Effect of Carbon Amount of Dual-Phase Steels on Deformation Behavior Using Acoustic Emission

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Abstract—In this study acoustic emission (AE) signals obtained during deformation and fracture of two types of ferrite-martensite dual phase steels (DPS) specimens have been analyzed in frequency domain. For this reason two low carbon steels with various amounts of carbon were chosen, and intercritically heat treated. In the introduced method, identifying the mechanisms of failure in the various phases of DPS is done. For this aim, AE monitoring has been used during tensile test of several DPS with various volume fraction of the martensite (VM) and attempted to relate the AE signals and failure mechanisms in these steels. Different signals, which referred to 2-3 micro-mechanisms of failure due to amount of carbon and also VM have been seen. By Fast Fourier Transformation (FFT) of signals in distinct locations, an excellent relationship between peak frequencies in these areas and micro-mechanisms of failure were seen. The results were verified by microscopic observations (SEM).

Keywords—Dual Phase Steel, Deformation, Acoustic Emission.

I. INTRODUCTION

FERRITE-martensite dual phase (DP) steels are a class of high strength low alloy steels which have been developed since the mid-70s. The replacement for pearlite in conventional High Strength Low Alloy Steels (HSLAS) by the martensite phase resulted in an excellent strength and ductility combination. Because of their composite microstructure, dual-phase steels exhibit interesting characteristic mechanical properties such as continuous yielding (i.e. no sharp yield point), a relatively low yield stress, low yield stress to tensile strength ratios (YS/UTS), and relatively high formability. In general the DPS possess higher ductility than the conventional HSLAS at a given strength level [1]. DPS are produced by heating low carbon steel into the intercritical ($\alpha+\gamma$) phase field, and cooling at a rate so as to produce the desired microstructure containing martensite phase. They can also be obtained directly from the hot rolling mill, by control of composition and processing [2].

Acoustic emission (AE) is a stress wave produced by sudden movement in stressed material [3]. AE is a natural phenomenon occurring in the widest range of materials, structures, and processes; so, it can produce during deformation, crack nucleation and growth, dislocation motion, twin formation, etc. Hence, the thorough investigation of AE during deformation of all metals and composites, can improve understanding the dynamic processes of deformation. Especially in these types of steels, because of their complex dynamic processes of deformation, studying the microstructural procedure of deformation and fracture, is very difficult [4].

In order to identify the types of damage in DPSs, many researchers have done [5]-[14]. Some researchers reported the type of damage in DPSs involves only Ferrite/Martensite decohesion [5], [6], however, the others showed this damage also contains Martensite fracture [7]-[10]. So that recognize the types of damage, fractography [12], [13] and in-situ tests [14] are applied.

With respects to the above review, it is seen that, there is no one conclusive idea about the mechanisms of failure in DPS.

The present paper, continuing previous works [15]-[18], studies the carbon amount effect of two kinds of DPS on the AE behavior under tensile loading. To perform this goal, an assay has been done to correlate the peak frequencies of AE phenomena corresponding to yield and plastic deformation area. Using this method displays a good relationship between failure micro mechanisms and FFT based analysis.

II. EXPERIMENTAL MATERIAL AND PROCEDURE

The chemical composition of the steels used in this study is given in Table I. The high purity alloys was chosen to minimize the effects of coarse inclusions. Tensile test samples were made following ASTM E08. The samples have heated for 20 min in 920°C and then air cooled. The effects of the alloying elements on the lower critical temperature line (A1) and the upper critical temperature line (A3) of the Fe-Fe_3C equilibrium diagram can be calculated by Leslie method [2].

TABLE I
CHEMICAL COMPOSITION OF THE USED STEELS (WT.%)

Samples	C	Mn	Si	Nb	Fe
1	0.186	1.345	0.015	0.014	Bal.
2	0.094	1.294	0.013	0.015	Bal.

Samples	Al	V	S	P
1	0.04	0.001	0.008	0.016
2	0.03	0.001	0.006	0.013

For the 1st sample of this study, the A_1 and A_3 temperatures were calculated to be 709°C and 823°C and for the 2nd one were 708°C and 849°C, respectively.

Intercritical heat-treatment was done and the samples were heated to 730, 760, 780 and 810°C for 20 min and then quenched in iced brine of -8°C. After heat treatments, cross-sections of the samples were polished, etched with 2% nital, and observed under the optical microscope to reveal the VM.

For these intercritical temperatures, VMs are obtained 12, 32, 48 and 69% for the 1st sample and 12, 34, 49 and 65% for the 2nd sample respectively.

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Fig. 1 shows schematic diagram of the mentioned heat treatment.

Principally, for the sake of understanding the behavior of martensite and ferrite phases separately on the AE signals, samples of pure ferrite and full martensite were produced by the heat treating of C40 steel, the composition of which is shown in Table II. Fig. 2 shows ferrite, martensite and one of the DPS (2nd sample which has intercritically annealed at 760°C) microstructures.

Tensile tests are conducted at room temperature using a universal testing machine with a cross-head speed of 3 mm/min.

The AE analysis was performed using an AE detector made by PAC Co., with the wide band sensor PAC WD, frequency range was 100-1000 kHz. The data processing was done under the condition of a pre-amplification of 40dB. The sensor was coupled to the polished jig using grease under constant pressure. To remove the noise from AC motor, ballscrews etc., threshold amplitude was specified to be 35dB. All connections of the jaw jig and tensile test machine is coated with a layer of grease to minimize the friction and noises. The AE data acquisition was realized by means of the AE Win program operated during the tensile tests.

TABLE II
CHEMICAL COMPOSITION OF THE PURE FERRITE AND MARTENSITE (WT.%)

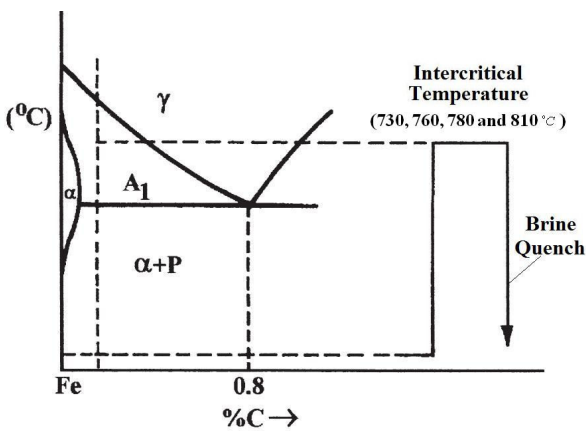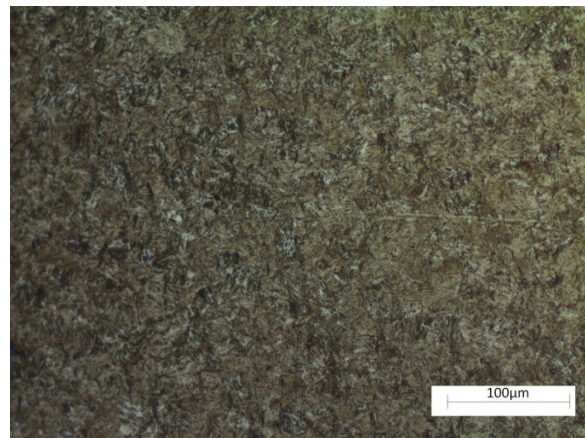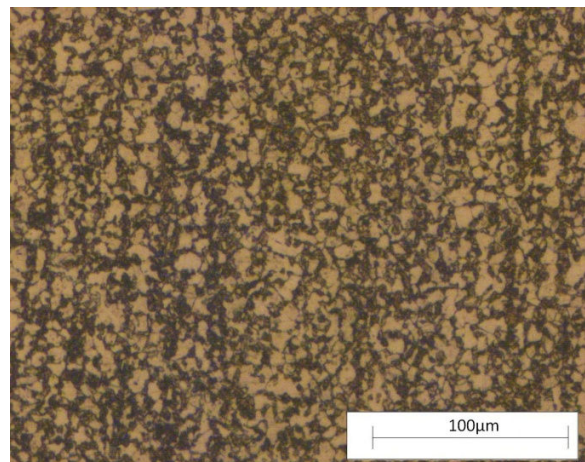| SAM	C	Mn	Si	P	S	Cu	Fe
Martensitee	0.43	----	----	0.018	0.01	----	Bal
Ferrite	0.003	0.03	0.03	0.025	0.04	0.032	Bal

Fig. 1 Schematic diagram of the Intercritical Annealing

(a)

(b)

(c)

Fig. 2 Ferrite (a), Martensite (b) and one of the DPS microstructures (c)

III. RESULTS AND DISCUSSIONS

Table III illustrates the tensile tests results:

Frequency spectrum analysis has the advantage of being able to distinguish and characterize different types of sources operating during deformation because different deformation or

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damage processes usually correspond to different frequency spectrum [19], [20].

Tests of the martensite and ferrite samples illustrate the frequency range for ferrite sample deformation is between 150-175 kHz and for martensite fracture is in the range of 520-700 kHz.

The FFT method is an excellent method for the frequency spectrum analysis and is employed in the present research to analyze the AE signals detected in the specific cases of the ferrite deformation, the ferrite-martensite interfacial cracking and Martensite phase fracture.

DPS tensile tests show two AE peaks of energy (one peak during the yield and the other one close to UTS), and each peak has a distinct range of peak frequency. During the yield point, all of the samples show frequency range of 150-175 kHz which illustrates ferrite deformation; but, for the post yield, the frequency range of AE activities has differences among various samples.

Fig. 3 shows an instance for the AE signals frequency spectrum in the post yield area of 1_IA810 sample.

In these experiments, some Investigations by AE method on the Incidence of crack initiation in the Ferrite-Martensite interface and Martensite phase identification have been done. In the paper of Heiple and Carpenter [21] has been documented that plastic deformation of most structural alloys (such as steels) generates acoustic emission that reaches a maximum at or near the yield stress at the onset of macro-plastic deformation resulting from simultaneous motion of many dislocations. After macro-yielding starts, AE decreases continuously because of dislocation velocity decreases [22].

The observations further indicated that while most of the cracks occurred at the interfaces, a small portion of the cracks occurred in martensitic particles. This means that the main contribution to the post-yield AE peak stems from cracking at the interfaces. Martensite phase fracture only plays a secondary role. Apparently the cracking is related to the residual stress at the interfaces and to the toughness of the martensitic particles themselves [22].

In agree with Long et al. [22] and Lee et al. [20] two peaks of AE energy rate has been seen during tensile tests of all of DPS samples with.

AE activities peak frequency of the yield area was in the rage of 150-175 kHz. This range is for ferrite phase deformation and it illustrates that in the yield point, the dominant micro mechanism is only the ferrite phase deformation. Peak frequency of the post yield area (1_IA730, 1_IA760, 1_IA790, 2_IA730 and 2_IA760) was in the range of 110-120 kHz, and this peak frequency for the samples with high amount of VM (1_IA810, 2_IA790 and 2_IA810) was in two ranges (107-124 kHz and 545-660 kHz).

The almost same ranges of peak frequencies in the samples with low VM exhibits predominant mechanism of failure in these samples is ferrite-martensite decohesion; but, in the samples with high VM, post-yield AE activities show two ranges of frequencies. Presumably the rage of 107-124 kHz pertains to ferrite-martensite decohesion and the rage of 545-600 kHz pertains to martensite phase fracture. The remarkable point is the comparison between the ranges of frequencies according to VM. The chemical composition of the DPS samples is almost the same except the amount of carbon.

TABLE III
TENSILE TEST RESULTS OF MARTENSITE AND FERRITE SAMPLES

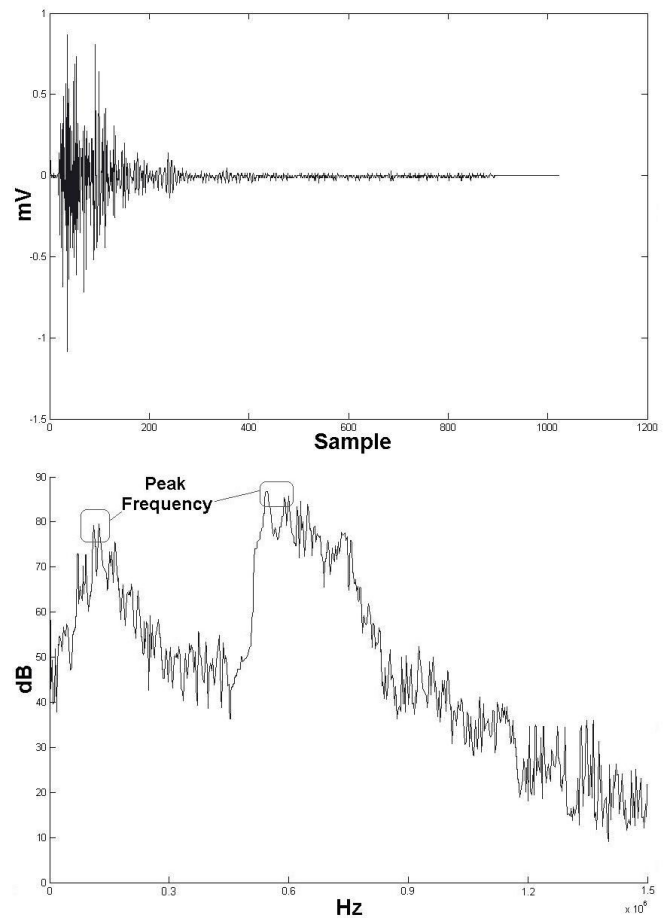| Samples	Intercritical Temperature	Brief Name	YS	UTS	ε_u (%)	ε_t (%)
1st DPS	730	1_IA730	412	642	12.8	16.1
	760	1_IA760	473	881	9.2	11.4
	780	1_IA790	569	1139	6.7	8.6
	810	1_IA810	681	1286	5.1	6.6
2nd DPS	730	2_IA730	347	591	16	22
	760	2_IA760	386	850	11.5	16.5
	780	2_IA790	472	1030	9	12
	810	2_IA810	526	1160	7	9.7
Ferrite(F)	---	---	286	587	25	29.5
Martensite	---	---	---	2100	---	1

Fig 3 AE waveform (upper diagram) and frequency spectrum (lower diagram) for the 1_IA810 sample.

Increasing the carbon content of martensite increases the hardness. In the 1_IA790 the carbon amount of martensite second phase is almost two times of the 2_IA790. So, the hardness of martensite second phase in the 1_IA790 sample is more than 2_IA790. More amount of martensite hardness causes the only failure mechanism of the 1_IA790 is ferrite-martensite decohesion; but, in the 2_IA790 sample, because of low amount of martensite hardness, martensite phase fracture is observed in addition to ferrite-martensite phases decohesion. Although the absolute values of the characteristic frequencies are different, due to different alloy systems [20].
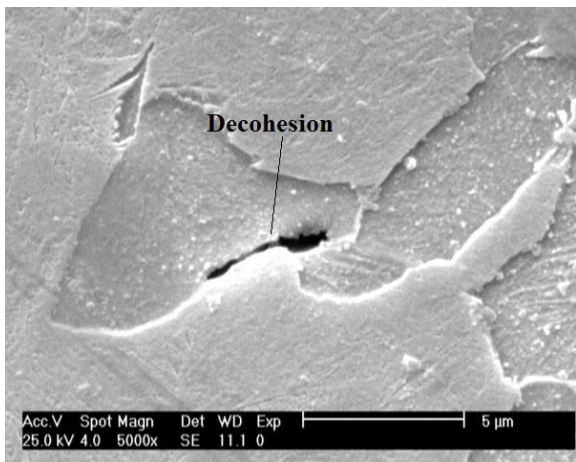
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Fig. 4 exhibits the SEM observations if the fracture areas of the samples which confirm the theories discussed in this paper.
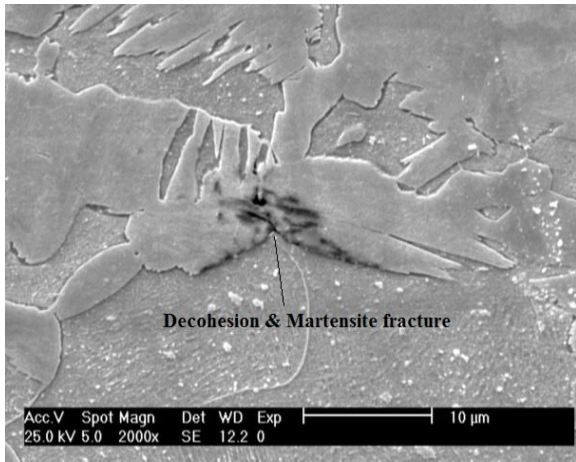
(a)
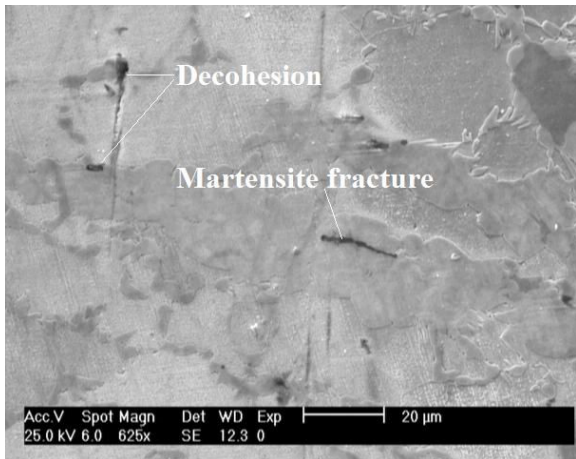
(b)

(c)

Fig. 4 SEM images from the necked region of (a) 2_IA810 (b) 2_IA790 and (c) 1_IA790 samples

IV. CONCLUSION

In this paper, the AE behavior during the tensile tests of some DPS with various VM and carbon content has been examined and frequency spectrum analysis has established for the post-processing of the AE waveforms recorded during these tests. In the samples with low VM, the dominant micro mechanism of fracture is ferrite/martensite phases decohesion; but in the sample with high VM, other than previous mechanism, martensite phase fracture has observed. These micro mechanisms of fracture are the source of AE signals and each of them are related to the distinguished frequency range that clarified by FFT based method. Due to the increasing amount of carbon increases the hardness of martensite phase, at the same VM, the sample with less amount of carbon, shows both mechanisms of failure (ferrite-martensite decohesion and martensite phase fracture). The above results indicate that the AE signal analysis by FFT based method can used as an effective tool for monitoring and characterizing of micro mechanisms of fracture even in DPS with a very complex micro-mechanism of deformation and failure.

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