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Fracture Toughness (K_{1C}) Evaluation for Dual Phase Medium Carbon Low Alloy Steels Using Circumferential Notched Tensile (CNT) Specimens

Kenneth Kanayo Alaneme

*Department of Metallurgical and Materials Engineering,
Federal University of Technology, PMB 704, Akure, Nigeria*

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The fracture behavior of dual phase medium carbon low alloy steels produced using two different chemical compositions (A – 0.34C, 0.75Mn, 0.12Cr, 0.13Ni steel and B – 0.3C, 0.97Mn, 0.15Cr steel) was investigated using circumferential notched tensile (CNT) specimens. Intercritical treatments were performed on samples with composition A by 1) austenitizing at 860 °C for 1 hour cooling in air, then treating at 770 °C for 30 minutes before oil quenching; 2) austenitizing at 860 °C for 1 hour quenching in oil, then treating at 770 °C for 30 minutes before quenching in oil; and 3) austenitizing at 860 °C for 1 hour, super-cooling to 770 °C and then quenching in oil. Samples of composition B were subjected to intercritical treatment at temperatures of 740, 760, and 780 °C for 30 minutes, followed by quenching rapidly in oil. Tensile testing was then performed on specimens without notches and the CNT specimens. It was observed that the dual phase steel produced from procedure (2) yielded a fine distribution of ferrite and martensite which gave the best combination of tensile properties and fracture toughness for composition A while the dual phase structure produced by treating at 760 °C yielded the best combination of tensile properties and fracture toughness for composition B. The fracture toughness results evaluated from the test were found to be valid (in plain strain condition) and a high correlation between the fracture toughness and notch tensile strength was observed. The fracture toughness values were also found to be in close agreement with data available in literature.

Keywords: *fracture toughness, circumferential notched tensile specimens, intercritical treatment, medium carbon low alloy steel*

1. Introduction

Medium carbon low alloy steel grades are widely utilized for the design of components and structural parts for moderate to high stress applications. Such applications require the selection of materials having an optimum combination of high strength, ductility, and toughness for effective service performance. Moreover, failure of stress bearing components can be catastrophic in nature, leading to grave economic and technical losses[1,2]. It is for these reasons there is a sustained interest in the development of steel microstructures with excellent high strength – toughness characteristics[3-5]. The development of high strength – ductile microstructures in medium carbon low alloy steel has been explored with the adoption of intercritical treatment with encouraging results obtained[6,7]. The tensile and fatigue properties of dual phase microstructures produced in medium carbon low alloy steels by intercritical treatment have been reported to be superior to that obtained from conventional heat-treatment processes[7]. However, very little has been reported on the fracture toughness of dual phase medium carbon low alloy steels[8]. Research in the area of fracture behaviour is widely acknowledged to be highly specialized requiring the use of standard facilities and testing procedures. The absence of such standard facilities for fracture toughness testing has been a constraint for most African materials mechanics researchers. However, the standard test procedures has its challenges - the compact-tension (CT) and single edge notch bend (SENB) specimens which are the most widely utilized specimen configuration for fracture toughness evaluation require specimen preparation and test methods which are quite tedious and time consuming[9]. Also, the sample sizes needed to obtain valid plain strain fracture toughness (K_{1C}) are quite large particularly for the compact-tension specimens[10]. Fatigue pre-cracking which is also an essential part of the testing method requires a lot of care and strict monitoring if the results obtained are to be valid[11]. A rapid, cost effective and reliable technique for fracture toughness evaluation requiring easy to machine specimen type has been proposed with the use of circumferential notch tensile specimens. The advantage of the CNT specimens for fracture toughness evaluation include: 1) attainment of plain strain crack loading conditions with smaller specimen dimension in comparison with the CT specimen[10]; 2) radial symmetry which makes them suitable for studying the impact of the microstructure on fracture toughness[9]; 3) ease of machining to desired test configuration[12]; and 4) ease of testing using simple testing facilities like the tensometer[9]. The advantages make the use of CNT specimens very attractive for fracture toughness evaluation especially in developing African countries. In the present work, the fracture toughness of dual phase medium carbon low alloy steels produced using different chemical compositions and intercritical treatment procedures is investigated with the aid of CNT specimens. The validity of the results obtained from the technique is discussed and the effect of microstructure on the tensile and fracture properties is assessed.

2. Materials and Methods

2.1. Materials and specimen preparation

The materials for the investigation are two medium carbon low alloy steels as-supplied as cylindrical rods of 14 mm diameter with chemical compositions as presented in Tables 1 and 2; and designated

*e-mail: kalanemek@yahoo.co.uk

Table 1. Chemical composition of the medium carbon low alloy steel (Composition A).

Element	C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Fe
wt. (%)	0.34	0.23	0.75	0.0377	0.0404	0.126	0.135	0.00247	0.0024	0.172	Balance

Table 2. Chemical composition of the medium carbon low alloy steel (Composition B).

Element	C	Si	Mn	P	S	Cr	Ni	Mo	V	Fe
wt. (%)	0.3	0.28	0.97	0.0341	0.0021	0.15	0.035	0.0034	0.0012	Balance

composition A and B respectively. The rods were initially subjected to normalizing treatment to annul the thermal and mechanical history of the steel. The normalizing treatment was carried out at 860 °C for 1 hour in a muffle furnace and then cooling in air. The rods from composition B were then cold rolled to approximately 50% of the original diameter. Conventional tensile test specimens and circumferential notch tensile (CNT) test specimens were then prepared for testing. The tensile test specimens were machined with gauge length of 30 mm and diameter of 6 mm; while the CNT specimens were machined with gauge length of 30 mm, specimen diameter of 6 mm (D), notch diameter of 4.5 mm (d) and notch angle of 60°. The specimen configuration of the CNT specimens produced is shown in Figure 1.

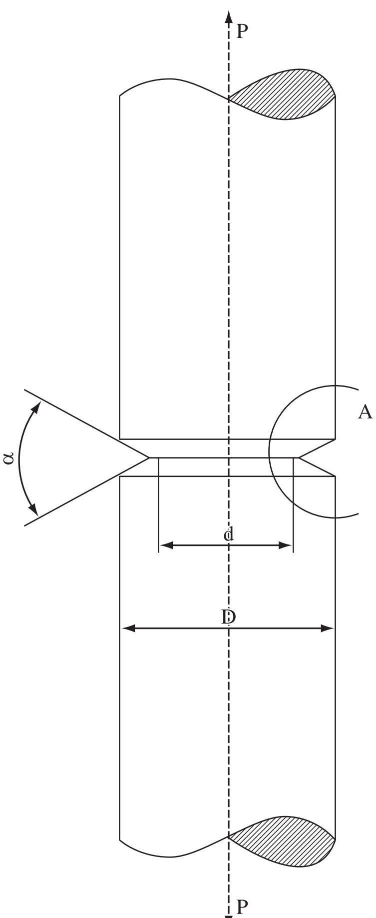


Figure 1. Schematic representation of the circumferential notched tensile specimen (Nath and Das[9]).

2.2. Intercritical treatment

Intercritical treatment was performed on the Tensile (without notch) and CNT test specimens of the medium carbon steel with composition A at 770 °C using three different intercritical treatment procedures, which are: 1) austenitizing at 860 °C for 1 hour and cooling in air, then treating at 770 °C for 30 minutes and quenching in oil; 2) austenitizing at 860 °C for 1 hour and quenching in oil, then treating at 770 °C for 30 minutes and quenching in oil; and 3) austenitizing at 860 °C for 1 hour, and then super cooling to 770 °C for 30 minutes and quenching in oil. The samples subjected to the treatments (1), (2), and (3) were designated DP1, DP2, and DP3 respectively. The use of oil quenching is to avoid the development of quench cracks which arise with the use of water quenching for the above composition. Control samples were prepared by normalising a set of the as-received steel at 860 °C for 1 hour and then air cooling. The samples produced from the control heat-treatment were designated as N. Samples of composition B were subjected to intercritical treatment at temperatures of 740, 760, and 780 °C for 30 minutes, followed by quenching rapidly in oil. Control samples for this composition were prepared by normalising at 860 °C for 30 minutes and then air cooling. The samples produced from the treatments were designated A740, B760, C780, and N_0 respectively.

2.3. Tensile testing and fracture toughness evaluation

Tension test was performed at room temperature on the tensile and CNT specimens with composition A using a universal tensile testing machine following standard test procedures in accordance with the ASTM E8M – 91 standards[13]. The samples were tested at a nominal strain rate of 10^{-3}/s until failure. Multi tests where performed for each treatment to ensure reliability of the data generated. The tensile properties evaluated from the stress-strain curves developed from the tension test are - the ultimate tensile strength (σ_u), the yield strength (σ_y), and the strain to fracture (ε_f). The fracture load (P_f) obtained from the load – extension plots of the CNT specimens were used to evaluate the fracture toughness using the empirical relations[14]:

$$K_{1C} = \frac{P_f}{(D)^{\frac{3}{2}}\left[1.72\left(\frac{D}{d}\right) - 1.27\right]} \quad (1)$$

Where, D and d are respectively the specimen diameter and the diameter of the notched section. The attainment of plain strain condition for the CNT fracture toughness evaluation was determined using the relation[9]:

$$D \geq \left(\frac{K_{1C}}{\sigma_y}\right)^2 \quad (2)$$

The notched tensile strength (σ_{NTS}) and notch strength ratios (NSRs) were also evaluated following standard procedures in accordance with Bayram et al.[15]. The notched tensile strength (σ_{NTS}) values obtained for each treatment condition was utilized to validate the reliability of the fracture toughness results obtained from Equation 1, using the relation Kang and Grant[16]:

$$K_c = 0.454\sigma_{NTS}(D)^{\frac{1}{2}} \quad (3)$$

A minimum of two repeat tests were performed for each treatment condition and the results obtained were taken to be highly consistent if the difference between measured values for a given treatment condition is not more than 2%.

2.4. Metallography and fractography

The microstructural investigation was performed using a ZEISS Axiovert 200MAT optical microscope. The specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500-1500 μm; while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10-0.5 μm with ethanol solvent. The specimens were etched with 2%Nital solution by swabbing for between 10-20 seconds (followed by rinsing in water and drying) before observation in the optical microscope. Optical micrographs were produced at a magnification of 500×. Morphological features of the CNT fractured specimen surfaces were examined using a SERION scanning electron microscope with secondary electron imaging performed using an applied voltage of 15 kV.

3. Results and Discussion

3.1. Microstructure

Figure 2 shows the microstructures of the samples with composition A subjected to intercritical treatment. It is observed that

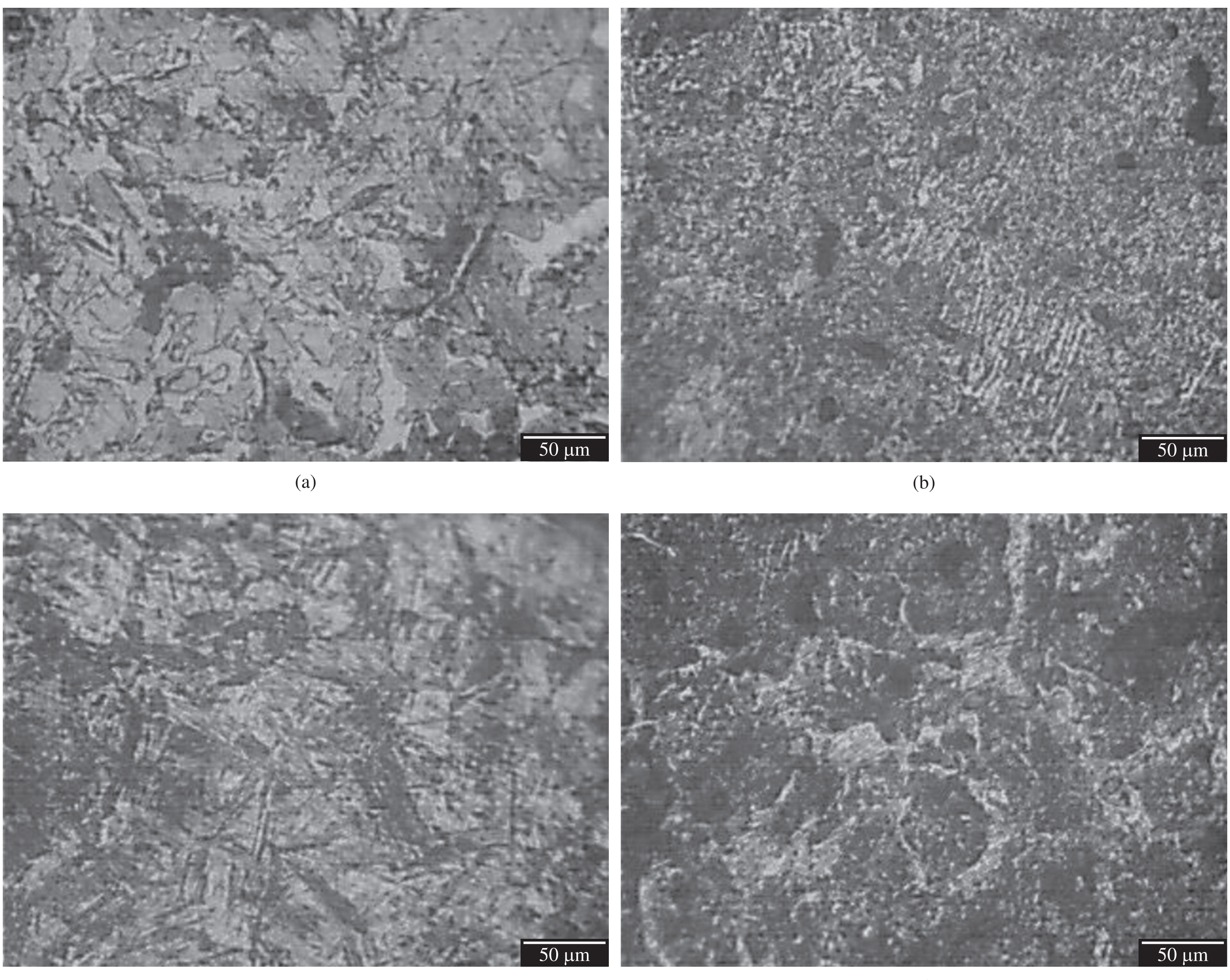


Figure 2. a) Dual Phase structure produced by austenitizing at 860 °C for 1 hour and cooling in air, then treating at 770 °C for 30 minutes and quenching in oil (DP1). The structure reveals ferrite grains (white phase) with slightly elongated shape and martensite (gray phase); b) Dual Phase structure produced by austenitizing at 860 °C for 1 hour and quenching in oil, then treating at 770 °C for 30 minutes and quenching in oil (DP2). The structure reveals a fine distribution of ferrite (white phase) and martensite (dark phase); c) Dual Phase structure produced by austenitizing at 860 °C for 1 hour, and then super cooling to 770 °C for 30 minutes and quenching in oil (DP3). The structure reveals large presence of lath martensite and little noticeable ferrite distribution; and d) Dual Phase structure produced by austenitizing at 860 °C for 1 hour and then air cooling (N). The structure reveals grain boundary ferrite (gray phase) and pearlite (dark phase).

there is a marked difference in the microstructures of the samples. The dual phase structure produced from the DP1 treatment is observed to have ferrite grains with slightly elongated morphology. In the case of DP2 (produced from a martensitic initial microstructure), it is observed that there is fine distribution of ferrite (white phase) and martensite (dark phase) in the microstructure. This is due to the higher number of potential nucleation sites which are offered by the martensitic structure which has more stored energy to propel the $\alpha + \gamma$ transformation process[6,17]. The DP3 structure obtained by super-cooling from the austenitic range (860 °C) to 770 °C, is observed to have a large presence of lath martensite and little noticeable ferrite distribution. This may be due to the likelihood of having a sluggish $\gamma \rightarrow \alpha$ transformation on super-cooling to 770 °C. The normalized structure (Figure 2d) has the characteristic grain boundary ferrite and pearlite structure typical of normalized structures. The above observation reveals that the intercritical treatment procedure affects the ferrite/martensite morphology and distribution.

The microstructures of the samples with composition B subjected to intercritical treatment at 740, 760, and 780 °C has been presented and discussed by Alaneme et al.[7]. They reported that the microstructures consisted primarily of ferrite and martensite but with 36, 68 and 80% volume percent of martensite obtained respectively for the 740, 760, and 780 °C intercritical treatments.

3.2. Tensile properties

The stress-strain curves for the test samples from composition A are presented in Figure 3. The three dual phase samples exhibited continuous yielding behavior while the normalized sample (N) has defined discontinuous yielding profile. The tensile properties generated from the stress-strain plots are summarized in Table 3. The DP3 treatment procedure yields the highest UTS value (969.71MPa) in comparison to the other dual phase steel samples. However it yields the least strain to fracture (12.5%) which indicates a poor response to plastic flow. The DP1 sample has comparable UTS value (942.68 MPa) with the DP3 (a slight decrement of 2.79%), however the yield strength of the DP1 (601MPa) is significantly lower than that of the DP3 (710 MPa) which yields a more enhanced plastic flow characteristic as reflected by the increased strain to fracture (16%). The DP2 treatment procedure yielded the best strain to fracture (20%) among the Dual Phase steels but had UTS value (882.61 MPa) lower than either of the other Dual Phase samples 9% in respect to DP3 and 6.3% in respect to DP1. Thus the DP2 treatment has a relatively better post-yielding resistance to fracture. The superior combination of tensile properties of DP1 and DP2 over that of DP3 can be attributed to the more defined ferrite and martensite distribution in both microstructures (Figure 2a, b). Table 4 presents the tensile properties of the test samples from composition B (the stress–strain behaviour, and the tensile properties have been originally reported by Alaneme et al.[7]). The yield strength and ultimate tensile strength is observed to increase with increase in the intercritical treatment temperature. Alaneme et al.[7] attributed it to be as a result of the increase in the volume percent martensite produced with increase in the intercritical temperature. Also, the percent elongation is observed to be within the range of 17-21.5% and was higher than that of the normalized sample (N).

3.3. Fracture toughness

The fracture toughness values obtained from the tension test on the CNT specimens are reported in Table 5. It should be noted that fatigue pre-cracking was not performed on the test specimens before the tension test. This implies that the test speed will be faster when compared with the use of compact tension (CT) and single edge notch bend (SENB) specimens, which require fatigue pre-cracking before tension test is performed. The reliability of the results was assessed by determining if nominal plain strain condition was achieved for the CNT specimen dimension (D) of 6 mm utilized for the test. It is observed that the minimum specimen thickness required to attain plain strain conditions when the relation $D \geq (K_{1C}/\sigma_y)$ is utilized is less than 6 mm for all treatment conditions. Thus the results are reported as plain strain fracture toughness under tensile mode (K_{1C}).

It is observed that the dual phase steels developed from composition A (DP1, DP2, and DP3) and composition B (A740, B760, and C780) have higher fracture toughness values in comparison to their respective normalized samples (N_0 - 31.18 MPa.m$^{-1/2}$; N – 32.1 MPa.m$^{-1/2}$). For composition A, it is observed that the DP2 treatment yielded the highest fracture toughness, K_{1C} of 40.88 MPa.m$^{-1/2}$ with the DP1 treatment procedure yielding fracture toughness of 35.55 MPa.m$^{-1/2}$ (a decrement of 13.0% in comparison to DP2). The DP3 treatment yielded the least fracture toughness of 34.46 MPa.m$^{-1/2}$ (a decrement of 15.7% in comparison to DP2). The SEM micrograph (Figure 4a) show that the fracture mode of the DP2 is essentially ductile fracture while the DP3 exhibited dominantly

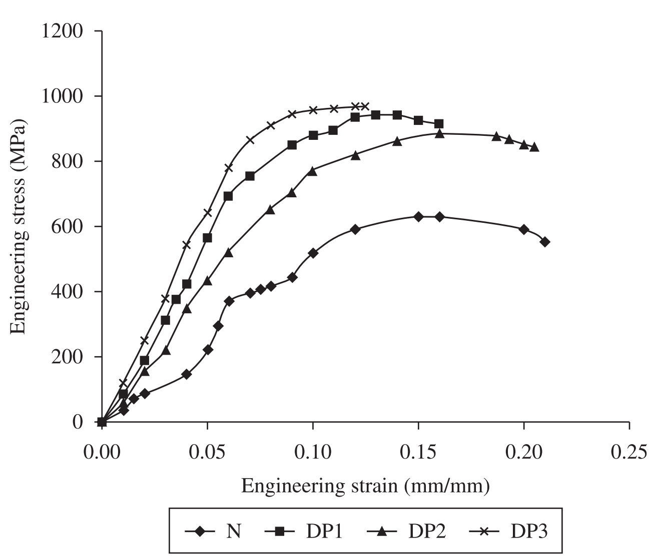


Figure 3. Engineering stress – strain curves for the heat-treated steels.

Table 3. Tensile Properties of the Heat-treated MCLA Steel Specimens (Composition A).

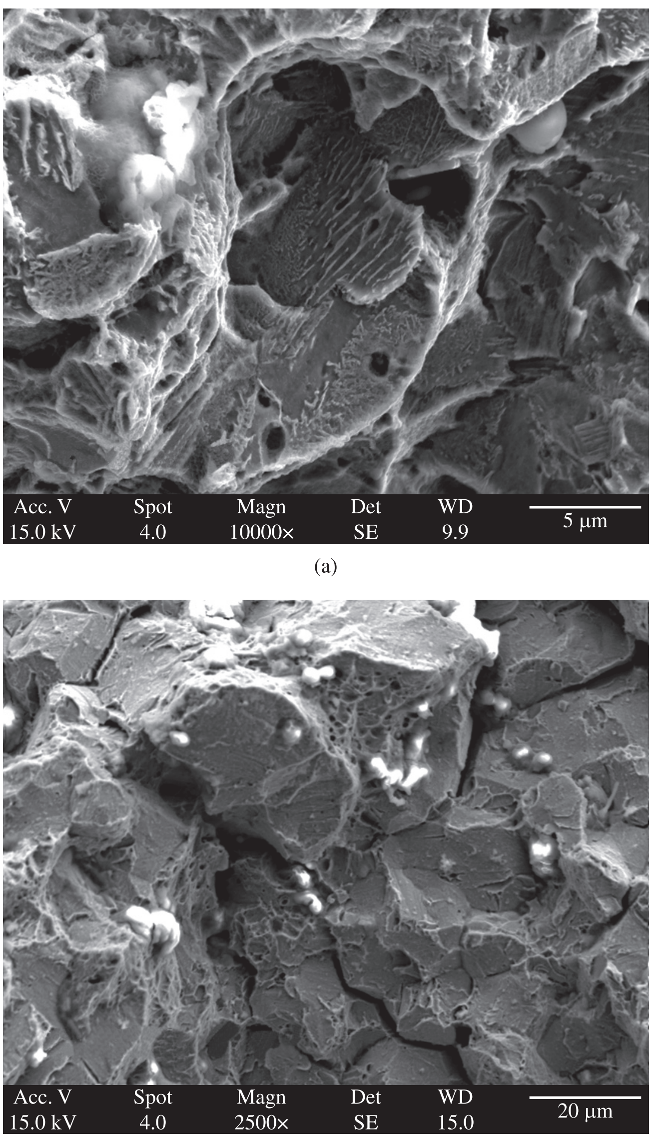
Treatment	UTS, σ_u (MPa)	Yield Strength, σ_y (MPa)	Strain to failure, ε_f (%)
N	630.33	420	21
DP1	942.68	601	16
DP2	882.61	565	20
DP3	969.71	710	12.5

Table 4. Tensile Properties of the Heat-treated MCLA Steel Specimens (Composition B) (Alaneme et al., 2010).

Treatment	UTS, σ_u (MPa)	Yield Strength, σ_y (MPa)	Strain to failure, ε_f (%)
N_0	754	560	16
A740	702	530	18
B760	884	585	22
C780	984	680	17

Table 5. Summary of Fracture Toughness and Notch Strength values for the Heat-treated MCLA Steel specimens.

Treatment	Force (KN)	σ_{NTS} (MPa)	UTS, σ_u (MPa)	K_{1C} (MPa.m$^{-1/2}$) (Equation 1)	NSR	K_{1C} (MPa.m$^{-1/2}$) (Equation 3)	% Diff K_{1C} (Equations 1 and 3)
N	14.16	890.3	630.3	31.2 ± 0.8	1.41	31.3	0.32
DP1	16.15	1015.1	942.7	35.5 ± 0.5	1.08	35.7	0.56
DP2	18.56	1167.3	882.6	40.9 ± 0.1	1.32	41.0	0.24
DP3	15.65	984.0	969.7	34.5 ± 0.1	1.01	34.6	0.28
N_0	14.60	917.0	754.0	32.1 ± 0.9	1.22	32.3	0.62
A740	18.50	1163.8	702.0	39.7 ± 1.3	1.65	40.0	0.75
B760	19.71	1238.8	884.0	43.4 ± 0.2	1.34	43.6	0.46
C780	16.90	1062.2	984.0	37.2 ± 0.3	1.08	37.4	0.54



(b)

Figure 4. a) Representative high magnification view of the morphology of the fracture in the DP2 treated steel showing dimples characteristic of ductile mode fracture. b) Representative image of the morphology of the fracture in the DP3 treated steel showing predominantly cleavage fracture.

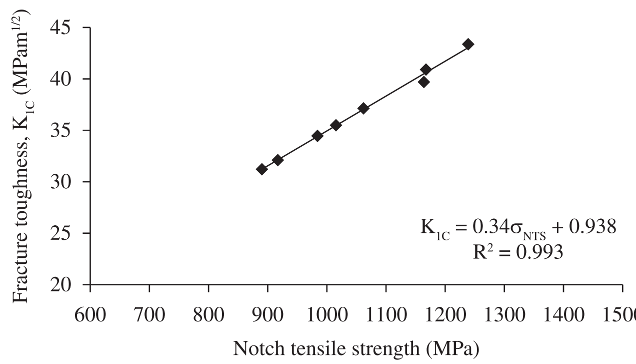


Figure 5. Relationship between the fracture toughness and the notch tensile strength.

cleavage fracture (Figure 4b) due to the higher martensite content as discussed in section 3.1. For composition B, it is observed that the B760 treatment yielded the highest fracture toughness, K_{1C} of 43.4 MPa.m$^{-1/2}$ with the A740 treatment yielding a fracture toughness of 40.7 MPa.m$^{-1/2}$ (a decrement of 6.6% in comparison to B760). The C780 treatment yielded the least fracture toughness of 37.2 MPa.m$^{-1/2}$ (a decrement of 16.7% in comparison to B760). The relatively lower fracture toughness of the C780 sample is as a result of its high martensite volume percent (80%)[7].The higher fracture toughness of the B760 is attributed to the synergy of the soft ferritic phase and the hard martensitic phase, which helps in increasing the materials resistance to crack propagation and fracture[5]. Generally, the fracture toughness values obtained from the CNT testing are in close agreement with fracture toughness values of medium carbon steels reported in literature[8,9]. The notch strength ratios (NSRs) for all test samples are observed to be greater than unity, indicating that the specimens are not notch sensitive. Despite the tri-axial stress state and steep stress gradients induced by the creation of a notch[14], the specimens still maintain appreciable ductility, and hence will show good resistance to crack propagation. The notch tensile strength (σ_{NTS}) has been reported to give a good measure of fracture toughness by the relation $K_C = 0.454\ \sigma_{NTS}\ D^{1/2}$ (Equation 3). The fracture toughness values obtained from eqn 1 are found to be in close agreement with that obtained from Equation 3 (less than 0.76% difference as presented in Table 2). The close correlation relationship between the fracture toughness and the notch tensile strength is demonstrated in Figure 5. It is observed that a correlation coefficient (R^2) of 0.993 is obtained when the fracture toughness and notch tensile strength data from the experiment were fitted to a linear curve. Bayram et al.[15] reported this strong correlation arises from that fact that the fracture toughness values were calculated by using the fracture loads of the notched specimens. Summarily, the results indicate that the best combination of tensile properties and fracture toughness is achieved by the DP2 treatment which yields a finely distributed ferrite and martensite dual phase microstructure for composition A while the B760 treatment yielded the best combination of tensile properties and fracture toughness for composition B.

4. Conclusions

The reliability of circumferential notched tensile testing for evaluation of fracture toughness was investigated using dual phase medium carbon low alloy steels produced using two different chemical compositions (A – 0.34C, 0.75Mn, 0.12Cr, 0.13Ni steel and B – 0.3C, 0.97Mn, 0.15Cr steel) and different intercritical treatment procedures. From the results it was observed that despite the samples were not fatigue pre-cracked, the fracture toughness results evaluated from the CNT test were valid (in plain strain condition) and a high correlation between the fracture toughness and notch tensile strength was observed. The fracture toughness values were also found to be in close agreement with data obtained from standard K_{1C} testing. Dual phase structures produced by utilizing an initial martensitic structure before treating at 770 °C yielded a fine distribution of ferrite and martensite which gave the best combination of tensile properties and fracture toughness for composition A. The dual phase structure produced by treating at 760 °C yielded the best combination of tensile properties and fracture toughness for composition B.

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