Microstructure-fatigue Crack Growth Rate Correlation in Multipass Submerged Arc C–Mn Steel Weld Deposit

P. K. GHOSH, Potluri NAGESH BABU and P. C. GUPTA

Welding Research Laboratory, Department of Mechanical and Industrial Engineering, University of Roorkee, Roorkee-247 667, India.

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All-weld blocks of C–Mn steel were prepared by multipass submerged arc weld deposit, using different welding currents (500–750 A) and speeds (40–60 cm/min), filler wire of 4 mm diameter and a basic bonded type flux. The dendrite content of the weld blocks was estimated by quantitative metallography technique. The fatigue crack growth rate of the weld at LT direction of the block was evaluated by using C-T specimens and correlated with the area fraction of dendrite (D_f) of the matrix. The increase in dendrite content of the matrix was found to reduce the crack growth rate by influencing significantly the material constant C and exponent m of Paris law, $da/dN = c(\Delta K)^m$, where, ' a ' is the crack length, ' N ' is the number of loading cycle and ΔK is the stress intensity factor range. The modification of C and m with D_f was found to provide a satisfactory basis for the evaluation of fatigue crack growth rate of multipass C–Mn steel weld deposit having a given amount of dendrite.

KEY WORDS: submerged arc weld; multipass deposit; C–Mn steel; microstructure; fatigue crack growth rate; correlations.

1. Introduction

The knowledge of mechanical properties of weld deposit, especially under dynamic loading is of paramount importance in recent days of technologies for the quality assesment of weld joint. The mechanical properties of weld metal is largely dependent on its microstructure. In case of multipass welding the microstructure of weld deposit, primarily consisting of the randomly distributed region of cast co-axial dendrites and heat affected zone of reheat refined grains, is to a great extent determined by the welding parameters affecting the bead geometry and repeating weld thermal cycle. The variation in microstructure is found to influence considerably the mechanical properties of weld deposit.^{1,2)} The fatigue crack growth rate along LT direction, having fracture plane perpendicular to the direction of welding, is quantitatively found to be reduced with the increase in dendrite content of a multipass submerged arc C–Mn steel weld deposit.³⁾ However, this behaviour is found to be more pronounced at the lower range of stress intensity (ΔK) below about $50 \text{ MPa}\sqrt{\text{m}}$, because the sensitivity of the crack growth rate to ΔK markedly varies with the dendrite content of the martix.³⁾ Thus, for a precise understanding over the fatigue crack growth behaviour of a multipass weld, required for the quality assesment under a specific service condition of a weldment of thick section or a shape welded component, a correlation among the fatigue crack growth behaviour, microstructure and stress intensity level may

be very much useful. Viewing the lack of knowledge in this direction, the present investigation has been targeted towards finding a correlation among the fatigue crack growth rate, stress intensity and dendrite content of a multipass submerged arc C–Mn steel weld.

2. Experimental

Some all-weld metal blocks of C–Mn steel (Fig. 1) were prepared by multipass submerged arc welding process, where a filler wire of diameter 4.0 mm and a basic bonded type flux (automelt Gr. IV) were used. The deposition of weld metal was carried out (Table 1) by varying the welding current and speed in the range of 500–750 A and 40–60 cm/min, respectively. During multipass deposition the preheating or interpass temperature was maintained

Fig. 1. Typical photograph of weld block.

at 448 ± 25 K. The chemical composition of filler wire and the weld blocks were analysed under vacuum emission spectrometer.

The LT, SL and TS sections (Fig. 2) of the weld blocks were prepared by standard metallographic procedure and etched by using 5% alcoholic nitric acid solution. The quantitative analysis of microstructure, accounted as the amount (area fraction) of cast co-axial dendrite present in the reheat refined matrix of the weld blocks, was carried out on each section by lineal intercept method⁴⁾ and evaluated as an average of the three sections of the blocks.

The hardness distribution in the matrix was measured by Vicker's diamond indentation at a comparatively low load of 50 N. The load was selected to avoid interference of different microstructural regions especially at HAZ. The characterization of different microstructural regions was more precisely done by microhardness measurement at desired location at a load of 24.5×10^{-3} N.

The Compact-Tension (C-T) specimens collected from the LT direction of the weld blocks (Fig. 2) were used for fatigue crack growth rate studies. The dimension of the C-T specimens are schematically shown in Fig. 3. The experiments were carried out following ASTM E647. The tests were performed under constant-load-amplitude procedure using a hydraulically operated pulsator at a stress ratio (minimum stress/maximum stress) of 0.06 and frequency of 5 Hz. Before carrying out the crack growth

rate measurements the crack from the initial machined notch was extended upto 4 mm under dynamic loading where, during the last 2 mm of crack extension the stress ratio as mentioned above was maintained carefully by keeping the minimum and maximum load at 1.6 and 25 KN respectively. The similar condition of loading was maintained during the crack growth measurement of the specimens. The crack growth behaviour was investigated by noting down the elapsed number of cycle, N , for every 0.5 mm of crack growth till final fracture. The monitoring of crack growth was carried out by using a suitable travelling microscope ($\times 10$) having linear measuring facility of least count 0.1 mm. The fatigue crack growth rate of the specimens containing different amount of dendrite was analysed in the light of the Paris law.

$$da/dN = C(\Delta K)^m \dots\dots\dots(1)$$

Where, a : the crack length (m),
 ΔK : the stress intensity factor range ($\text{MPa}\sqrt{\text{m}}$),
 c and m : Paris constants.

The determination of constants m and c for crack growth rate was carried out by incremental polynomial method⁵⁾ and linear regression analysis.

3. Results And Discussions

3.1. Chemical Analysis

The chemical compositions of the filler wire and the weld blocks prepared at different welding parameters are shown in Tables 2 and 1, respectively. The Table 1 shows that the variation in welding parameters has not changed the chemical composition of the blocks significantly.

3.2. Microstructure

The typical appearance of the TS section of the weld blocks, containing different amount of dendrite of 17.5 and 55% are shown in the micrographs presented in Figs. 4(a) and 4(b), respectively. To reveal the physical state of microstructural orientation in the blocks the macrographs of the LT and SL sections of the weld block

Fig. 2. Schematic diagram of the weld block showing the identification of different sections and collection of C-T specimen.

Fig. 3. Schematic diagram of C-T specimen.

Table 1. Welding parameters used in this work and chemical composition of the blocks prepared at different parameters.

Welding parameters			Chemical compositions (wt%)				
Current (A)	Speed (cm/min)	Arc voltage (V)	C	Mn	Si	S	P
500	50	30	0.045	1.74	0.39	0.022	0.038
600	50	30	0.049	1.77	0.35	0.21	0.032
750	50	30	0.049	1.67	0.29	0.02	0.027
600	40	30	0.04	1.74	0.29	0.023	0.035
600	60	30	0.053	1.67	0.25	0.023	0.032

Table 2. Chemical composition of the filler wire. (wt%)

C	Mn	Si	S	P
0.13	1.65	0.155	0.019	0.024

Fig. 4.
Macrographs of the TS section of the weld blocks containing different amount of dendrite; (a) 17.5% and (b) 55%.

Fig. 5.
Macrographs of different sections of the weld block containing 55% dendrite: (a) LT and (b) SL.

Fig. 6.
Typical microstructure of (a) dendrite region and (b) heat affected zone of the weld metal.

containing 55% dendrite are also shown in **Figs. 5(a)** and **5(b)**, respectively. The microstructures of the dendritic region, containing primary dendritic arms and interdendritic region of fine pearlite with some amount of lower bainite, and the HAZ (1.5mm from the fusion line), containing ferrite grains and fine pearlite, are typically shown in **Figs. 6(a)** and **6(b)**, respectively.

3.3. Hardness

The measurements of hardness are primarily carried out to characterise the matrix of each weld block in micro level, affecting the crack growth behaviour to a great extent. The hardness distribution in the weld blocks prepared at different welding currents and speeds, containing various amount of dendrite, are shown in **Figs. 7** and **8**, respectively. The figures show that the hardness of dendrite region is comparatively higher than that of HAZ. However, on an average the hardness of dendritic and heat affected zones has not been found (**Figs. 7** and **8**) to vary significantly with a change in dendrite content of the matrix. The microhardness survey on the matrix reveals that in the comparatively harder

dendritic region the primary dendritic arms are having relatively lower hardness (200 ± 17 VHN). In the HAZ the ferrite grains and the fine pearlite regions are found to have microhardness of the order of 170 ± 9 and 212 ± 10 VHN respectively.

3.4. Fatigue Crack Growth

The fatigue crack growth behaviour of the weld block is carried out along its LT direction, primarily because along this direction the block shows¹⁾ comparatively lower C_v -impact toughness than that observed along the TS and SL directions.

At different levels of ΔK of 15, 45 and 75 $\text{MPa}\sqrt{\text{m}}$ the influence of area fraction of dendrite, D_f , on the fatigue crack growth rate (da/dN) of the weld deposit is shown in **Fig. 9**. The figure shows that at a given ΔK the fatigue crack growth rate decreases significantly with the increase in D_f of the matrix. However, the rate of decrease of da/dN with the increase in D_f has been found to be enhanced with the reduction in ΔK as follows:

$$\Delta K = 15 \text{ MPa}\sqrt{\text{m}} \quad \log(da/dN) = -6.147D_f - 0.0167 \quad \dots\dots\dots(2)$$

Fig. 7. Hardness distribution observed in the weld blocks prepared at different welding currents.

Fig. 8. Hardness distribution observed in the weld blocks prepared at different welding speeds.

$$\Delta K = 45 \text{ MPa}\sqrt{\text{m}} \quad \log(da/dN) = -0.0093D_f - 4.879 \quad \dots\dots\dots(3)$$

$$\Delta K = 75 \text{ MPa}\sqrt{\text{m}} \quad \log(da/dN) = -0.006D_f - 4.285 \quad \dots\dots\dots(4)$$

At a given D_f the fatigue crack growth rate of the matrix, analysed in the light of Paris law, has been shown in Fig. 10. It is also confirmed that the variation in D_f

Fig. 9. At different levels of stress intensity (ΔK) the influence of D_f on fatigue crack growth rate.

Fig. 10. In the light of Paris law the fatigue crack growth behaviour of the weld blocks containing different amount of dendrite.

affects the crack growth rate significantly by influencing the material constant C and exponent m of the Paris law [Eq. (1)] as

$$D_f = 17.5\% da/dN = 0.126 \times 10^{-9} (\Delta K)^{2.947} \quad \dots\dots\dots(5)$$

$$D_f = 37\% da/dN = 0.263 \times 10^{-10} (\Delta K)^{3.268} \quad \dots\dots\dots(6)$$

$$D_f = 55\% da/dN = 0.811 \times 10^{-11} (\Delta K)^{3.424} \quad \dots\dots\dots(7)$$

Fig. 11. The influence of D_f on the Paris law constant C and exponent m .

Fig. 12. A comparison of the experimental crack growth rate data with the curve estimated by the modified version of Paris law.

The values of C and m are found to decreased and increase respectively with the increase in D_f as shown in Fig. 11 following the expressions, having coefficient of correlations of 97 and 93 %, respectively, as

$$\log C = -0.035D_f - 9.278 \quad \text{and} \quad \dots\dots\dots(8)$$

$$m = 0.015D_f + 2.662 \quad \dots\dots\dots(9)$$

Thus by substituting the values of C and m in Eq. (1) the Paris law may be modified as follows for estimation of fatigue crack growth rate of a multipass C-Mn steel weld deposit having a given area fraction of dendrite.

$$da/dN = 10^{(-0.035D_f - 9.278)} \{ \Delta K \}^{(0.015D_f + 2.663)} \dots\dots\dots(10)$$

The fatigue crack growth rate of the welds containing a given amount of dendrite, estimated by Eq. (10), has been compared with the results obtained under experiment in Fig. 12. It is observed that the values of crack growth rate estimated by the emperical relationship of da/dN with ΔK and D_f depicted in Eq. (10) is satisfactorily in agreement to the results/plots with a variation of the order of 3 %.

The reduction in da/dN with the increase in dendrite content of weld deposit may have been primarily occured due to more presence of comparatively softer (200 VHN) primary dendrite (marked by arrows in Fig. 6(a)) in the matrix. The soft dendritic arms can act as potential sites for the blunting of crack tip and thus may have reduced the growth rate.

4. Conclusions

- (1) The fatigue crack growth rate of multipass weld deposit is significantly dependent on dendrite content of the matrix.
- (2) The dendrite content of the matrix changes the material constants C and exponent m of Paris law.
- (3) A modification of constant C and exponent m of Paris law correlating them with dendrite content, D_f , provides a satisfactory basis for the estimation of fatigue crack growth rate of a given dendrite content multipass C-Mn steel weld deposit.

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