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EFFECT OF MICROSTRUCTURE ON MECHANICAL PROPERTIES AND ABRASIVE WEAR BEHAVIOR OF LOW CARBON DUAL-PHASE STEELS

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ABSTRACT

The mechanical properties and wear behavior of Dual Phase (DP) steels have been investigated and compared with those observed in normalized (N) steel that has the same chemical composition. The DP steels having different content and morphology of martensite were produced by varying intercritical annealing temperature and initial microstructures. Mechanical properties of four different DP steels and N steel have been investigated by carrying out tensile and macrohardness tests. Dry sliding wear tests have been conducted on four different the DP steels and the N steel using pin-on-plate to investigate their wear characteristics. It has been found that the yield and tensile strengths and macrohardness increase with increasing martensite content and decreasing martensite size. The yield and tensile strengths and macrohardness of the N steel were significantly lower than the DP steels whereas percentage of total elongation was higher. Wear properties are improved by increasing martensite volume fraction and size in the DP steels. The N steel specimen showed the highest wear rate.

INTRODUCTION

Low carbon dual phase steels developed in 1970s have aroused considerable attention in the last three decades. Compared to the High Strength Low Alloy (HSLA) steels, they display improved strength, ductility and formability characteristics [1-7]. These properties make them attractive for weight-saving applications in automotive industry. By using dual phase steel sheets, vehicle weights can be reduced and significant savings in fuel consumption can be obtained.

Low carbon DP steels have higher wear resistance and lower friction than ferrite-pearlite steel having the same carbon content [8]. One another application area of low carbon DP steels might be the mineral processing industry in making pipelines for transportation of mineral slurry and mining equipments handling abrasive material such as soil, sand, stones, etc. Tyagi et al. [9] have studied wear and mechanical properties of medium carbon DP steels (0.42 wt-%C) and observed that further wear resistance improvement can be achieved with increasing martensite content and lower friction coefficient can be obtained at the same time. The DP steels have also good potential for use as tillage tools where strength and wear resistant become of great concern [10].

Dual phase steel is described by the composite microstructure comprising 20-25% hard martensite particles in a soft ferritic matrix. They are mainly produced by heating the low carbon steel between AC_1 and AC_3 temperatures in the austenite plus ferrite phase field followed by rapid cooling in order to transform the austenite to martensite. It is possible to control the range of transformation products which can be formed from the austenite subsequent intercritical annealing by varying intercritical annealing temperature (ICAT) and cooling rate.

The main purpose of this study is to explore the effect of the martensite contents and morphologies on the mechanical properties and wear behavior of DP steel. In this work, The DP steels having two different volume fractions and morphologies of martensite have been developed by intercritical heat treatment. In addition, normalizing heat treatment has been applied to as received ferrite-pearlite steel. The effect of MVFs and martensite morphologies on the mechanical properties of the DP steels have been studied and compared to the N steel. Dry sliding wear test have been carried out to evaluate wear behavior of the investigated steels for their tribological applications.

EXPERIMENTAL PROCEDURE

Chemical composition of the steel used in the present investigation is given in Table 1. The material was produced in induction furnace and poured into silica sand mould as a block of 26x300x300 mm in size. The block was then cut into smaller pieces of 26x26x300 mm. These pieces were hot rolled in which the thickness of each was reduced to 4 mm.

The critical annealing temperatures, AC_1 and AC_3, were identified as 711 ºC and 862 ºC, respectively by using the following Andrews empirical formulas [11].

$$A_{C1}(^{\circ}C) = 751-16.3C-27.5Mn-5.5Cu-5.9Ni+34.9Si+12.7Cr +3.4Mo \quad (1)$$

$$A_{C3}(^{\circ}C) = 881-206C-15Mn-26.5Cu-20.1Ni-0.7Cr+53.1Si \; 41.7V \quad (2)$$

Table 1 Chemical composition of the steel used (weight percent)

C	Mn	Si	Ni	Cr	Cu	P	S	Fe
0.09	1.65	0.55	0.69	0.07	0.02	0.015	0.013	Bal

Small specimens of 10x10 mm size were subjected to different heat treatment procedures to produce dual phase microstructures as follows:

i. intercritical annealing of the specimens at 725 ºC and 745 ºC for 30 min followed by quench water (DA725 and DA745),
ii. austenization of the specimens at 900 ºC for 30 min followed by quench water to obtain almost fully martensitic structure and after that re-annealing of the specimens at 725 ºC and 745 ºC for 30 min followed by quench water (DQ725 and DQ745),
iii. Normalizing heat treatment of the sample was carried out at 920 ºC for 30 min followed by air cooling.

The heat treatment cycles are presented schematically in Fig. 1. Each specimen, namely DA725, DA745, DQ725 and DQ745, was coded according to the applied heat treatment procedures. The left-hand letters DA and DQ represent direct annealing and double quenching respectively and the right-hand numbers represent the intercritical annealing temperatures (ICAT). The as-received sample and normalized samples are designated by AR and N, respectively.

The heat treated samples were ground, polished and etched in 2% nital solution of 2% nitric acid in 98% ethanol for microstructural characterization by using light microscope. After etching with 2% nital, the samples were further etched in a solution of 10% sodium metabisulfide in 90% pure water in order to make martensite more obvious. The volume fraction of phases (martensite and pearlite) was determined by using Image J software on etched metallographic sections.

The tensile tests were performed on heat treated specimens using a Shimadzu machine with crosshead speed of 10 mm min^{-1} at room temperature. Three tensile specimens were tested for each microstructure and average tensile data is taken. Macrohardness of the samples were measured and expressed in terms of Rockwell C.

Wear tests were performed on polished rectangular specimen of 40x35x3mm in size using pin on plate wear testing machine. The wear test was carried out against the counterface of a hardened and polished pin made of AISI 52100 steel with HRC 62 to 65. Abrasive wear test were conducted for sliding distances of 200, 400, 600, 800, 1000 m respectively. All heat treated steel samples were tested at a load of 20 N and at a fixed sliding speed of 10 mm/s under laboratory conditions. The specimens were ultrasonically cleaned in acetone prior to and after the wear tests and weighed using a Shimadzu microbalance. The volume loss [(weight loss/density) x1000] and the wear rate (volume loss/sliding distance) were computed using weight loss technique.

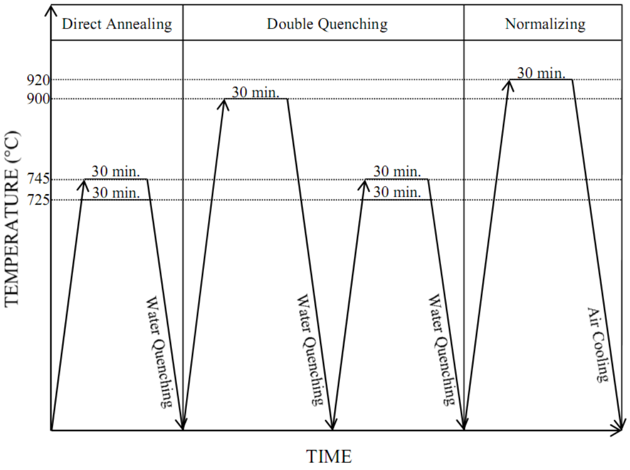

Figure1. Schematic representation of heat treatment cycles.

RESULTS AND DISCUSSION

Microstructure

Microstructures of the as-received and normalized specimens are displayed in Fig.2a and 2f, respectively. In these micrographs, pearlite appears as dark color in light ferrite matrix. It can be seen that pearlite colonies are distributed along the ferrite grain boundaries. As can be observed from Fig.2f, normalizing heat treatment resulted in grain refinement in ferrite and pearlite microstructures.

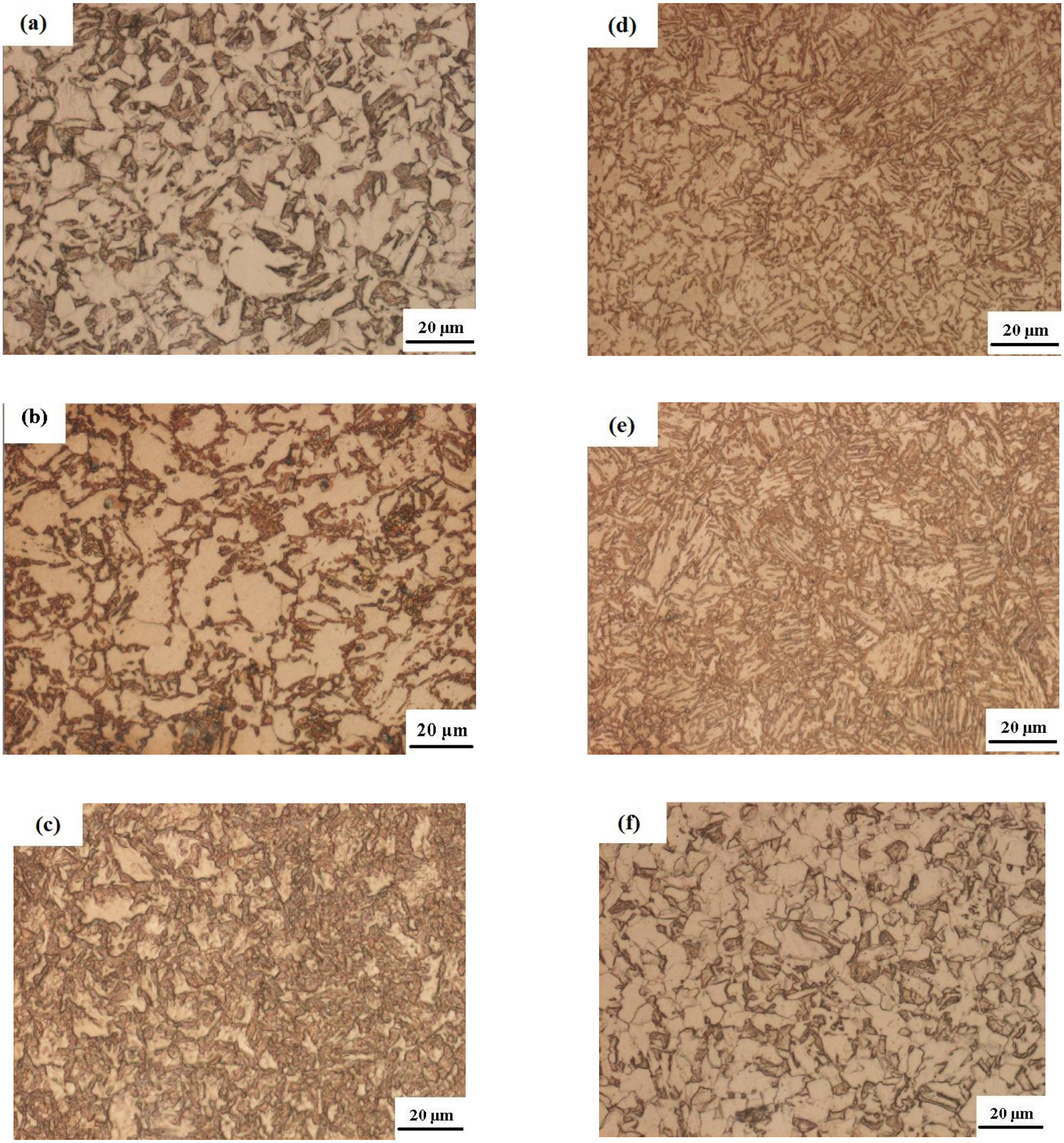

Figure 2. Optical micrographs of (a) AR, (b) DA725, (c) DA745, (d) DQ725, (e) DQ745, (f) N steel samples (Etched in nital 2%).

Optical micrographs of DA725 and DA745 DP steel samples having a pearlite and ferrite starting microstructure are shown in Fig.2b and c, respectively. The heat treating of the specimens directly to the intercritical temperature produced martensite network along the ferrite grain boundaries. It can be seen from Figs. 2b and c that ferrite is surrounded with a ring of martensite. Such morphological distribution of martensite is termed as ring, chain or continuous network of martensite. The network model of formation of martensite was explained by Speich et al. [12]. They found that the growth of austenite into ferrite is controlled by manganese diffusion in ferrite which is much easier along the grain boundaries. Thus the austenite which transforms to martensite during quenching grows along the ferrite grain boundaries.

On the other hand, the dual phase microstructures of DQ725 and DQ745 samples are significantly different from that of DA725 and DA745 samples as represented in Fig.2d and e. Microstructures of the double quenched DP steel samples with almost fully martensitic initial microstructure consisting of fine, well-dispersed martensite particles in ferrite matrix. Such finely dispersed ferrite and martensite phases are termed as a fibrous structure.

The results of the quantitative metallographic measurements of MVF and PVF are summarized in Table 2.

Table 2 Microstructure and quantitative metallographic data for steel samples

Specimen code	Microstructure	Volume Fraction of Pearlite/Martensite (%)
DA725	Ferrite-ring martensite	41
DA745	Ferrite-ring martensite	53
DQ725	Fibrous ferrite and martensite	41
DQ745	Fibrous ferrite and martensite	53
N	Ferrite-Pearlite	29

In the present study, basically two types of microstructures were produced: one with ferrite-pearlite structure produced by normalizing of as-received material and the other with ferrite-martensite structure produced by intercritical annealing through different routes which varies the amount and morphologies of phase constituents and phase compositions.

The martensite volume fraction (MVF) increased with increasing the ICAT, as shown in Table 2. This can be explained by lever rule. MVF of DA725 or DQ725 are found to be 41%, whereas MVF of DA745 or DQ745 are higher (53%).

Although the specimens DA725 and DQ725 or DA745 and DQ745 contain constant amount of martensite, they had different microstructures such as network or fibrous martensite. This difference may be due to the distinct initial microstructures of them.

Mechanical Properties

The effect of various heat treatment procedures on the mechanical properties of the low carbon steel was studied by tensile and hardness tests. The room temperature mechanical properties of the DP steels and the N steel are summarized in Table 3.

It is obvious that the 0.2% yield strength (YS), ultimate tensile strength (UTS) and hardness (HRC) increased as martensite content increased. Conversely, percentage of total elongation showed the opposite trend, decreasing with increasing MVF. Similar results have been reported by Davies [13].

DP steels showed a markedly higher the YS, the UTS and the hardness than the N steel. The higher strength and hardness of the DP steels could be attributed to the presence of hard martensite phase. The N steel showed the highest ductility, measured by the elongation the fracture, of the all steel samples investigated in the present study.

DQ725 with fibrous martensite exhibited higher the YS, the UTS and the hardness values than DA725 with the same martensite content, which is 41%. On the basis of these results, it may be concluded that a finely dispersed, hard second phase in a soft matrix should offer more effective barriers to dislocation motion which leads to increase in strength. Predictably, the percentage of total elongation value for DQ725 was lower than this for DA725. Similar trend has been reported by other researchers [14, 15].

On the other hand, DQ745 showed a bit lower the YS, the UTS and the hardness than DA745. Comparing to DA745, the decrease in strength and hardness in DQ745 may be explained by suggestion of Bag et al. [16-17].They studied tensile and impact properties of high martensite dual phase steels consisting of fibrous martensite. They reported that UTS increases by increasing the MVF up to approximately 50% and then decreases further increase in the MVF. According to Bag et al. [16] the model developed on the basis of a rule of mixture is inadequate to predict the tensile strength of a specimen containing more than 50% of martensite and there is no linear relation between, $\sigma_{TS,DP}$ and V_m.

According to rule of mixture, tensile strength of a DP steels ($\sigma_{TS,DP}$) can be written as Eq. (3):

$$\sigma_{TS,DP}= \sigma_{TS,m} V_m + \sigma_{TS,f} (1-V_m) \qquad (3)$$

where, $\sigma_{TS,m}$ is the tensile strength of the martensite, $\sigma_{TS,f}$ is the tensile strength of the ferrite and V_m is martensite volume fraction.

Therefore they developed a new theory based on the mean free path of ferrite and the mean free path of martensite to explain unusual tensile behavior of high martensite DP steels. In this work, it seems that this theory could be used to clarify the decrease in the YS, the UTS and the hardness values of DQ745.

MVF and carbon content of martensite are two important factors that affect the strength and hardness of DP steels. Increasing MVF has two contradicting effects. Increasing MVF increases strength and hardness of the DP steel but decreases carbon content of martensite. Therefore, the investigated DP steels in the present study were being under the influences of both effects simultaneously.

Based on the present results, it may be concluded that DQ has not additional beneficial effect on the mechanical properties of DP steels containing more than 50% martensite.

Table 3 Average room temperature tensile and hardness test results

Specimen code	0.2% yield strength (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)	Hardness (HRC)
DA725	529	913	19	26.3
DA745	707	1017	13	29.9
DQ725	605	978	16.5	27.4
DQ745	648	1000	14	29.6
N	410	699	24	15.8

Wear Behavior

Wear test results of the investigated specimens for total sliding distance of 1000m are presented in Table 4 in terms of volume loss and wear rate. Comparing to the N steel, the lower wear rate was observed in the DP steels. This may be attributed to the relatively higher hardness in the DP steels. Furthermore, it was also observed that increasing martensite content in the DP steels caused a decrease in wear rate. This has been related to the higher hardness imparted by martensite. The present result is in accord with the existing literature [18,19].

Although DA725 and DQ725 had same martensite content, DQ725 showed slightly higher wear rate than DA725, despite of its higher hardness. The wear appears mainly delamination mechanism involves nucleation of cracks, their propagation and finally separation in the form of flake wear particles. Cracks generally nucleate at the interface of ferrite and martensite. Finer martensite morphology in DQ725 increased the interfaces between the ferrite and martensite which are the suitable places for nucleation and propagation of cracks, thus increased the wear rate. Conversely, DA745 showed a bit higher wear rate than DQ745.

Table 4 Wear Test Results

Specimen code	Wear Loss (mm^3)	Wear Rate (mm^3/m)
DA725	17.035	0.01703
DA745	12.716	0.0127
DQ725	19.586	0.0195
DQ745	11.423	0.0114
N	43.742	0.0437

CONCLUSIONS

Present investigation conducted on the DP steels with different amount and morphologies of martensite and the N steel led to the following conclusions:

1. The hardness, the YS and the UTS in DP steels increased with increasing MVF.

2. However ductility in terms of percentage total elongation decreased with increasing MVF.

3. The N steel showed the lowest hardness, YS and UTS and the highest ductility in the all investigated steel samples.

4. DQ725 consisting of finer martensite exhibited higher hardness, YS and UTS, but lower ductility than DA725.

5. Conversely, the hardness, YS and UTS decreased in DQ745 compared to DA745.

6. The wear rate was higher in the N steel than in the DP steels.

7. The wear rates of the DP steels decreased with increasing the MVF.

8. Refinement of martensite size decreased the wear rate for DQ745, whereas increased the wear rate for DQ725.

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