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Mechanical Properties and Fracture Behavior of Medium Carbon Dual Phase Steels

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Abstract - Dual phase (DP) steels have been developed from plain medium carbon (MC) steel containing 0.42wt % carbon. Intercritical austenitisation (ICA) treatment was carried out at 740^{o}C for different ICA time followed by water quenching to obtain different martensite volume fraction (MVF) in DP steels. Normalizing treatment (850^{o}C for 30 minutes) was carried out before ICA treatment. Normalized steel and DP steels have been characterized by optical and scanning electron microscopy (SEM), Vickers hardness measurements and tensile properties determination. The effect of MVF on various mechanical properties and fracture behavior of MC dual phase steels have been explained in the present work. Normalized steel showed fully ductile failure whereas DP steels showed different fracture mode depending upon MVF.

Index Terms – Dual phase steel; Martensite; Hardness; Fracture.

1. INTRODUCTION

The steels having two phases namely ferrite and martensite are known as dual phase (DP) steels. Ferrite is soft and provides good ductility whereas martensite is hard and is responsible for high strength [Das *et al,* (2009)]. The desire to produce high strength steels with formability greater than microalloyed steel led to the development of DP steel in 1970s. It is prepared by heating a carbon steel sample at a temperature between A_1 and A_3 followed by rapid quenching or thermo-mechanical controlled process [Speich *et al,* (1981); Yu *et al,* (2010)]. The properties which make DP steels most popular include good combination of strength and ductility, absence of yield point phenomena, low yielding, high initial work hardening rate, high uniform and total elongation, high strength to weight ratio and good formability [Bag *et al,* (1999); El-Sesy *et al,* (2002)].

The absence of yield point phenomena in DP steels provides good surface finish. This is not possible with most low carbon and microalloyed steels due to presence of luders bands [El-Sesy *et al,* (2002)]. For same ultimate tensile strength, DP steels further show higher % elongation than high strength low alloy steels [Paruz *et al,* (1989), Samuel *et al,* (1985)]. The strength and hardness of DP steels can be adjusted by controlling the amount, distribution and carbon content of martensite [Speich *et al,* (1981); El-Sesy *et al,* (2002)]. Combination of such properties (good surface finish, high strength and good formability) initially attracted researchers for using it in manufacturing car bodies like bumper, wheel rim, door panel etc. These parts are made from DP steels because of its high strength to weight ratio which provides higher fuel efficiency [Saghafian *et al,* (2007)]. Now a days dual phase steel has also find applications as wear resistance material if proper combination of strength and ductility is obtained [Tyagi *et al,* (2001); Modi *et al,* (2007); Saghafian *et al,* (2007)]. After reviewing the existing available literature, it is found that martensite volume fraction (MVF) plays a very important role in controlling mechanical properties like hardness, strength, ductility (% elongation), toughness and wear resistance. In the present work an attempt is being made to develop a heat treatment cycle to form DP steel with optimum amount of MVF which will give better mechanical properties.

2. EXPERIMENTAL WORK

The chemical composition of medium carbon steel used in the present study is 0.42wt% C, 0.6wt% Mn, 0.15wt% Si, 0.04wt % S and 0.04wt% P. As received material in the form of circular rod of diameter 8mm was machined in a lathe machine to obtain tensile specimens. Figure 1 shows schematic diagram of tensile specimen used first for normalizing and later for intercritical austenitisation (ICA) treatment. Specimens were normalized at 850^{o}C for 30 minutes in a muffle furnace.

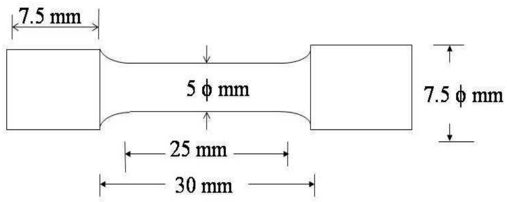


Fig. 1: Schematic diagram of tensile specimen.

The intercritical austenitisation was carried out in a vertical tube furnace. Figure 2 shows schematic diagram of the vertical tube furnace used to obtain dual phase steels. After heating samples at ICA temperature of 740^{o}C for different time (1, 3, 6, 9 and 15 minutes), samples were dropped into water bath at room temperature. Ferrite plus pearlite structure at room temperature is converted into ferrite plus austenite structure when heated in intercritical region and after water quenching it is converted into ferrite plus martensite structure. Water quenching is necessary to obtain required cooling rate for austenite to martensite transformation. These specimens have been characterized by optical microscope and SEM for microstructural studies and fracture surface study. In mechanical characterization, tensile strength, % elongation and hardness values have been determined.

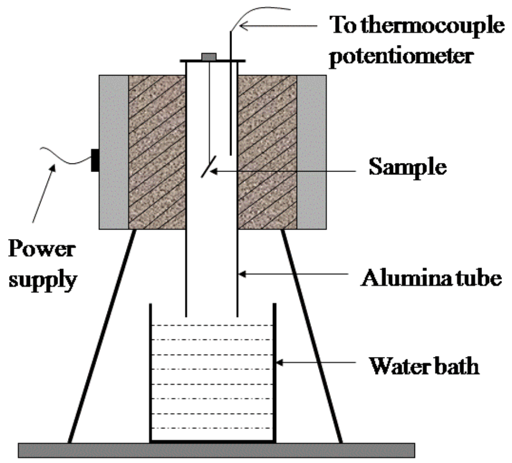


Fig. 2: Schematic diagram of vertical tube furnace used for intercritical heat treatment.

3. RESULTS AND DISCUSSION

3.1 Optical Microscopy

The microstructure of MC normalized steel is shown in Fig. 3a. White regions in this figure are ferrite and dark regions are pearlite. Similarly, the microstructures of MC DP steels developed at ICA temperature of 740ºC for different ICA time are shown in Figs. 3b-f. In these microstructures (Fig. 3b-f) the white regions are proeutectoid ferrite phase and dark regions are primarily martensite. It is observed that martensite content in DP steels increases with increase in ICA time. Apart from martensite small amounts of pearlite, bainite and retained austenite may also be present. However, these micro constituents are difficult to be identified under optical microscope. The martensite volume fractions obtained in MC DP steels for different ICA time are given in table 1. Apart from MVF, Table 1 also shows variation in Vickers hardness, UTS and % elongation with ICA time.

Table 1: MVF and mechanical properties of MC DP steels prepared at 740^{o}C ICA temperature for different ICA time.

ICA Time (Minute)	MVF (%)	Hardness (VHN)	UTS (MPa)	% Elong -ation
1	45	342	876	17.1
3	55	578	844	8.8
6	90	676	536	5.8
9	94	816	497	4.1
15	95	784	547	5.0
Norma-lized	-	217	526	26.5

3.2 Mechanical properties

The effect of ICA time on MVF and hardness of DP steels is also shown in Table 1 and graphically represented in Fig. 4a. The figure shows that MVF increases sharply from 45vol % to 90vol % as ICA time increases from 1 minute to 6 minute. Further increase in ICA time marginally increases MVF and reached up to 95vol % at 15 minutes of ICA time. It can also be observed from the figure that as ICA time increases, there is first increase in hardness (342-816VHN) attains a maximum at 9 minute of ICA time and then hardness decreases faintly at 15 minute (784VHN) of ICA time. It might be an indication that martensite content cannot be increased further by increasing ICA time at ICA temperature of 740^{o}C.

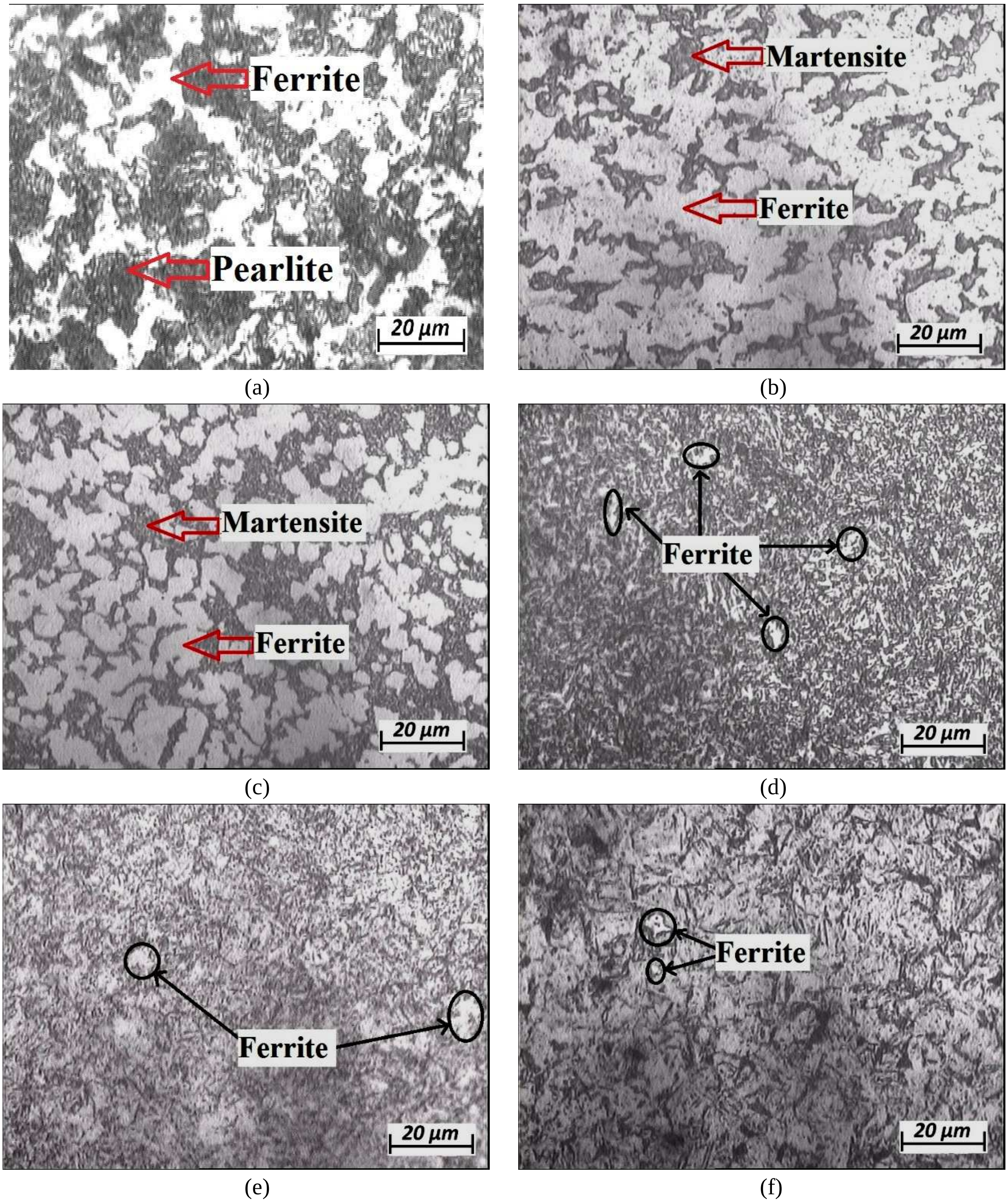


Fig. 3: Optical micrographs of MC steels (a) normalized at 850°C and heat treated at 740°C for (b) 1 min, (c) 3 min, (d) 6 min, (e) 9 min and (f) 15 min of ICA time.

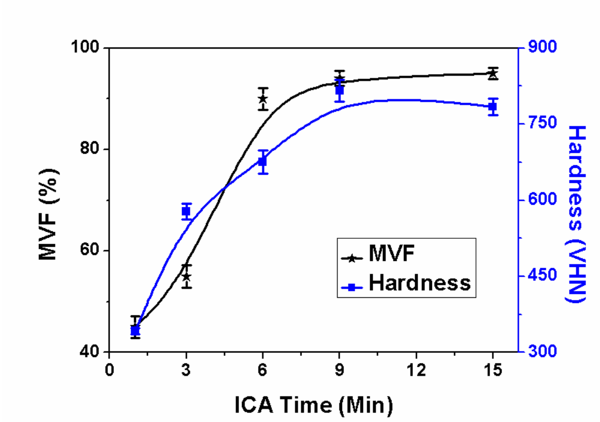
The increase in hardness with ICA time is due to increase in MVF of DP steels. However, marginal decrease in hardness may be either due to presence of retained austenite in the DP steel or due to grain growth or both. It is reported that with increase in carbon and manganese content of austenite, M_S (martensitic transformation start) and M_f (martensitic transformation finish) temperature decreases [Lakhtin, (1998)].

If M_f temperature reached to subzero temperature, martensitic transformation cannot complete at room temperature and correspondingly a small amount of austenite is retained. It is further known that presence of retained austenite decreases hardness of martensitic steel [Lakhtin, (1998)]. The hardness of MC normalized steel is found to be 217 VHN.

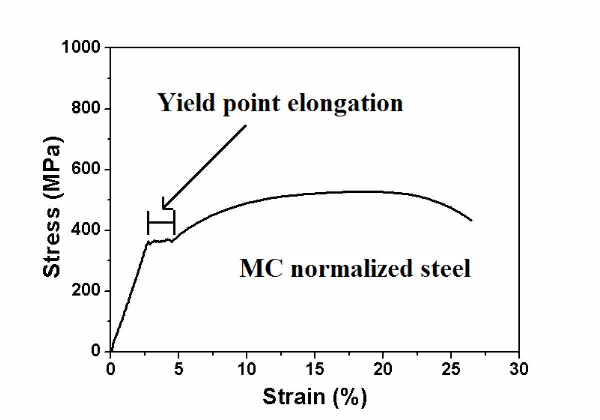
Figure 4b and c show stress-strain curve of MC normalized steel and DP steels prepared at 740ºC for different ICA time, respectively. It is observed that normalized steel shows yield point elongation (Fig. 4b) but DP steels do not show the same (Fig. 4c). The smooth transition from elastic to plastic deformation in DP steel is due to austenite to martensite transformation which occurs during quenching from ICA temperature. It is also noticed from Fig. 4c that % elongation (% strain) of DP steels decreases as ICA time (or MVF) increases.

26.5%. The decrease in % elongation with increase in ICA time is due to increase in hardness of DP steels. However, decrease in UTS with increase in MVF/ICA time is unusual. The reason for such variation is found to be presence of microcracks which are introduced in to the material during quenching. Figures 5a, b, c, d, e and f show fracture surfaces of MC normalized steel and DP steels prepared at 740ºC for 1, 3, 6, 9 and 15 minutes of ICA time, respectively.

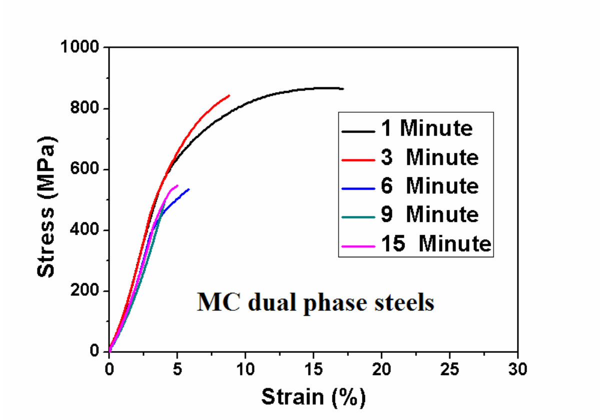
The fracture surface of MC normalized steel shows numerous dimples which are characteristics of ductile failure. In this process excessive plastic deformation occurs and material consumes high energy before



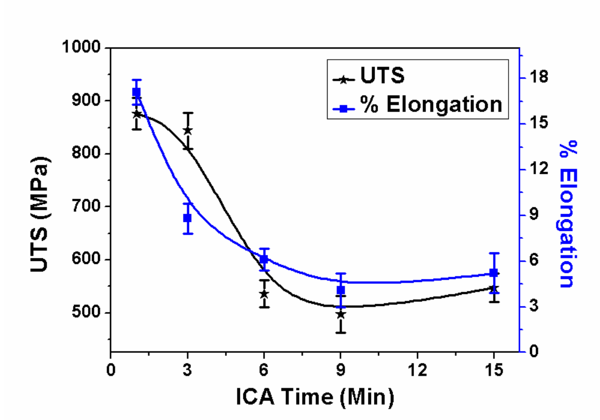
(a)



(b)



(c)



(d)

Fig. 4: (a) variation in MVF and hardness with ICA time; Stress-strain curves of (b) MC normalized steel and (c) MC DP steels; and (d) variation in UTS and % elongation with ICA time.

The variation in UTS and % elongation with ICA time is shown in Fig. 4d. It can be observed form the figure that UTS decreases from 876 MPa to 547 MPa as ICA time increases from 1 minute to 15 minute. The UTS of MC normalized steel is found to be 526 MPa. The figure also shows that % elongation of MC DP steels decreases from 17.1% to 5% as ICA time increases from 1 minute to 15 minutes. The % total elongation of MC normalized steel is found to be

fracture. Dimples are formed by coalescence of microvoids during tensile loading. Many inclusions can be easily observed in the figure at the centre of bigger size dimples. These inclusions are the preferred locations from where crack starts to nucleate and grow leading to final fracture. EDAX analysis of such an inclusion has been carried out and shown in Fig.6.

Figure 5b shows the fracture surface of DP steel which was intercritically treated for 1 minute. In this figure river patterns are also visible along with dimples. As river patterns are characteristics of brittle fracture by cleavage, it suggests that the mode of fracture surface of DP steel which was intercritally treated for 3 minute. The mode of fracture in this DP steel is found to be quasi-cleavage.

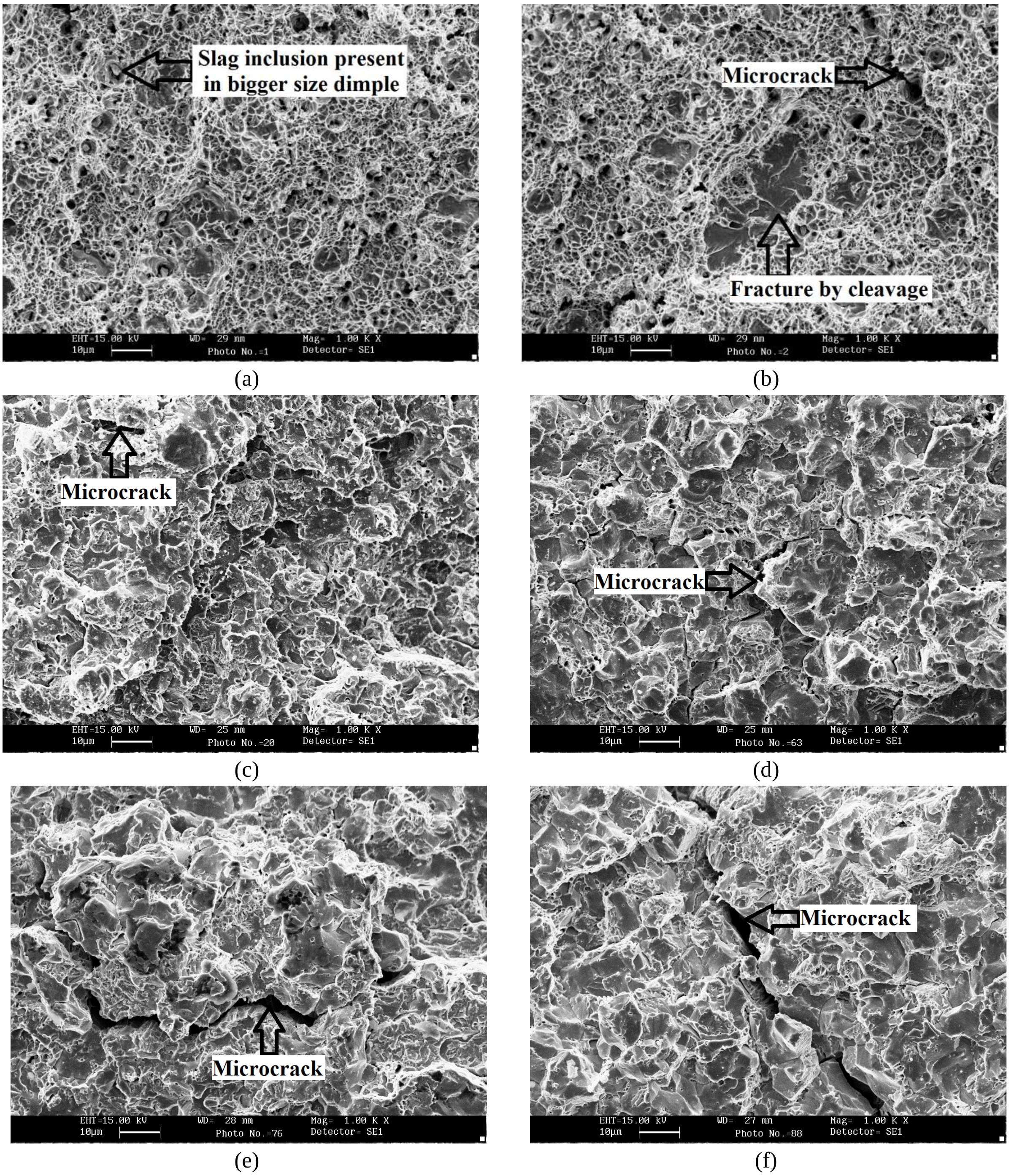
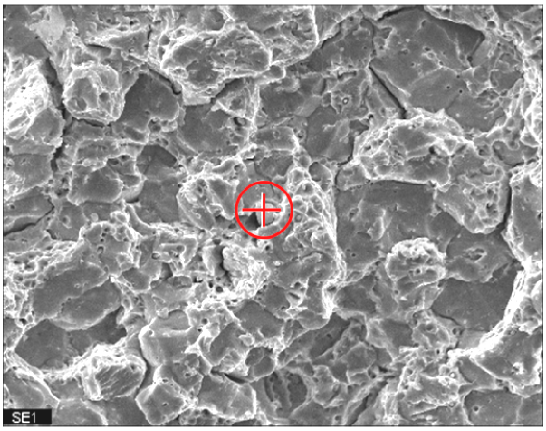


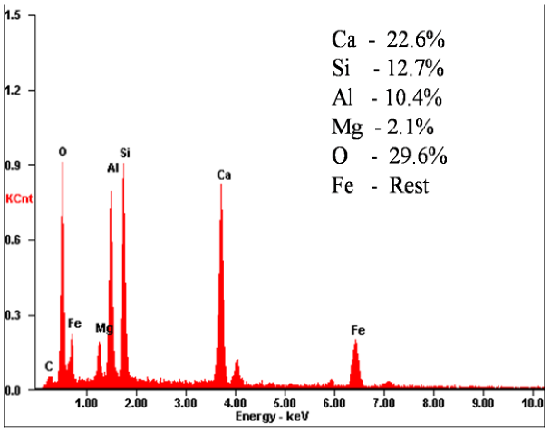
Fig. 5: Fracture surface of (a) MC normalized steel and DP steels for (b) 1 minute, (c) 3 minute, (d) 6 minute (e) 9 minute and (f) 15 minute of ICA time.

fracture in the DP steel is mixed mode (ductile+brittle). During fracture by cleavage, crack grows along cleavage plain and consumes less energy as compared to ductile failure. Figure 5c shows This type of fracture surface has characteristics of both ductile (dimple) and brittle (cleavage) failure. However, dimples in such failure are smaller and shallow. The fracture surfaces of MC DP steels which were intercritically treated for 6 minutes or longer time have shown intergranular fracture (Figs. 5d-f). These figures suggest that crack propagation has occurred mainly along grain boundaries. Failure along grain boundaries suggests that material has become quite brittle due to generation of microcracks during quenching from intercritical region.

for higher plastic deformation and provide higher hardness and strength. However, excessive volume expansion can cause microcracking in the surrounding ferritic grains. Size of microcracks affect the stress required for propagation of the microcrack and final fracture. Hence, it can be concluded that microcracks are responsible for the observed variation in UTS.



(a)



(b)

Fig. 6: (a) Fracture surface of MC DP steels showing slag inclusion as '+' marked inside a circle and (b) EDAX analysis of slag inclusion.

These microcracks can grow easily and cause failure even at lower stress. Energy required for propagation of crack along grain boundary is further reduced. A relation among crack length, plastic work and fracture stress has been proposed by Orowan and is as follows [Dieter, (1988)].

$$\sigma_f = \sqrt{(E\gamma_p/c)}$$

Where, σ_f is the stress required to propagate crack of length 2c and γ_p is the required plastic work for extension of crack in brittle failure of metals.

It can be observed from Figs. 5b-f that size of microcrack has been found to increase with increase in ICA time. Therefore, stress required for crack propagation and final fracture is decreasing with increase in ICA time. The decrease in % total elongation with increase in ICA time is mainly due to increase in hardness, however, size of crack present in the material may also contribute to decrease in % total elongation.

Microcracks are formed in DP steels during quenching and are associated with austenite to martensite transformation. It is reported that austenite to martensite transformation is associated with volume expansion [Moyer *et al*, (1975)]. The increase in volume causes plastic deformation in the surrounding ferrite grains. Higher MVF is responsible

However, presence of microcracks does not affect hardness. It is well known that crack propagation is affected only in tensile load and not in compressive load. Therefore, hardness of DP steel is found to increase with increase in ICA time but UTS of DP steel is found to decrease with increase in ICA time.

4. CONCLUSIONS

- Dual phase (ferrite + martensite) microstructure is successfully developed in medium carbon (0.42% C) steel at 740^{o}C intercritical austenitisation (ICA) temperature.
- Higher MVF is found to be responsible for higher hardness of DP steels. However, decrease in % elongation is due to increase in hardness of DP steels.
- Decrease in UTS with increase in MVF/hardness is found to be due to presence of microcracks. These microcracks are developed due to austenite to martensite transformation and increases with increase in MVF.
- Normalized steel showed fully ductile failure whereas DP steels showed different fracture mode depending upon MVF or ICA time. MC DP steels showed mixed mode (ductile+brittle) failure for 45% MVF, quasi-cleavage failure for

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MVF 55% and intergrainular failure for MVF greater than 55%.

- Dual phase steel containing MVF higher than 55% showed higher hardness but lower strength and lower % elongation due to presence of microcracks.

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