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# Effect of Intercritical Heat Treatment on Mechanical Properties of Plain Carbon Dual Phase Steel

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## ABSTRACT

Mechanical properties of DP (Dual Phase) steels are greatly influenced by the microstructural features such as grain size, morphology and martensite volume fraction ( $V_m$  %). These microstructural features can be altered by changing the soaking time and temperature within intercritical zone. Present study aims to study the effect of intercritical annealing temperature and soaking time on  $V_m$  % and its effects on mechanical properties of plain low carbon steel grade (AISI 1020) steel having ferrite-martensite microstructure. Nine DP steel specimens with various amount of martensite were produced via intercritical heat treatment. Mechanical properties including TS (Tensile Strength), hardness and toughness were characterized and co-related with martensite volume fraction. It was found that increasing the intercritical annealing temperature and soaking time increases the  $V_m$  %. The optimum TS and hardness were found at 64 $V_m$  % and then decrease with further increase in  $V_m$  %. The toughness was found to have linear relationship with  $V_m$  %.

**Key Words:** Dual Phase Microstructure, Martensite Volume Fraction Intercritical Annealing Zone.

## 1. INTRODUCTION

DP steels are kind of advanced strength steel mostly used by automobile industry due to their special mechanical properties such as continuous yielding, high TS, high work hardening rate as well as good ductility [1-4]. As a result, the automotive industry is continuously exploring methods of enhancing their ductility and strength simultaneously to develop superior grades of such steels [2]. These properties are result of special microstructure designed to produce in DP steel which consists of soft matrix of ferrite in which islands of hard martensite are embedded [3,4]. It is like composite material where martensite is strengthening element and ferrite matrix assures good formability. The

actual distribution between these two phases allows them low yield stress, a smooth flow stress curve, better plasticity and formability with a high strain hardening coefficient [5]. Processing to produce the DP steels is usually done by intercritical annealing from room temperature to two-phase ( $\alpha + \chi$ ) region [6]. This involves rapidly cooling from a suitable temperature between upper and lower critical temperatures within the intercritical zone. During cooling the austenite phase being metastable transforms to martensite but ferrite remains unchanged resulting in the formation DP micro-structure which consist of ferrite and martensite structure instead of the conventional ferrite-pearlite microstructure [7].

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The mechanical properties of DP steels are directly related to the synergistic effect of two phases present in these steels in which martensite controls the strength of the steel while ferrite is responsible for formability properties [7-9]. Numerous studies have reported that the mechanical properties of ferrite-martensite DP steels have been quite variable depending on ferrite and martensite volume fractions in microstructures. Movahed et. al. [1] and Ebrahimian and Ghasemi, [10] have reported a linear variation of yield strength with martensite volume fraction and a non-linear one for TS consisting a peak hardening value around 50% martensite in a low carbon ferrite-martensite DP steel. Speich and Miller [11] have suggested a completely linear dependence between hardness and martensite volume fraction in a low carbon low alloy ferrite-martensite DP steel.

Chen and Cheng [8] found that martensite fraction increases the tensile strength up to a certain limit and then decreasing significantly making a non-linear relationship. Fallahi [9] showed that for DP steel consisting of 35-40% of fiber martensite and 4 μm grain size gives the optimum tensile and impact properties whereas Bag et. al. [12] showed that of finely dispersed ferrite and martensite phases at 50% proportion gives the optimum combination of high ductility, strength, and toughness. Pierman et. al. [13] demonstrated that TS results are not in line with expectations based on the mixture law in DP steels containing 10-70 vol.% martensite. The observations of various researchers [1,3,5-6,8-10,12-13,] suggest that the mechanical behavior of ferrite-martensite DP microstructure cannot be predicted by the general rule of mixture law. These findings are still controversial and no agreement has yet been developed

Although many investigations have been made to characterize the microstructure- property relationship of micro alloyed low carbon DP steels, literature pertaining to formation of ferrite-martensite DP microstructure and its effect on mechanical properties of plain low carbon steels has not been well studied. Present study therefore, aims to investigate the effect of intercritical annealing temperature and soaking time on martensite volume fraction and mechanical properties of AISI 1020 plain carbon steel.

## 2. MATERIALS AND MEHTOD

Chemical composition of a plain carbon steel grade (AISI 1020) used in present study is given in Table 1. The as-received steel microstructure was consisting of ferrite and pearlite. Samples for impact test were prepared according to ASTM E23 standard while for tensile test samples were prepared according to ASTM E8M-04 standard.

The specimens were intercritically annealed at temperature of 775, 800 and 825°C for different time intervals and then quenched it in ice water. The ( $A_{e_3}$ ) and ( $A_{e_1}$ ) critical temperatures were determined using Andrews equations [14].

The complete intercritical heat treatment scheme performed on all specimens is given in Table 2. Toughness and tensile test was conducted at room temperature on as-received and heat treated specimens using Charpy impact testing machine (Model No: Tinius Olsen IT542) and universal tensile testing machine (Model No: zwickroell Z1200E). Hardness of each specimen was evaluated using digital Rockwell hardness testing machine (Model No: Indentec 4150BK) on C scale.

TABLE 1. COMPOSITION OF THE STEEL IN WEIGHT PERCENTAGE USE IN STUDY

C (%)	Mn (%)	Si (%)	S (%)	P (%)	Fe (%)
0.23	0.54	0.46	0.004	0.0005	98.76

Microscopic examination was done by optical microscope and SEM (Scanning Electron Microscope) (Model No: Jeol 6380LV). The samples were prepared according to the standard metallographic procedure. Nital solution (2% HNO<sub>3</sub>) was used for etching. Percent phase analysis was done according to ASTM E562 standard.

### 3. RESULTS AND DISCUSSION

#### 3.1 Microstructure

The optical and SEM micrographs of as-received steel specimen are shown in Fig. 1, which clearly shows fingerprint like microstructure consisting of 72% ferrite (white areas) and 28% pearlite (dark areas). The optical and SEM micrographs of all heat treated specimens are shown in Figs. 1-10 respectively which reveals the DP microstructure consisting of martensite phase (dark areas) and ferrite phase (light areas). The values of percent martensite volume fraction ( $V_m$  %) found in each specimen are listed in Table 3. Phase analysis indicated that  $V_m$  % increases with increasing temperature and time within intercritical region. The amount of martensite formed in each specimen is in agreement with levers rule, according to which increasing the temperature within ferrite-austenite region increases the amount of austenite which will then transforms into martensite. Increase in grain size was also observed for the specimens soaked for 3hrs due to sufficient time available for grain growth.

Also at high magnification, plate type martensite was found in the specimens intercritically heat treated at relatively lower temperatures i.e. 775 and 800°C as shown in Fig. 11(a-b) whereas, lath type martensite was found in the specimens intercritically heat treated at 825°C as shown in Fig. 11(b).

#### 3.2 Mechanical Properties

The changes encountered in the mechanical properties due to variation of microstructure are summarized in Table 3.

##### 3.2.1 Tensile Strength

TS values are listed in Table 3. The higher TS of DP steel specimens is the result of presence martensite phase in the microstructure. Martensite has highly distorted lattice due to entrapment of carbon atoms, making it stronger phase and enabling it to sustain higher load compared to pearlite present in as-received steel.

Fig. 12 shows that TS of DP specimens first increases and then decreases with increase in intercritical annealing temperature and soaking time. For DP specimens maximum TS reached to 1277 MPa.

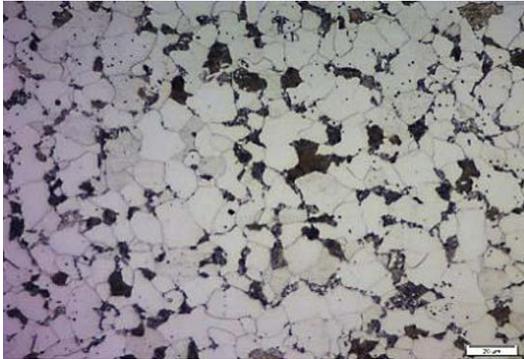
TS of DP specimens increases due to higher volume fraction of martensite formed with increasing intercritical

TABLE 2. HEAT TREATMENT SCHEME EMPLOYED TO OBTAIN DUAL PHASE MICROSTRUCTURE

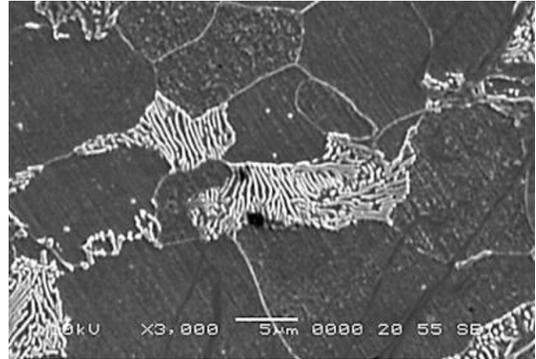
Material	Sample ID	Temperature (°C)	Time (hours)
AISI 1020	A1	775	1
	A2		2
	A3		3
	B1	800	1
	B2		2
	B3		3
	C1	825	1
	C2		2
	C3		3

annealing temperature and soaking time. However, increasing volume fraction of martensite has two contradiction effects:

- (1) The TS generally increased due to higher volume fraction of martensite formed in DP steel specimens.

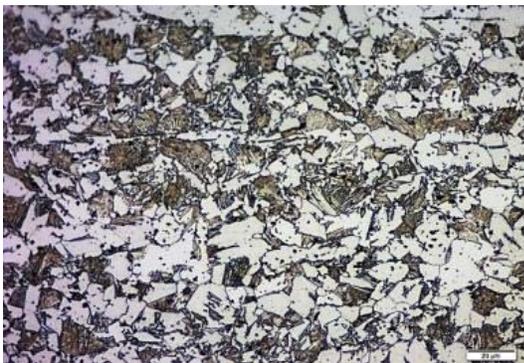


(a) OPTICAL (500X)

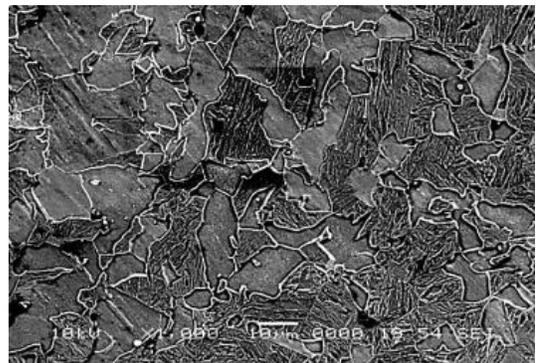


(b) SEM (3000X)

FIG. 1. MICROSTRUCTURE OF AS-RECEIVED SPECIMEN SHOWS FERRITE (LIGHT) AND PEARLIATE (DARK)



(a) OPTICAL (500X)

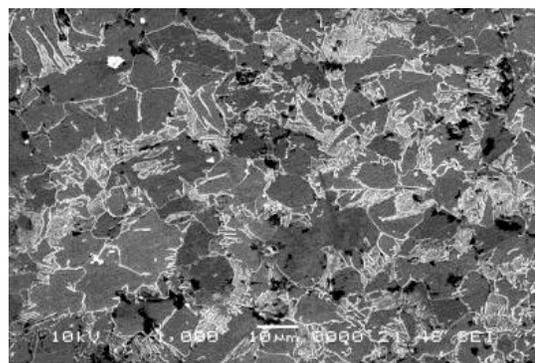


(b) SEM(1000X)

FIG. 2. MICROSTRUCTURE OF SPECIMEN A1 SOAKED FOR 1HRAT 775OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)



(a) OPTICAL (500X)



(b) SEM(1000X)

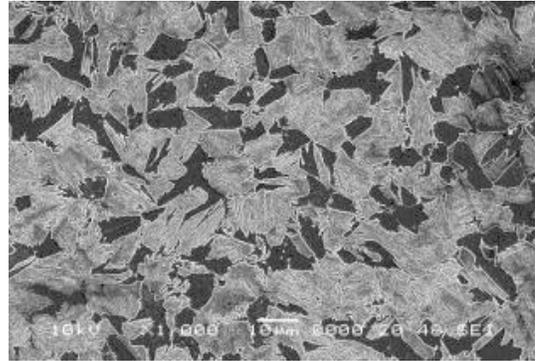
FIG. 3. MICROSTRUCTURE OF SPECIMEN A2 SOAKED FOR 2HR SAT 775OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)

- (2) On contrary, martensite carbon content itself decreased with increasing its volume fraction. As it is well known that strength of martensite

phase mainly depends on its carbon content. As carbon content decreases the martensite deform plastically at much lower stress [1,8].



(a) OPTICAL (500X)

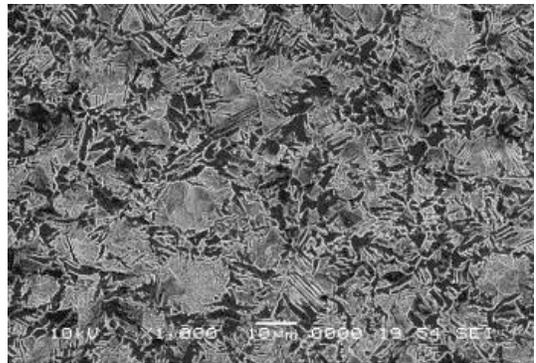


(b) SEM(1000X)

FIG. 4. MICROSTRUCTURE OF SPECIMEN A3 SOAKED FOR 3HRS AT 775OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)

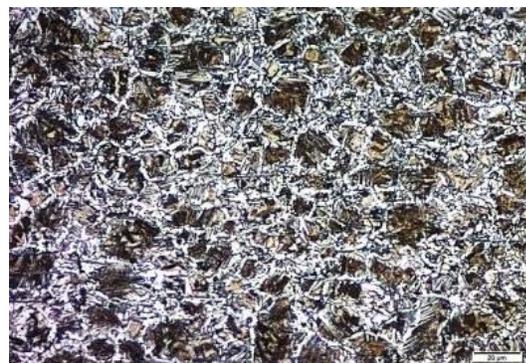


(a) OPTICAL (500X)

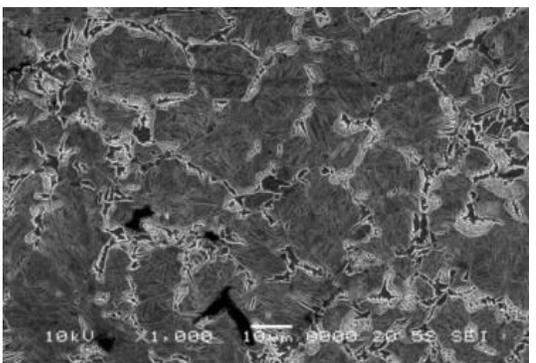


(b) SEM(1000X)

FIG. 5. MICROSTRUCTURE OF SPECIMEN B1 SOAKED FOR 1HRAT 800OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)



(a) OPTICAL (500X)



(b) SEM(1000X)

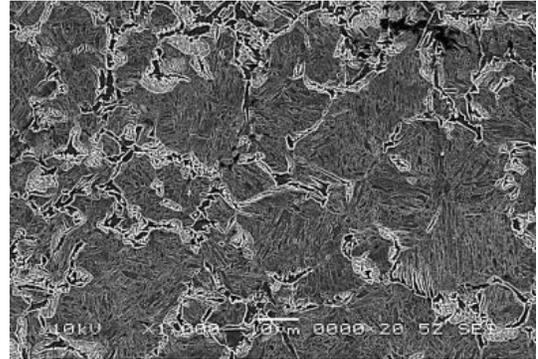
FIG. 6. MICROSTRUCTURE OF B2 SOAKED FOR 2HRSAT 800OC CONSIST OF FERRITE (LIGHT) AND MARTENSITE (DARK)

Also it is widely acknowledged in the literature [15-16], that the morphology of martensite changes from plate to lath type with a decrease in martensite carbon content.

Substantial improvement in the TS of DP specimens A1-A3 and B1-B3 intercritically annealed at 775 and 800°C, respectively for different time intervals was resulted due the formation to high carbon plate type martensite. On



(a) OPTICAL (500X)

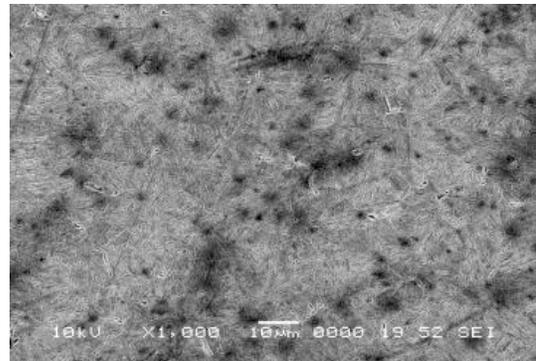


(b) SEM(1000X)

FIG. 7. MICROSTRUCTURE OF B3 SOAKED FOR 3HRS AT 800OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)



(a) OPTICAL (500X)

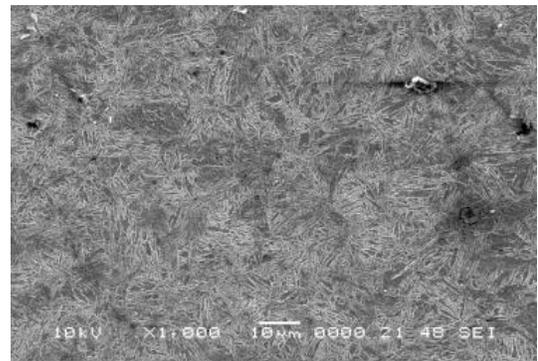


(b) SEM(1000X)

FIG. 8. MICROSTRUCTURE OF SPECIMEN C1 SOAKED FOR 1HR AT 825OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)



(a) OPTICAL (500X)



(b) SEM(1000X)

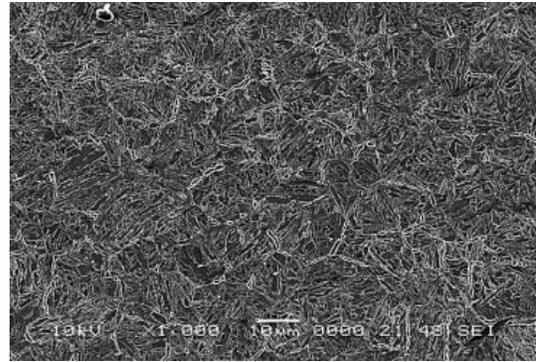
FIG. 9. MICROSTRUCTURE OF SPECIMEN C2 SOAKED FOR 2HRS AT 825OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)

the other hand, TS of DP specimens C1-C3 intercritically annealed at 825°C decreases with the formation of lath martensite typical of low carbon. This trend is against the law of mixture, according to which, TS increases linearly with  $V_m$ %. The marginal decrease of TS for DP specimens soaked for 3hrs can be attributed to grain coarsening of ferrite and martensite.

Experimental results obtained in present study clearly reveal that carbon content and volume fraction of martensite are major two factors that control the overall properties of DP specimens. Reduction in strength due to higher  $V_m$ % and less carbon in martensite observed in present study is in agreement with the findings of other researchers [1,8,12,17].



(a) OPTICAL (500X)

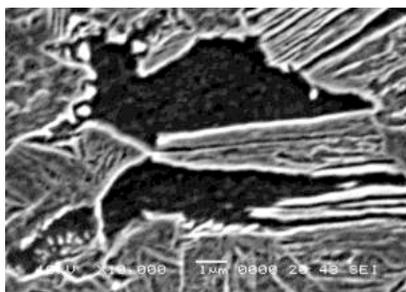


(b) SEM(1000X)

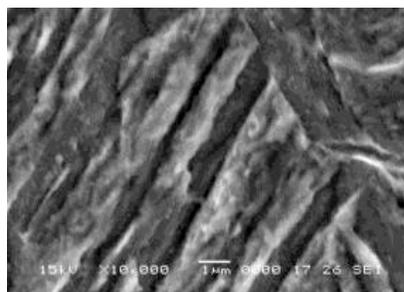
FIG. 10. MICROSTRUCTURE OF SPECIMEN C3 SOAKED FOR 3HRS AT 825OC CONSISTS OF FERRITE (LIGHT) AND MARTENSITE (DARK)

TABLE 3. SUMMARY OF MECHANICAL PROPERTIES

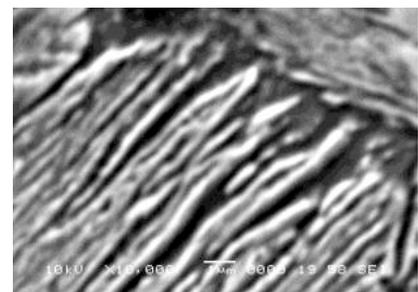
Material	Intercritical Heat Treatment Temperature (oC) and Soaking Time (hrs)	Specimen ID	Tensile Strength (MPa)	Hardness (HRC)	Toughness (Joule)	Martensite Volume Fraction $V_m$ (%)
AISI 1020 Steel	-	As-Received	710	5	157	-
	775, 1 hr	A1	945	29	60	37
	775, 2 hrs	A2	1084	32	65	40
	775, 3 hrs	A3	1045	31	67	45
	800, 1 hr	B1	1153	38	69	59
	800, 2 hrs	B2	1277	41	72	64
	800, 3 hrs	B3	1135	36	78	66
	825, 1 hr	C1	1080	30	84	68
	825, 2 hrs	C2	1045	29	88	71
825, 3 hrs	C3	935	24	135	83	



(a) PLATE TYPE (10000X) AT 775°C



(b) PLATE TYPE (10000X) AT 825°C



(c) LATH TYPE (10000X) AT 800°C

FIG. 11. MORPHOLOGY OF MARTENSITE PHASE

To provide a reasonable explanation for significant variation of TS of DP specimens the phase transformation occurs during intercritical heat treatment has to be taken into consideration. The austenite to martensite phase transformation upon quenching from intercritical annealing temperature is accompanied by 4% volume change theoretically. Actual volume change depends upon the amount of carbon trapped within martensite bct (body centered tetragonal) crystal lattice [15,18]. Another reason for the significant change in mechanical properties of DP specimens is the tetragonality of bct lattice of martensite which depends upon its carbon content. The degree of tetragonality (usually measured by  $c/a$  ratio) given in Equation (1) indicates linear relation with amount of carbon present in the martensite ( $C_m$ ). Moreover, carbon content of each grain of martensite ( $C_m$ ) can be expected to decrease with increase in the amount of martensite

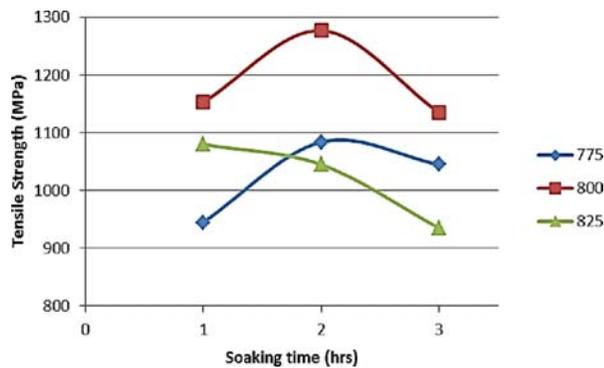


FIG. 12. EFFECT OF INTERCRITICAL SOAKING TIME AND TEMPERATURE ON TENSILE STRENGTH

( $V_m$ ) according to Equation (2).

$$c/a = 1.005 + 0.045 (C_m) \tag{1}$$

$$C_m = C_s/V_m \% \tag{2}$$

Where  $c/a$  is Tetragonality ratio,  $C_m$  is Carbon content of martensite,  $C_s$  is Carbon content of steel,  $V_m$  is martensite phase volume (%).

In present case the tetragonality ratio of martensite formed in DP specimens was determined by using the empirical Equations (1-2). To calculate percent of carbon in martensite ( $C_m$ ) percent  $V_m$  was used in Equation (2). Thereafter, tetragonality ratio was determined using the Equation (1). Using the Equations (1-2), the value of tetragonality ratio calculated from each microstructure at all intercritical heat treatment conditions is given in Table 4. This difference in axial ratios corresponds to higher lattice volume change of lower martensite fraction so that the impact of martensitic transformation on surrounding ferrite matrix should be definitely stronger for high carbon content grains. However, on a larger scale the total lattice volume expansion effect is controlled by much higher martensite volume fraction. As a consequence, in order to accommodate the lattice volume change martensite induces the plastic deformation into the surrounding ferrite phase by the exertion of compressive force at the vicinity of ferrite-martensite interface due to which TS increases for the DP.

TABLE 4. TETRAGONALITY RATIO OF MARTENSITE LATTICE (C/A)

No.	Sample ID	Micrograph Figs.	$V_m$ (%)	$C_s$ (%)	$C_m$ (%)	$c/a$
1.	A1	Fig. 2(a)	37	0.23	0.0062	1.005279
2.	A2	Fig. 3(a)	40	0.23	0.0057	1.005257
3.	A3	Fig. 4(a)	45	0.23	0.0051	1.005200
4.	B1	Fig. 5(a)	59	0.23	0.0038	1.005171
5.	B2	Fig. 6(a)	64	0.23	0.0035	1.005158
6.	B3	Fig. 7(a)	65	0.23	0.0035	1.005158
7.	C1	Fig. 8(a)	68	0.23	0.0033	1.005149
8.	C2	Fig. 9(a)	71	0.23	0.0032	1.005144
9.	C3	Fig. 10(a)	83	0.23	0.0027	1.005122

### 3.2.2 Hardness

Hardness values of as-received and intercritically heat treated specimens are listed in Table 3. Fig. 13 shows the effect of intercritical annealing temperature and soaking time on hardness of DP specimens. Hardness and strength are interrelated in a way that increasing the hardness generally improves the strength. Therefore, hardness result shows the similar trend compared to TS. The hardness of as-received specimen was found to be lower than hardness of DP specimens. The higher hardness is due to formation of harder phase i.e. martensite in DP specimen. Fig. 13 also shows that hardness first increases and then decreases with increasing soaking time at a particular temperature. This suggests that  $V_m\%$  is not only the microstructural feature that controls the properties of dual phase steels but the effect of carbon content of martensite must also be taken into account as previously discussed for TS results.

### 3.2.3 Toughness

Toughness values of as-received and intercritically heat treated specimens are listed in Table 3. It can be noted from Table 3 the toughness of as-received specimen is higher than DP specimens annealed at range of intercritical temperatures. The higher toughness of as-received specimen is due to higher ductility and ability of pearlite phase to co-deform with ferrite compared to the martensite phase present in DP specimens. From Fig. 14 it can be seen that toughness of DP specimens increases with increasing temperature and time during intercritical annealing. At low martensite fraction the ductility of martensite phase is low due to its higher carbon content, while ductility significantly improves with high  $V_m\%$  owing to decrease in its carbon content. At high  $V_m\%$  the flow stress of martensite decreases and its ability to co-deform with ferrite increases. Due to increase in  $V_m\%$  and improvement in ductility of martensite phase, the maximum toughness of 135 Joules was recorded for DP specimen (C3) corresponding to 83%  $V_m$ . However, this trend is opposite with observations of researcher's Movahed et. al. [1] and Bag et. al. [12] that fine distribution of martensite content upto 60-78% results in sharp drop in impact energy measurements.

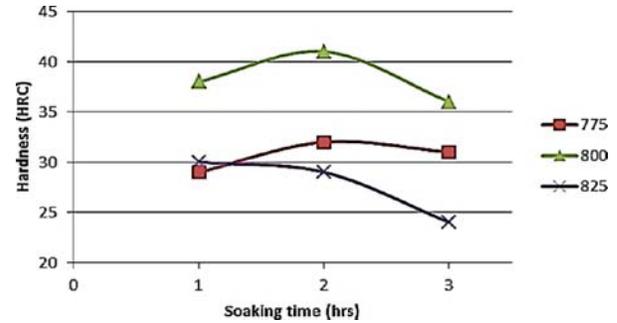


FIG. 13. EFFECT OF INTERCRITICAL SOAKING TIME AND TEMPERATURE ON HARDNESS

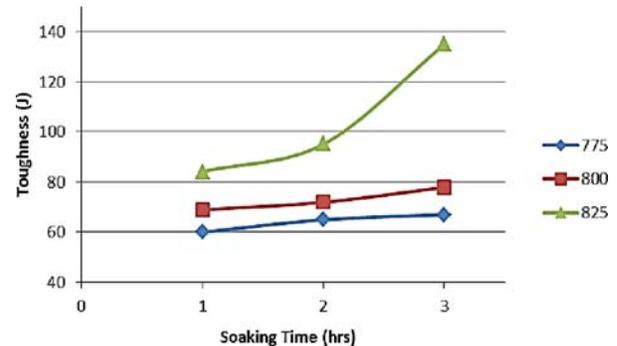


FIG. 14. EFFECT OF INTERCRITICAL SOAKING TIME AND TEMPERATURE ON TOUGHNESS

## 4. CONCLUSION

A range of specimens having DP microstructures were produced by subjecting AISI 1020 steel to intercritical heat treatment. Characterization of mechanical properties was done by means of hardness, impact and tensile test. Based on experimental results following conclusions can be drawn.

- (i) The amount martensite fraction increases with increasing temperature and time during intercritical annealing.
- (ii) Higher percent martensite volume fraction lowers the martensite carbon content and change the morphology from plateto lath type. Also martensitetetragonality ratio was found be dependent of carbon content.

- (iii) Decrease in carbon content softens the martensite and significantly improves its plastic formability.
- (iv) The hardness and TS was found to increase with increasing  $V_m$  % with optimum value of 1277 MPa and 41 HRC. A further increase in  $V_m$  % was found to decrease both TS and hardness.
- (v) The toughness of DP specimens was lower compared to as-received and increase with increasing  $V_m$  %.

## ACKNOWLEDGMENT

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