Effect of Fatigue Crack Growth Rate on Varied Percentage of Martensite for Welded DP Steel

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Abstract: The objective of this investigation is to study the fatigue behaviour of Dual phase (DP) steel with varying percentage of martensite. The study is conducted on samples of welded Dual phase steel prepared by intercritical annealing process with temperature varying from 730^0 C to 810^0 C. In this process both coarse and fine ferrite- martensite structures are produced with volume fraction of martensite varying from 48 to 69%. It has been observed from the investigation that the fatigue crack propagation rates were found to decrease and threshold values of stress intensity factor increase with the increase in martensite content up to 69% for the intercritically annealed structures.

Keywords: **Dual Phase Steel, Intercritical Temperature, Microstructure, Volume Fraction, Fatigue Crack growth.**

I. INTRODUCTION

The energy crisis in the world has led to the exploration of newer materials with improved combinations of strength, ductility and toughness. This has led to the emergence of a series of composite structures, in which Dual Phase (DP) steels represent a distinguished class. Dual phase steels were developed to satisfy an increasing need, primarily in automobile industry, ship building, Earth moving equipments etc, for new high strength steels which permit weight reduction without sacrificing formability. The DP steels usually exhibit microstructures consisting of about 80% ferrite and 20% martensite with small amounts of retained austenite and or bainite, depending on their chemistry and processing. Over the last four decades, dual phase steels have received considerable attention because of their excellent combination of strength, ductility and formability. Dual phase steels are primarily used as a substitute for high strength low alloy (HSLA) steels. HSLA steels generally exhibit very poor fracture toughness. In contrast to this, it has been recognized recently that, production of a combination of two phases, such as ferrite and martensite, by a process of intercritical annealing can improve the fracture toughness without sacrificing strength. The present investigation is to study the variation of fatigue crack growth with the volume percentage of martensite in welded Dual phase steel.

II. LITERATURE SURVEY

A large number of structures and components, particularly in the critical areas of transportation and energy production, are fatigue-limited in design. To specify the interaction between fatigue-life, applied cyclic stress and initial defect size, it is necessary to possess a detailed knowledge of crack growth rates in service conditions. Usually, the cyclic stresses are well below yield, so that the problem can be treated by linear elastic fracture mechanics (LEFM). For quasi-elastic (LEFM) conditions, the most popular empirical relationship between the crack growth increment per cycle (da/dN) and parameters of stress range ($\Delta\sigma$) and instantaneous crack length (a) is that proposed initially by Paris and Erdogan [1] which gives :

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

Where C and m are constants and ΔK is the range of stress intensity factor given by

$$\Delta K = K_{max} - K_{min},$$

The engineering application of Equation (1) may be illustrated by considering the case of a large (infinite) body containing a central, through-thickness crack of length 2a lying normal to a constant stress-range. The expression then becomes:

$$\Delta K = \Delta\sigma \ \sqrt{\pi a}$$

Equation (1) has been found to correlate with experimentally determined crack growth rates varying generally from 10^{-6} mm/cycle to 10^{-2} mm/cycle. Crack growth rates lower than this range are essentially microstructure-dependent and crack growth rates asymptotically approach zero due to increase in contributions from crack closure [2]. Crack closure is the partial closing of cracks due to the influence of asperities or plastic wake behind the crack tip in a cyclic loading situation. At crack growth rates well above this range, static fracture modes such as inter granular, quasicleavage, cleavage and void nucleation predominate as the ΔK approaches the fracture toughness of the material [3]. The general fatigue crack growth curve showing the three stage behaviour is shown in Fig. 1. At crack growth rates lower than 10^{-6} mm/cycle, the crack grows depends on the size of the micro structural unit. Hence, an increased sensitivity of crack growth [3,4] to stress ratio environment, grain size and yield strength has been found by several investigators [4]. Its effects have been generally attributed to various crack closure mechanisms promoted by crack wake plasticity [5], oxide particles [6] and fracture surface roughness [7] near threshold.

III. METHDOLOGY

The HSLA steel (AH36, a ship building steel) was selected as the starting material for making Dual phase microstructures by suitable heat treatment. The steel received was in the form of 14 mm thick hot rolled plates in quenched and tempered condition. The chemical composition of the steel was ascertained with the help of

inductively coupled plasma optical emission spectrometer (Model: ICP-OES), an Abrolins Carbon & Sulphur determination apparatus (Model: AI/302/84). The analyzed composition of the steel was found to be in good agreement with the supplier's certificate values. The chemical composition of the alloy was analyzed and is given in the Table 1.

Table 1: Chemical Composition of Specimens

Element	Wt. (%)
C	0.13
Mn	1.18
S	0.010
P	0.001
Si	0.3
Cr	0.047
Mo	0.057
B	0.001
Ni	0.048
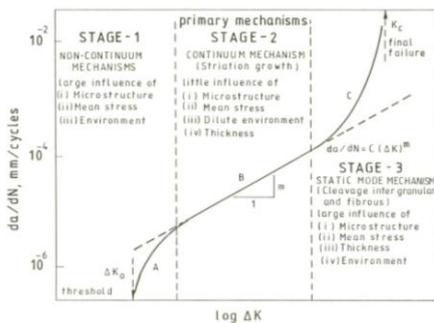
Fig. 1: Schematic Diagram Indicating The Three Regimes Of Quasi-Elastic (LEFM) Fatigue Crack Growth [3,8]

A. Heat Treatment Schedule for IQ Treatment

Specimen blanks of size 100mm X 100mm X 14mm were subjected to intermediate quench (IQ) heat treatment schedule as described in Fig. 2 & Fig. 3 using a Abrolins Muffle furnace (Model: LW/M-4). The IQ treatment consists of double quench operation. The specimens are first soaked at 920° C for 30 minutes and were quenched in 9% iced – brine solution (-7^oC). These were held at different intercritical temperatures (ICT) (730,750,780 & 810° C) for 60 minutes and were finally quenched in oil (25° C). The temperature control for intercritical soaking in IQ treatment was within $\pm 2^o$C. Precautions were taken uniformity of cooling during quench operations by continuous stirring of the bath containing the specimen blanks. The critical annealing temperatures of the base metal are estimated using Andrew's equation [9], [10]. The lower and upper critical temperatures are approximated as 720^0 C and 816^0 C respectively. The specimens are then heated to different intercritical temperatures ranging from 730^0 C to 810^0 C before finally quenched in Servo quench 707 oil at 25^0 C to obtain dual phase microstructure.
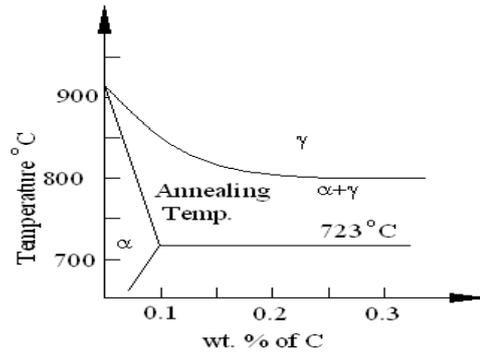

Fig. 2: Fe-C Equilibrium Diagram for Intercritical Annealing Heat Treatment
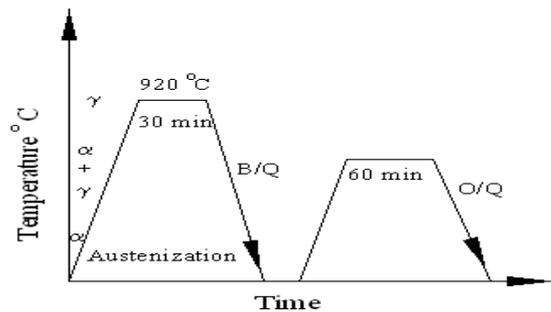

Fig.3: Intercritical Annealing Cycle

B. Welding Procedure

The welding parameters for welding of dual phase steel plates of 14 mm thick using MAG welding process were optimised using Bead on plate experiments [11]. The optimum specifications of MAG welding process were found to be, the suitable electrode ER 705-6 with 3.15 mm diameter, and current was vary from 96 Amps to 120 Amps, voltage vary from 19 V to 26 V, welding speed of 0.0041mm/sec, heat input 0.4KJ/mm to 0.6 KJ/mm with an input pass temperature from 160° C to 240° C. Welding was carried out by qualified welder on edge prepared plates with single V-butt joint of geometry shown in Fig. 4.
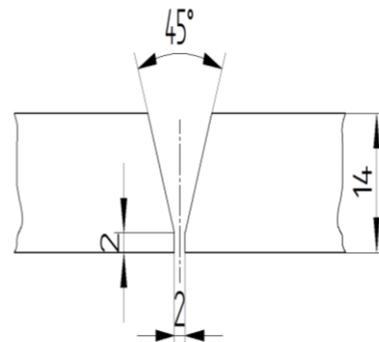
All dimensions are in mm.

Fig. 4: Joint Design for Single V-butt welds

After welding the plates were subjected to radiographic examinations to ensure the soundness of the joint and only sound welds were used in this investigation.

IV. EXPERIMENTAL DETAILS

A. Fatigue Crack Growth Test

Fatigue crack growth (FCG) tests were carried out as per ASTM E 647 standard on CT specimen using INSTRON UTM Model-8032 servo hydraulic closed loop test system of capacity 100 KN. The test programme was selected in such a way that ΔK values were decreased in a stepwise fashion with the reduction in ΔK in any step not exceeding 10% of the ΔK value of the previous step, a common manual test procedure followed to arrive at low crack growth rates. The initial ΔK levels were arbitrarily selected such that the crack growth rate corresponded to the transition from stage II to stage III in the FCG curve. In the load reduction step, care was taken to ensure that the crack lengths were recorded after the crack tip had grown out of the maximum plastic zone corresponding to the previous load step. While load reduction at intermediate crack growth rates were made after the crack propagated at least 0.3mm each time, at low crack growth rates, the loads were shed after the crack growth was advanced by 0.1mm, each time. The threshold in this study is defined as the stress intensity range at which a crack length increment of 0.1mm or less occurred in 10^6 cycles (crack growth rate, 10^{-7} mm/cycle). Crack lengths were monitored using a travelling microscope having a least count 0.01mm. FCG tests were performed at room temperature (26-28° C) and at a frequency of 25Hz with a load ratio, R= 0.1, the relative humidity of the laboratory air environment was 60-75%. The crack growth rate (da/dN) at each ΔK level was calculated using the relation,

$$\frac{da}{dN} = \frac{a_{n+1} - a_n}{N_{n+1} - N_n}$$

and ΔK calculated using the formula,

$$\Delta K = \frac{\Delta P \left[2 + \left(\frac{a}{W}\right)\right] \times \left[\left(0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right)\right]}{BW^{\frac{1}{2}}\left[1 - \left(\frac{a}{W}\right)\right]^{\frac{3}{2}}}$$

Where "a" is the average crack length given by

$$a = \frac{a_n + a_{n+1}}{2}$$

V. RESULTS AND DISCUSSIONS

The properties which govern the deformation behaviour of dual phase steels in static impact or fatigue loading conditions are continuous yielding, high initial work hardening rate, and superior uniform and total elongation for a given level of tensile strength. The results obtained from the fatigue crack growth test were recorded. From these values crack growth rate and stress intensity factor are calculated for known crack length. Mechanical properties for both base metal and welded joint are shown in Table 2.

Table 2: Mechanical Properties of welded DP steel

Specimen Code	Martensite Content (Vol. %)	0.2% YS (Mpa)	UTS (Mpa)	% Elong.	Threshold Stress intensity factor (Δk_{TH})	
					Base	Weld
S 73	48	548.6	726.43	18.5	12.4	12.1
S 75	56	598.08	745.68	19.6	14.6	13.9
S 78	63	574.41	753.46	20.3	14.9	14.3
S 81	69	549.8	728.62	20.03	15.8	15.2

FCG behaviour of intercritically annealed welded DP steel and DP steel samples with different volume% martensite V/s stress intensity factor are shown in Fig. 5 and Fig. 6 respectively [12, 13].
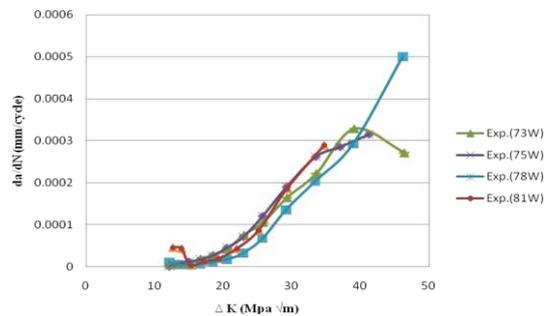

Fig. 5: FCG Behaviour of Interstitially Annealed Welded DP Steel Samples with Different Volume Percentage of Martensite
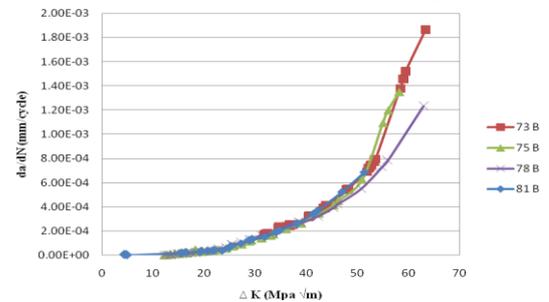

Fig. 6: FCG Behaviour of Interstitially Annealed Base DP Steel Samples with Different Volume Percentage of Martensite

From the above figures it is noticed that the curve reaches the threshold region in all the cases. The fatigue crack propagation rates were found to decrease and threshold values of stress intensity factor increase with the increase in martensite content up to 69%. The comparison of Fatigue stress concentration factor V/s Crack length for intercritically annealed welded dual phase steels having different volume percentage of martensite was also generated and is shown in Fig. 7 and Table 3.

Table 3: Experimental Stress concentration values

Crack length (mm)	Delta Kt (EXP) 73W	Delta Kt (EXP) 75W	Delta Kt (EXP) 78W	Delta Kt (EXP) 81W
5.1	12.19663	12.14248	12.14869	12.67126
6	13.52169	13.49047	13.47087	13.90903
7	15.07746	15.02008	15.0122	15.28893

8	16.75407	16.68853	16.67568	17.25297
9	18.56293	18.4928	18.47721	19.36478
10	20.6128	20.55417	20.53864	21.95879
11	23.01551	22.94395	22.91435	25.17099
12	25.81815	25.74748	25.73449	29.31191
13	29.30088	29.23634	29.16962	34.72109
14	33.5617	33.48652	33.42936	36.25436
15	39.11208	37.03452	38.96706	39.10731
16	46.42269	41.26345	46.21971	45.72109

It indicates that as the crack length increases the stress intensity factor is found to increase.
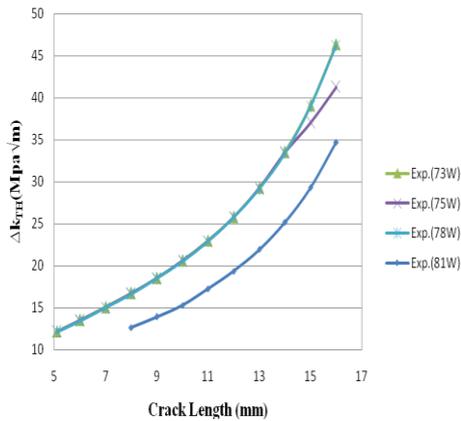
Fig. 7: Comparison of ΔK_{TH} V/s Crack length for welded DP steel samples having different volume percentage of martensite.

Effect of Microstructure on Fatigue Crack Growth behaviour.

The microstructure of different volume percentage martensite at crack region is shown in Fig. 8 to Fig. 11 and the fractographs of near threshold region are also shown in Fig. 12 to Fig. 15. From the observation it indicates that the microstructural grains are clearly seen on the fracture surfaces. Crack preferred to follow the ferrite regions as it is weaker of the two phases present in this dual phase structure. It has preferred to propagate through the interface of ferrite/martensite, as this region also a minimum energy path due to strain incompatibility between the two phases. Crack deflection is invariably observed in and around martensite regions. These aspects of crack deflection/branching have pronounced effects on FCG in the following ways.
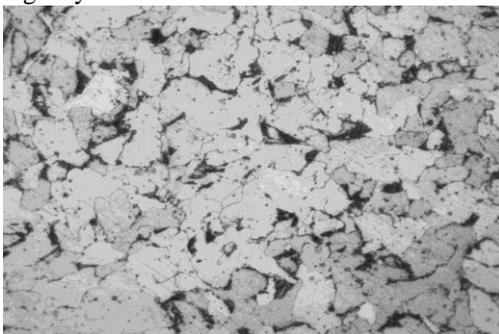

Fig. 8: Typical Microstructure of Weld Metal Region of Weldments Containing Different Volume Percentage of Martensite at 1000X Corresponding To S73

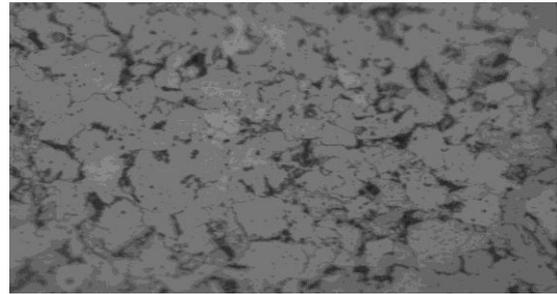**Fig. 9: Typical microstructure of weld metal region of weldments containing different volume percentage of martensite at 1000X corresponding to S75**

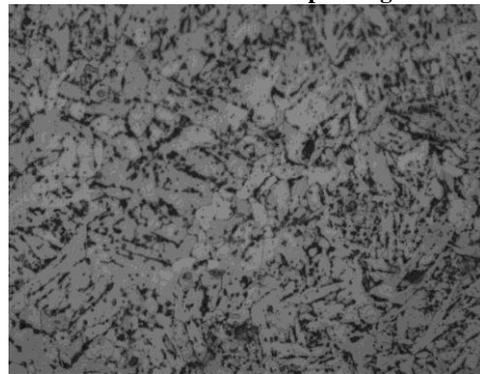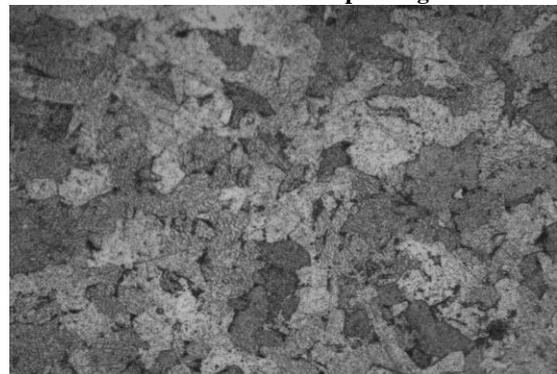

Fig. 10: Typical microstructure of weld metal region of weldments containing different volume percentage of martensite at 1000X corresponding to S78

Fig. 11: Typical microstructure of weld metal region of weldments containing different volume percentage of martensite at 1000X corresponding to S81
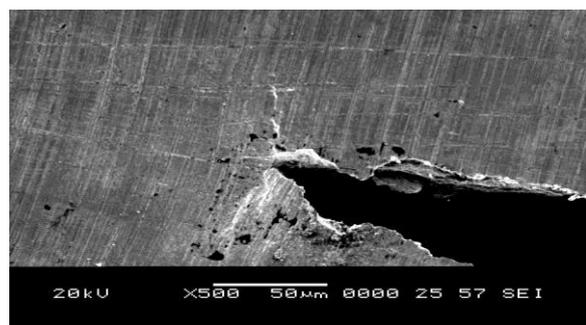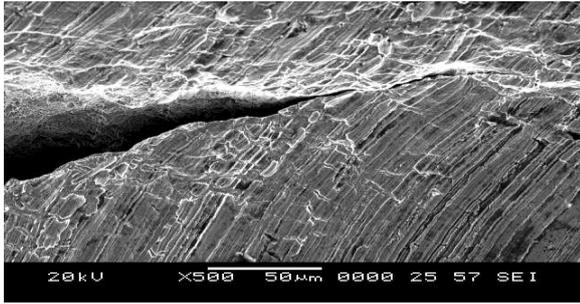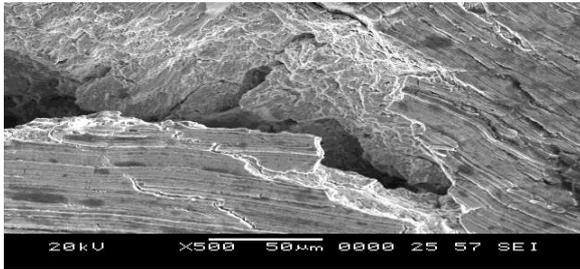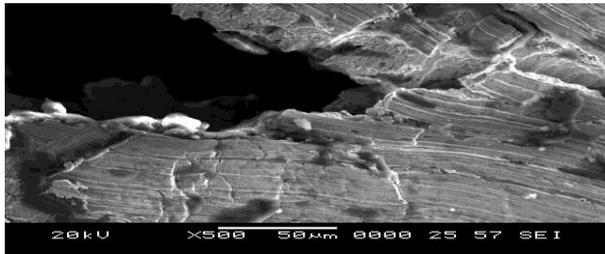

Fig. 12: Typical fractographs of welded specimen in HAZ region when observed under SEM at 500X corresponding to S73

Fig. 13: Typical fractographs of welded specimen in HAZ region when observed under SEM at 500X corresponding to S75

Fig. 14: Typical fractographs of welded specimen in HAZ region when observed under SEM at 500X corresponding to S78

Fig. 15: Typical fractographs of welded specimen in HAZ region when observed under SEM at 500X corresponding to S81

VI. CONCLUSION

It may be seen that the FCG rates decrease and threshold values increase with the increase in martensite content. It is clear that the DP steel containing 69% martensite has the lowest crack growth rate compared to the rest. Also, the threshold value of the stress intensity factor (ΔK_{th}) is maximum at 15.8 Mpa√m for DP steel and 15.2 Mpa√m for welded DP steel. Threshold value of the stress intensity factor is increased by 72% for DP steel containing 69% martensite than that containing 48% martensite. It may be seen from Fig. 8 to Fig. 11, that all intercritically annealed microstructures have a continuous network of martensite in ferrite. Martensite is platelet in type in most of the cases (although at higher martensite content they are also blocky in type). Further, with the increase in martensite content of the DP steel the martensite appears to acquire blocky form. It is also observed that the martensite in a welded dual phase structure will constrain the plastic deformation in the ferrite phase. These findings are also observed earlier for the base metal.

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