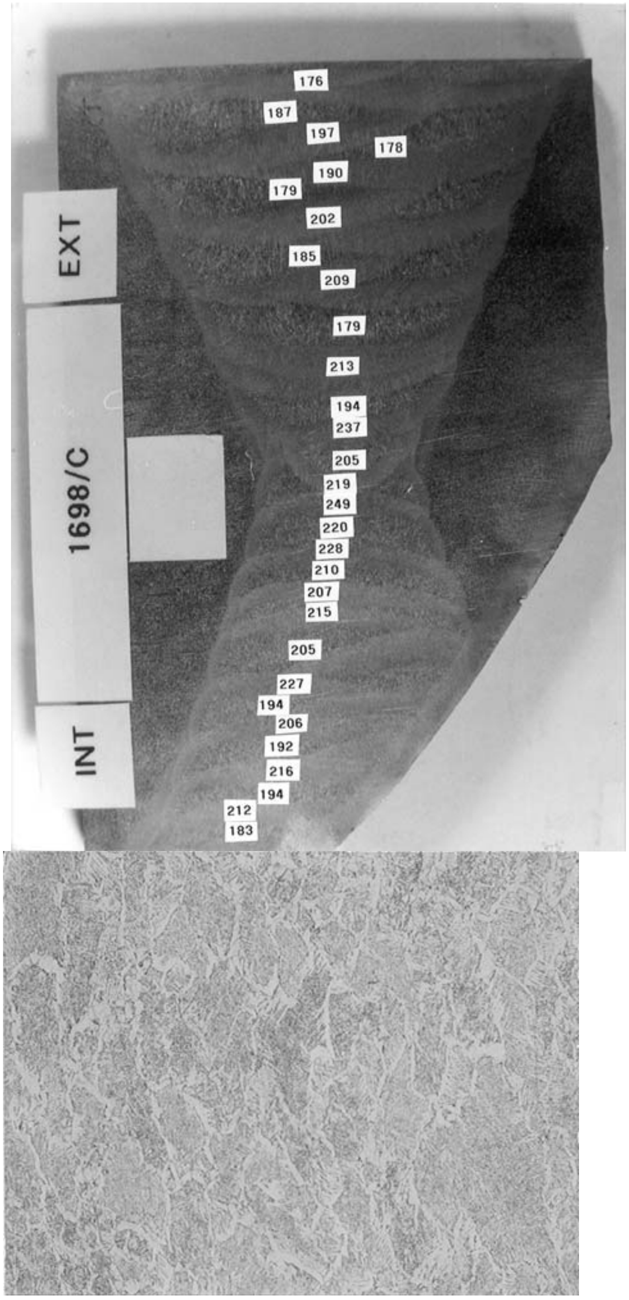

Figure 1 Shows a) typical macrostructure and hardness of double V butt MMA weld used for testing and b) microstructure of the columnar grains.

Chemical analyses were carried out on samples located on the centreline of the weld and taken 5 and 25mm below the free surfaces of the weld. The mean concentration of the main alloying and impurity elements for the weld metal was in weight percent 0.073%C, 0.39%Si, 0.84%Mn, 0.023%S and 0.027%P. In addition, chemical analyses of the parent plates gave: 0.13-0.16%C, 0.13%Si, 0.92-1.31%Mn, 0.030%S and 0.015%P. The mean values of 0.2% proof stress and the ultimate tensile stress as a function of temperature are given in Table 1 for stress relieved weld metal.

The stress relief heat treatment was carried out in a laboratory and comprised heating at a rate of 20ºC/hour to 600ºC, a dwell period of 6 hours, cooling at a rate of 10ºC/hour to 300ºC and then air cool.

TABLE 1. Tensile properties of stress relieved MMA weld metal as a function of temperature.

Temperature (°C)	21	100	150	200	250	300	350
0.2%PS (MPa)	362	343	332	320	309	297	286
UTS (MPa)	481	457	448	444	444	450	460

Fracture Toughness Testing

Fracture toughness testing was carried out on 25mm thick standard compact tension specimens. Following machining, spark eroded notches were further extended by fatigue to achieve an a_0/W, initial crack length to specimen width, ratio of approximately 0.5. The fatigue crack was developed with a maximum stress intensity of 25MPam$^{0.5}$. Specimens were instrumented with a LVDT gauge mounted on the loading rams and with a clip gauge mounted across the open mouth of the test piece between the knife edges. The test specimens and the loading shackles were enclosed in an environmental chamber in which the test temperature was controlled to within ±1°C. Loading of specimens was carried out under the displacement control at a crosshead speed of 1mm/min. Prior to breaking the specimens open, the extent of ductile crack growth was marked by heat tinting and then measured in an optical microscope. An average value of ductile crack growth extension was calculated from eight values comprising the mean of the two surface measurements and seven equally spaced measurements across the crack width. Values of J appropriate to the final load point displacement were calculated from load vs displacement records from:

$$J = \eta U/B(W\text{-}a_0) \qquad (1)$$

Whee $\eta = 1.97 + 0.815(1\text{-}a_0/W)$, U is the area under the load vs displacement curve appropriate to the final point and B is the specimen width. The values of the fracture toughness, J, obtained from equation (1) and the ductile crack growth, Δa, were compared with the validity criteria given in [4] summarised below:

a) J_{max} in N/mm should not exceed the smaller of

$$\frac{(w - a_0)R_f}{25} \text{ and } \frac{BR_f}{25} \qquad (2)$$

b) The observed values of Δa measured in mm should be in the range:

$$0.2 \text{ mm} \leq \Delta a \leq 0.06(W\text{-}a_0) + 0.2 \text{ mm} \qquad (3)$$

where R_f is the flow stress in MPa taken as the average of the yield and ultimate tensile stress. The values of R_f as a function of temperature were calculated from data in Table 1.

Results

To compare the as-welded and stress relieved weld metals, fracture toughness tests were performed at 200°C using specimens manufactured from the same weld. To examine the temperature dependence of fracture toughness, specimens in the as-welded condition, from the same weldment, were tested at 300°C. The temperature dependence of upper shelf fracture toughness in stress relieved condition was established by testing several specimens at temperatures of –20ºC to 40ºC, 200ºC, 300ºC and 360ºC using weld metal specimens from a different weldment than that used for tests at 200°C and 300°C mentioned earlier. The results for the first weld are presented in Table 2 and shown graphically in Figure 2. The results from the second weld are shown in Figure 3.

Comparison of the data in Table 2 with the validity criteria showed that the only violation of the validity requirements was for four values of Δa that are smaller than 0.2 mm. From inspection of Figure 2 it was judged that these values follow the same trend as the remaining data and thus it was decided to use them in statistical analysis.

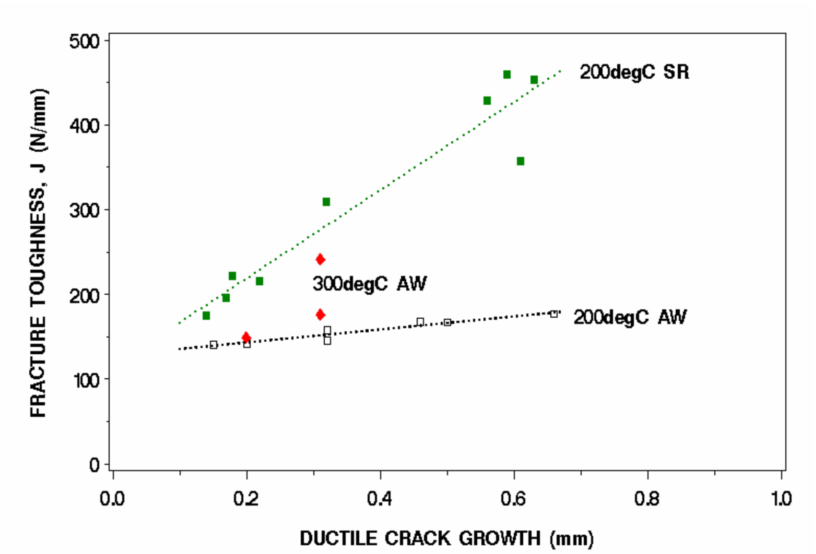

Figure 2 Comparison of fracture toughness of MMA obtained for the as-welded condition at 200ºC and 300ºC, and the stress relieved condition at 200ºC.

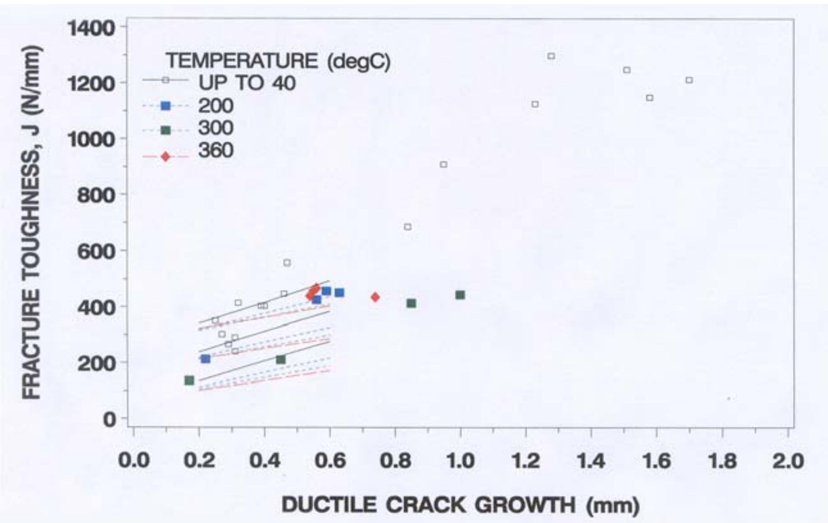

Figure 3 Fracture toughness of MMA weld metal in stress relieved condition as a function of temperature compared with estimates by Windle and Moskovic [3].

TABLE 2. Fracture toughness data for MMA weld metal in the as-welded and stress relieved conditions.

Sp. No.	Temp.	B (mm)	W (mm)	a_0 (mm)	Δa (mm)	J (N/mm)	HT Condition
S1	200	25.01	49.90	25.27	0.66	177	As-welded
S2	200	25.01	49.85	25.25	0.20	142	As-welded
S3	200	25.14	50.00	25.26	0.50	167	As-welded
S4	200	25.13	49.95	25.18	0.32	146	As-welded
Sp. No.	Temp.	B (mm)	W (mm)	a_0 (mm)	Δa (mm)	J (N/mm)	HT Condition
S5	200	25.01	49.95	25.28	0.32	158	As-welded
S6	200	25.14	49.95	25.28	0.15	141	As-welded
S7	200	25.15	50.03	25.37	0.46	168	As-welded
S8	300	25.14	50.00	25.15	0.20	150	As-welded
S9	300	25.07	49.95	25.21	0.31	242	As-welded
S10	300	25.17	50.00	25.18	0.31	177	As-welded
SR1	200	25.05	50.00	25.23	0.18	222	Stress Relieved
SR2	200	25.05	49.95	25.25	0.61	358	Stress Relieved
SR3	200	25.02	49.90	25.30	0.17	196	Stress Relieved
SR4	200	25.01	49.85	25.13	0.14	175	Stress Relieved
SR5	200	25.05	49.95	25.04	0.32	310	Stress Relieved
SR6	200	25.00	50.00	25.55	0.63	454	Stress Relieved
SR7	200	25.00	49.90	25.94	0.56	429	Stress Relieved
SR8	200	24.95	50.00	25.76	0.59	460	Stress Relieved
SR9	200	25.00	50.00	25.50	0.22	216	Stress Relieved

Analyses of data for as-welded and stress relieved weld metal

Upper shelf fracture toughness can be modelled by [3,5]:

$$J_i = C_0 + C_1\Delta a_i + \sigma\varepsilon_i \qquad (4)$$

In equation (4), J_i in N/mm and Δa_i in mm are the measured data (indexed by i), C_0, C_1 and σ are constants that need to be estimated by regression analysis, and ε_i is the random error in the data which is represented by a normal distribution with a mean of zero and variance of 1.

Visual comparison of the fracture toughness data at 200ºC, presented in Figure 2, shows that the data for the as-welded condition exhibit less scatter, are lower and have a lower crack growth resistance than the data for the stress relieved condition. Hence, all three constants in equation (4) will be different for the two sets of data and it is appropriate to analyse the two sets of data separately. The analyses give:

as-welded condition

$$J = 128.4 + 76.6\Delta a \qquad s = 4.49 \text{ N/mm} \qquad R^2 = 91.8\% \qquad (5)$$

stress relieved condition

$$J = 115.4 + 520.8\Delta a \qquad s = 35.87 \text{ N/mm} \qquad R^2 = 91.6\% \qquad (6)$$

where s^2 is the sample estimate of the variance about the regression and R^2 defines the goodness of fit of the model in % and is calculated as the ratio of the sum of squares due to the regression to the total sum of squares, corrected for the mean. Equations (5) and (6) have been used to estimate fracture toughness values for the mean, and the 5% and 95% prediction interval limits (PIL), single sided, as a function of ductile crack growth. The values of these estimates are given in Table 3.

TABLE 3: Estimates of fracture toughness obtained from regression analysis at 200ºC for MMA weld metal in the as-welded and stress relieved conditions.

Ductile crack extension (mm)	Estimates of J (N/mm)					
	As-Welded			Stress relieved		
	5% PIL	Mean	95% PIL	5% PIL	Mean	95% PIL
0.2	133.4	143.8	154.1	145.1	219.6	294.0
0.4	149.4	159.1	168.8	252.1	323.7	395.4
0.6	163.7	174.4	185.2	352.1	427.9	503.7
0.8	176.6	189.7	202.8	446.2	532.1	617.9
1.0	188.9	205.0	221.2	536.1	636.2	736.3

Table 3 shows that the difference in the estimates of fracture toughness for the two conditions varies with both ductile crack growth and the probability level. This is due to the fact that in equations (5) and (6) all three constants are different. For the as-welded weld metal, the increase in fracture toughness with ductile crack growth is smaller than for the stress relieved condition. Equations (5) and (6) also show that the standard deviation about regression is smaller for the as-welded than for the stress relieved weld metal. The intercepts in equations (5) and (6) are very similar. Overall behavour of the fracture toughness of the weld in the two different heat treatment conditions is such that the 5% prediction interval limits are similar at 0.2mm of ductile crack growth but the two sets of estimates of fracture toughness values diverge as both the ductile crack growh and the probability level for which the predictions are made increase. The estimates of fracture toughness in Table 3 can be also compared with those obtained by [3]. Comparison of the estimates given in Table 3 with those in [3] showed that for the stress relieved condition values in [3] bound the present data. Furthermore, at 0.2mm of ductile crack growth the estimates obtained by Windle and Moskovic [3] also bound the values for the as-welded condition.

Analysis of data for stress relieved weld metal

The data available for the analysis are shown in Figure 3. Several values of ductile crack growth were found to be smaller than 0.2mm, the minimum validity limit, and most of the J values associated with ductile crack growth greater than 0.4mm were higher than the maximum validity limit for J. A visual inspection of the data combined with some exploratory regression analysis showed that the J vs Δa values associated with Δa values in the range 0.13mm<Δa<1.1mm can be approximated by a straight line. The analysis was carried out using a statistical model of the form

$$J_i = \Sigma C_{0j} Z_j + \Sigma C_{1j} Z_j \Delta a_i + \Sigma \sigma_j Z_j \varepsilon_i \qquad (7)$$

where j indexes test temperatures with j=1 for T<50ºC, j=2 for T=200ºC, j=3 for T=300ºC and j=4 for T=360ºC. Z_j are dummy variables which take values of zero or one as follows:

TABLE 4. Values of dummy variables.

Temperature (ºC)	Z_1	Z_2	Z_3	Z_4
<50	1	0	0	0
200	0	1	0	0
300	0	0	1	0
360	0	0	0	1

Multiple regression gave as the best fit model:

a) for the mean

$$J = 106.58 + 763.06Z_1\Delta a + 545.48Z_2\Delta a + 356.03Z_3\Delta a \tag{8}$$

For the purpose of estimating the mean, no statistically discernible difference was found between the data for 200ºC and 360ºC. Hence, these data were assigned the same dummy variable, Z_2. The estimates of standard deviation about the regression as a function of temperature are given in Table 5.

TABLE 5. Standard deviation about the regression as a function of temperature.

Temperature (ºC)	<50	200	300	360
Standard deviation about regression (N/mm)	59.3	32	34	58

Discussion

In some cases, a structural integrity assessment of flaws in weld metal in the as-welded condition may need to be carried out. Measurements of fracture toughness values on MMA weld metal in the as-welded condition are less common since it is more usual to derive the fracture toughness properties from those for stress relieved condition by using scaling factors. The data reported by Mukherjee [6] for stress relieved and as-welded weld metal give a scaling factor of 0.42 between $J_{0.2}$ values for as-welded and stress relieved conditions. However, more comprehensive data in Table 3 give ratios between $J_{0.2}$ values for as-welded and stress relieved conditions of 0.52, 0.66 and 0.92 for the 95% prediction interval limit, mean and 5%prediction interval limit. The variability in the scaling factor with the probability level is due to the large difference in the variance for the two conditions.

In principle, the scaling factors derived from data obtained at 200°C, can be applied across the whole upper shelf temperature region. However, in order to apply the scaling factors obtained at 200°C to other temperatures it is necessary to show that this will result in pessimistic estimates of fracture toughness for the as-welded condition for use in structural integrity assessments. In order to make a judgement, it is necessary to consider how the upper shelf fracture toughness varies with temperature. Windle and Moskovic [3] have shown that the variability of fracture toughness with temperature is affected by the propensity of the weld metal to strain age. Ductile crack growth resistance may be considerably reduced by dynamic strain ageing and this also has a small effect on $J_{0.2}$. Test data for stress relieved MMA weld metal are presented as a function of temperature in Figure 3. Multiple regression analysis of these data showed that both the crack growth resistance and variance of the data vary with temperature. The analysis of the data reveals that with increasing temperature up to

300ºC the crack growth resistance decreases. The data obtained at 360ºC fall within the same scatter range as the data for 200ºC implying that the crack growth resistance increases above 300ºC. Furthermore, the variance about regression at 200ºC and 300ºC is less than one third of that below 50ºC and at 360ºC. A plausible explanation for this is that strain ageing may promote lower crack growth resistance at 200ºC and 300ºC. With regard to the variability of scatter in the data with temperature, the higher variance below 50ºC may have arisen because a single crack growth resistance curve was fitted to data obtained at several different temperatures. Even if temperature variability of fracture toughness is small in this temperature range, scatter may increase when data obtained at several different temperatures are pooled into a single set. At 360ºC, scatter would be increased if the material had a low propensity to strain age and the intensity of strain ageing would vary between specimens.

One of the beneficial effects of a stress relief heat treatment is a reduction in the propensity to strain age. In the upper shelf temperature region, dynamic strain ageing leads to a significant reduction in the slope of crack growth resistance curve. Fracture toughness tests performed on silicon killed plate steels [3] showed that the peak in dynamic strain ageing occurs between 165ºC and 275ºC, and that this temperature range is associated with a slope of the crack growth resistance curve which is independent of temperature [3]. Above approximately 275ºC, the crack growth resistance would be expected to increase. This is supported by inspection of data in Table 2, which shows that for the as-welded condition the values for 300ºC are higher than for 200ºC. Hence, the largest increase in crack growth resistance resulting from stress relief heat treatment would occur at these temperatures. The differences in the upper shelf fracture toughness between the stress relieved and the as-welded conditions established at 200ºC should be greater than at other temperatures:

i) The fracture toughness of the as-welded material is expected to be more reduced in relation to stress relieved condition at a temperature of 200ºC.
ii) The fracture toughness of the MMA weld metal in the stress relieved condition is higher at 200ºC than at 300ºC.
iii) The fracture toughness of the MMA weld metal in the as-welded condition is lower at 200ºC than at 300ºC.

As a consequence, the scaling factors estimated at 200ºC can be applied across the whole upper shelf temperature range to estimate conservatively the fracture toughness of the as-welded MMA weld metal.

Conclusions

1. Upper shelf fracture toughness properties of MMA weld metal for the as-welded and stress relieved conditions have been evaluated.

2. It has been found that the crack growth resistance and scatter in fracture toughness are both lower in the as-welded than in stress relieved condition.

3. The lower bound values of $J_{0.2}$ for the two conditions are similar. Scaling factors have been derived that can be used in structural integrity assessments to scale the fracture toughness of stress relieved weld metal to obtain that for the as-welded condition.

Acknowledgement

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