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Research Paper

Investigation of the Effect of Ferrite Grain Size on Acoustic Emission Signals

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Abstract
In this study, the effect of ferrite grain size on mechanical properties and failure micro-mechanisms of materials was investigated by using acoustic emission (AE) non-destructive testing (NDT). AE signals were obtained from tensile tests of fully annealed ferrite samples and the effective AE parameters for each sample were analyzed from the AE waveforms. Due to annealing, the ferrite grain size was different in each sample, which affected the AE signals, and to analyze the AE signals, the Sentry Function (SF) and Fast Fourier Transform (FFT) were used and the results show that performing a full annealing operation to change the grain size at different temperatures almost did not significantly affect the frequency parameter, which has a range of about 175 kHz. In addition, the amplitude was about 30-40 dB, which indicates the deformation of the ferrite, and also the amount of AE energy released during the tensile test was lower than the strain energy.

Keywords
Ferrite Grain Size, Acoustic Emission, Sentry Function, Frequency Distribution

1. Introduction

The soft phase of steel is ferrite, which can be called carbon-free iron. This phase has a bcc structure that can hold a very small percentage of carbon [1-2]. The main mechanism of ferrite solidification is solid solution solidification, precipitation hardening, dislocation solidification, second phase solidification, and grain size.

Acoustic emission (AE) is a natural phenomenon that occurs in a wide range of materials, structures, and processes. The smallest inspection done by AE is the discovery of the movement of dislocations in metals under stress. In laboratory studies, AE is a powerful tool to investigate and study deformation and failure in materials. Since the AE response of different materials is related to their microstructure, the materials are widely different from each other in this regard [3].

Baram et al. [4] conducted their research on the plastic deformation of copper samples using AE. AE emitted from copper samples was analyzed using a kinematic model. The data are interpreted in terms of an acoustic emission parameter related to the behavior of copper while undergoing plastic deformation. the results show that the cumulative number of counts passes through a maximum value for the 70 μm grain size and so do the cumulative number of acoustic events and the maximum average count rate. The acoustic count rate dependence on grain size exhibits the following behavior:

the maximum count rate is attained at the yield point only for samples with intermediate grain size, showing significant acoustic activity in the plastic deformation range. The specimens with a grain size of 130 µm do not emit any acoustic signals during yielding; they emit only at plastic strains of 3% and higher. Baram et al. [5] also searched for the effect of grain size on the AE generated during the plastic deformation of aluminum (AL 1100). An additional set of samples with a grain size of 40 µm had been heated at 320 °C for 24 h. Count rate maxima were not obtained at the yield point, as was the case for all other sets of samples, but rather at plastic strains of 0.5 - 1.0%. A decrease in the yield stress is observed with increased grain size, in agreement with the Hall-Petch relationship. The average number of counts per event was found to be much higher for the specimens with the 40 µm grain size which had been heated at 320 °C for 24 h. In general, the acoustic emission activity was much more pronounced in the specimens annealed for a long time, by almost two orders of magnitude. As mentioned, the size of ferrite grains can affect the mechanical properties, which is very important in many structures, including dual-phase steels. This study aimed to investigate the behavior of the ferrite phase and the effect of the deformation of this phase independently on the AE results. Therefore, the effect of annealing and ferrite grain size was investigated on acoustic activities. The Fast Fourier Transform (FFT) and Sentry Function (SF) were used to analyzing the AE signals.

2. Experimental procedure

Table 1 shows the chemical composition for making ferrite samples. Ferrite samples used in this study were made with a width of 12 mm, a thickness of 2 mm, and a length of 35 mm according to ASTM E08 standards.

Table 1. Chemical composition of the metal used (weight percentage)

	C	Mn	Si	P	S	Cu	Fe
Ferrite	0.003	0.31	0.03	0.025	0.04	0.032	Bal

To reduce the noise and acoustic signals caused by the presence of impurities such as sulfur **[6]**, samples were used with small amounts of sulfur and phosphorus. To investigate the effect of ferrite grain size on acoustic signals, 1 ferrite sample was made without any heat treatment and the other 3 samples were fully annealed at 730, 820, and 920 ° C for one hour. Samples were prepared as a standard for tensile testing.

A tensile test was performed with the Instron8032 device with a capacity of 250KN at a speed of 0.05 mm / sec. The AE system used in this study is PAC-PCI-DSP4 with a capacity of four sensors. The system consists of several parts, all designed and built by PAC (Physical Acoustics Corporation). The sensor used is PAC Nano30 with a diameter of 5 mm and a height of 4 mm. In AEWin software, several parameters were set to eliminate noise such as high and low pass filters and threshold which was set to 30 dB.

3. Sentry Function

To more accurately analyze the ferrite phase behavior, the sentry function was used to gather and analyze mechanical and acoustic energy information in relation. The sentry function is the logarithm of the ratio of mechanical energy to acoustic energy.

$$f(x) = Ln\left(\frac{E_s(x)}{E_{ac}(x)}\right) \tag{1}$$

So that $f(x)$ is a sentry function and X is the test variable (usually displacement or strain), $E_s(x)$ is the strain energy, and is the energy of the acoustic signals. The function represents the continuous balance between the stored strain energy and the acoustic energy released due to damage. This function is usually discrete and is expressed by a combination of the four functions shown in Figure 1, which include (I) the incremental function $P_1(x)$, (II) the abrupt decrement function $P_2(x)$, (III) the constant function, and (IV) the subtraction function $P_4(x)$. These functions are defined on the AE amplitude (Ω_{AE}) in which acoustic signals are recorded and collected during transmission. The following mathematical relation can be expressed by dividing the acoustic field Ω_{AE} into the subsets defined in Figure 1:

$$\Omega_{AE} = \Omega_{AE.I} \cup \Omega_{AE.II} \cup \Omega_{AE.III} \cup \Omega_{AE.IV} \tag{2}$$

In this case, the function is written as follows:

$$f = \begin{cases} P_I(x) & \Leftrightarrow \; x \in \Omega_{AE.I} \\ P_{II}(x) & \Leftrightarrow \; x \in \Omega_{AE.II} \\ P_{III}(x) & \Leftrightarrow \; x \in \Omega_{AE.III} \\ P_{IV}(x) & \Leftrightarrow \; x \in \Omega_{AE.IV} \\ 0 & \quad\;\; x \in \Omega_{AE.I} \end{cases} \tag{3}$$

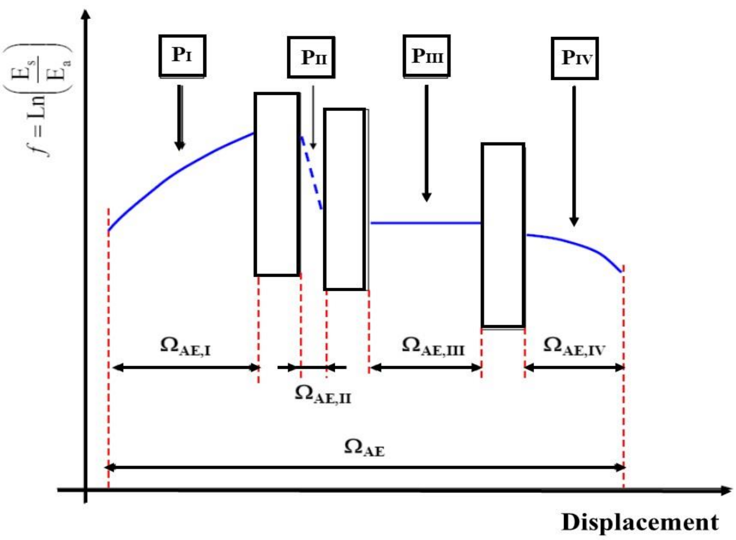

Figure 1. Main functions to express the function $f(x)$ [7]

When significant internal refraction occurs within the material, a significant amount of acoustic energy is released, producing high-energy acoustic signals, resulting in a sudden drop in the function. The $f(x)$ function can be used to advance damage within the material by using mechanical and acoustic information. On the other hand, because the above function contains the entire history of damage growth, it can be used as a criterion to determine the remaining life of the material. In this case, the integral of the function can be used to achieve this goal.

4. Results and discussion

After preparing the samples, the tensile test was performed, and acoustic signals were received and stored simultaneously. Figure 2 shows the various metallographic ferrite samples and the reference sample fully annealed at 1050 ° C for one hour. A noteworthy point in this figure is the microstructure of the fully annealed ferrite sample at 920 ° C. At this temperature, the growth is done with the preferential orientation of the grains towards the thickness of the sample, which is probably due to the loading history of the material. Macro separation (banding) in the fully annealed reference sample (Figure 2 (a)) is due to the type of freezing process during production.

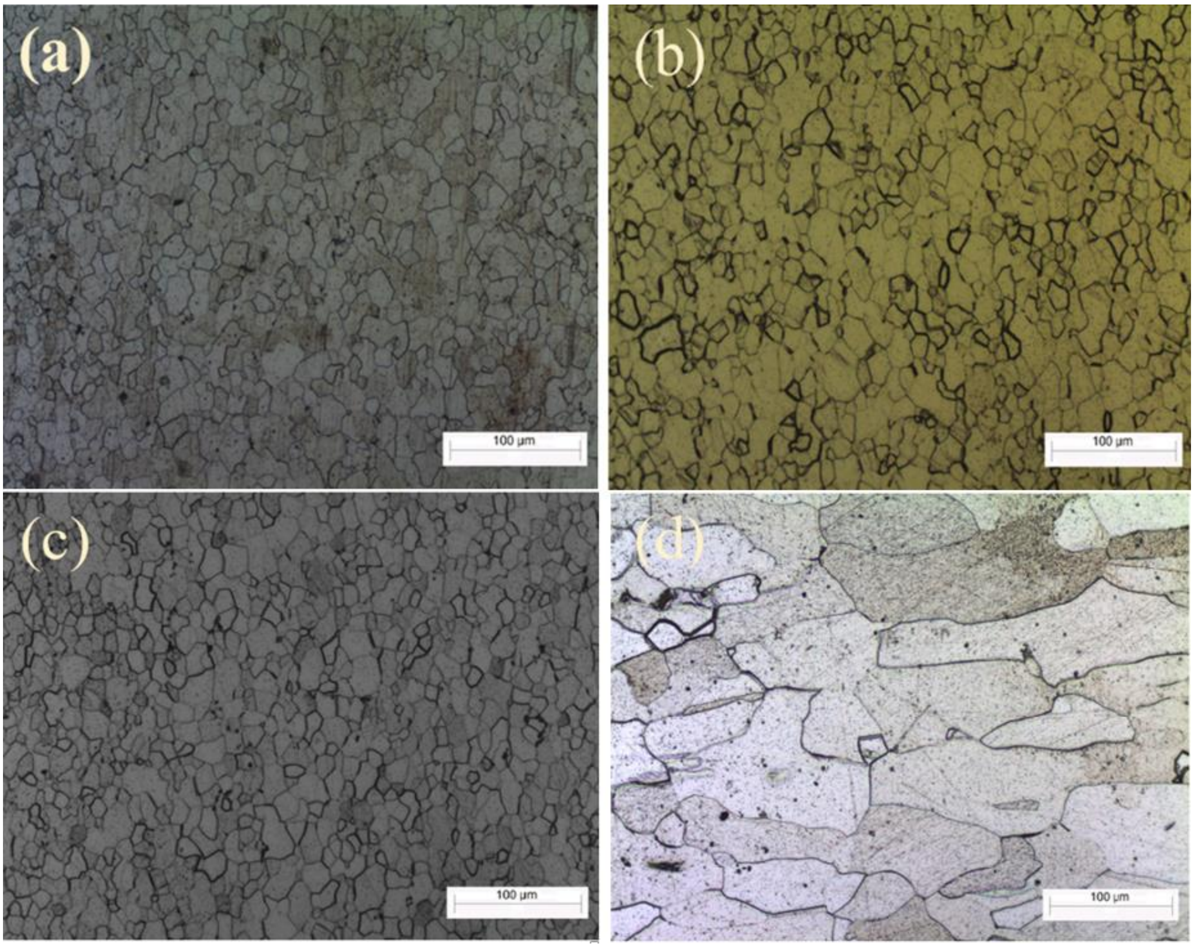

Figure 2. Optical metallographic images of typical low carbon ferritic steels: F (a), F730 (b), F820 (c), F920 (d)

The purpose of the tests performed on ferrite samples is to investigate the behavior of the ferrite phase and the effect of the deformation of this phase independently on the AE results. Figure 3 shows the graph of the results of one of the samples (F820).

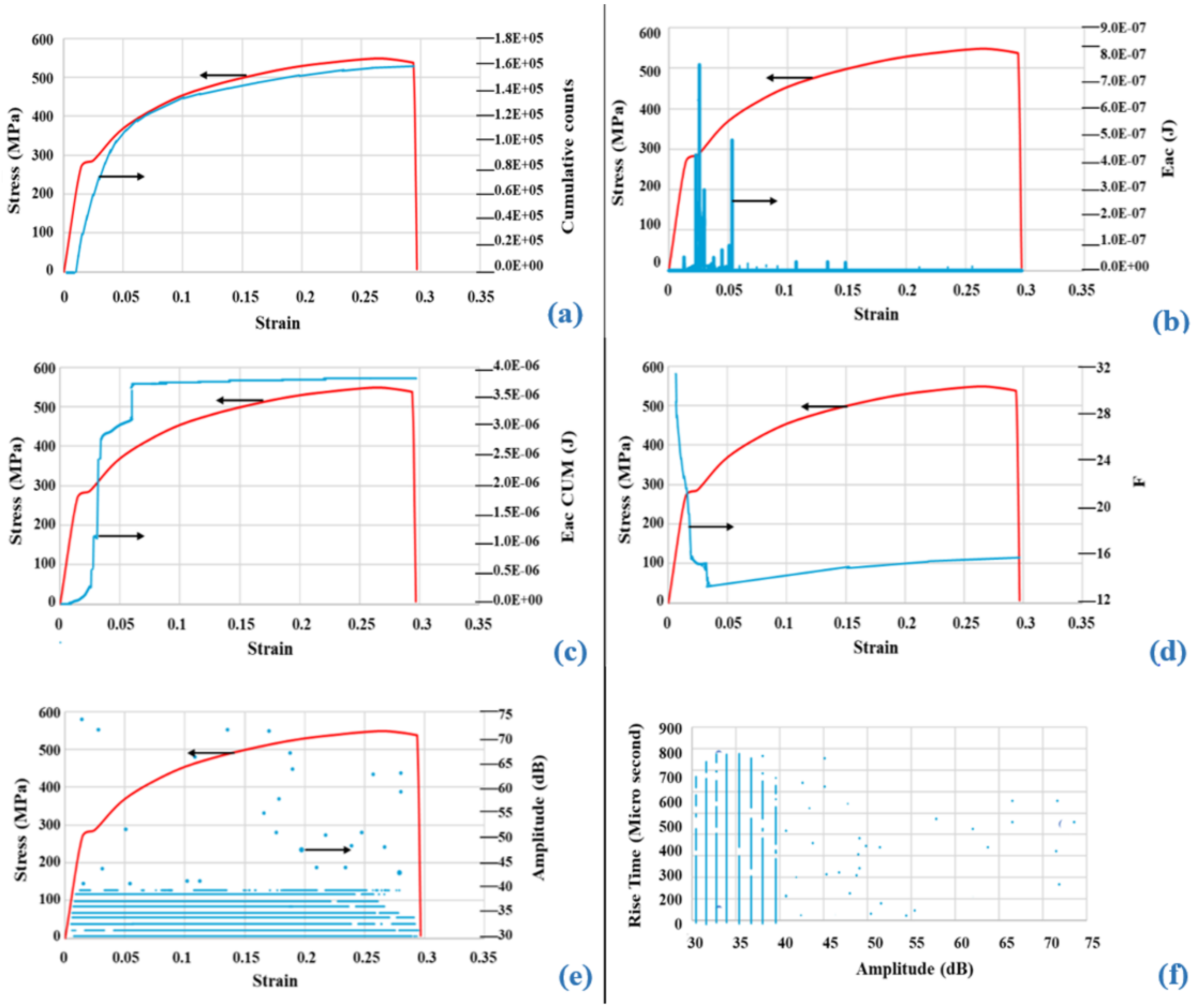

Figure 3. Stress-strain diagram in annealed ferrite sample at 820 (F820) and Cumulative Count (a), Acoustic Energy (b), Cumulative Acoustic Energy (c), Sentry Function (d), Amplitude (e), and Rise Time with Amplitude (f)

The results of these tests are shown in Table 2.

Table 2. Mechanical properties and acoustic results of ferrite with different grain sizes

Full Annealing temperature °C (Samples codes)	Ferrite grain size (μm)	YS	UTS	ε_u (%)	ε_t (%)	n	Strain Interval (%)	Max Eac (J)	Max Risetime (μSec)	Average Amp. (dB)	Average Risetime (μSec)	Eac Cum (J)	Count Cum
Ferrite (F)	9.6	286	587	25	29.5	0.26	1.4-25	2.5×10^{-9}	680	32.19	26.64	1.18×10^{-8}	4.7×10^{-4}
730 (F730)	10.2	282	461	20	31.3	0.23/ 0.11	2.2-10.2/ 10.2-20	1.8×10^{-7}	707	34.61	55.77	1.5×10^{-6}	1.3×10^{-5}
820 (F820)	11.2	268	544	24.6	29.8	0.25	1.4-24.6	8×10^{-7}	720	35.39	70.64	3.9×10^{-6}	1.6×10^{5}
920 (F920)	53.1	160	322	19.5	23	0.27	1-19.5	9×10^{-7}	839	36.85	85.25	4.9×10^{-6}	2×10^{5}

Figure 3 and Table 2 show that the mechanical behavior is almost consistent with the Hall-Petch equations. The amount of n (work hardening exponent) is approximately equal to the amount of strain at the beginning of the non-uniform deformation or the maximum force applied during the tensile test

[8-9]. As can be seen, the acoustic parameters increase dramatically with increasing full annealing temperature (increasing grain size). This increase in acoustic parameters is much more noticeable compared to samples without heat treatment. This issue has been reported in the works of other researchers [10-12]. In fact, in the yielding area, many dislocations start to move, creating a lot of AE.

Impurity atoms are more likely to move toward the grain boundaries, thus increasing the distance between these impurity atoms. Increasing this free distance between atoms will accelerate the movement of the dislocations and, of course, more AE will be emitted before the dislocations stop [9-12]. As a result, increasing the annealing temperature creates more AE in yield. These observations are in agreement with the results of previous researchers [13-14].

Another point is the sentry function mode. In all samples, this function is ascending after yielding, indicating that the ratio of AE energy released during the tensile test is less than the strain energy. The process of work hardening exponent can justify this issue. Figure 4 shows the sentry function in all ferrite samples together in a diagram. Comparing the sentry function mode in these samples, it is clear that the slope of the sentry function after yielding is almost equal in all samples, but as can be seen from the behavior of the samples, performing a complete full annealing operation reduces the amount of the sentry function. By comparing the model of the sentry function, just after yielding the ferrite sample without heat treatment with other samples, a greater slope of the function is evident in this sample. This issue is because of more work hardening exponent in the incomplete annealed sample. This slope decreases with increasing full annealing temperature, especially at 920 ° C.

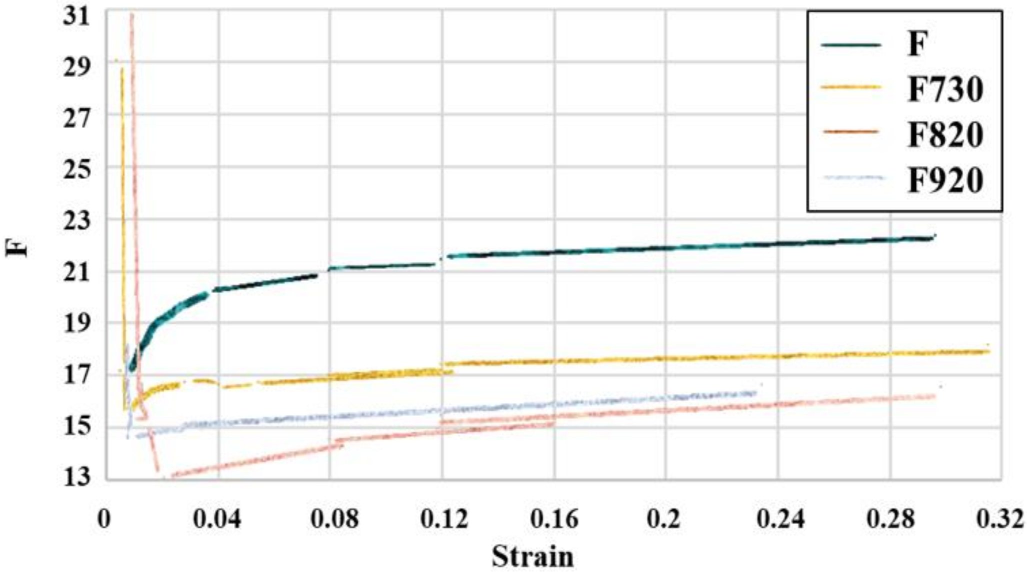

Figure 4: Sentry Function in ferrite samples

By analyzing the amplitude distribution diagrams, it is observed that in all samples, the amplitude is approximately between 30-40 dB and this amplitude is related to the ferrite phase deformation. Also, the maximum rise time in these samples is about 700-800 microseconds. In addition, by examining the peak AE frequency generated during the tensile test (Figure 5), the frequency in the range of 175 kHz has more density, which is in agreement with the results of previous researchers [13-14]. It is noteworthy that performing full annealing operations and different temperatures of this operation did not significantly affect this frequency range.

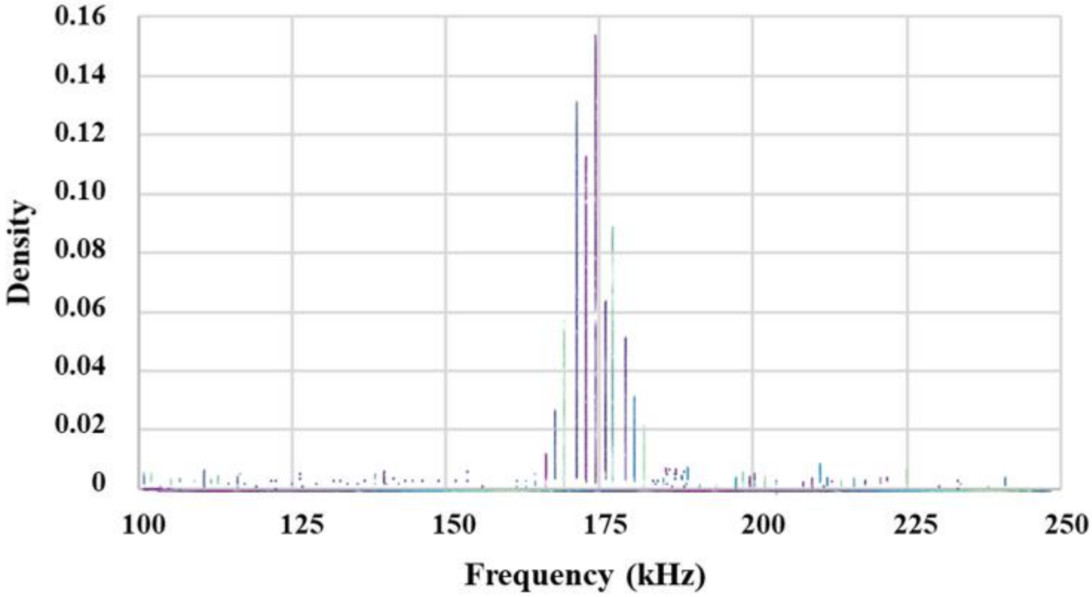

Figure 5. Dominant frequency distribution in the tensile test of ferrite specimens

5. Conclusion

In this study, the behavior of the ferrite phase and the effect of deformation of this phase were independently investigated on AE results. To investigate the effect of various annealing temperatures and ferrite grain size on acoustic activity, ferrite samples were fully annealed for 1 hour at 730, 820, and 920 ° C. A sample was also subjected to tensile testing without any heat treatment.

The results show that the mechanical behavior is almost consistent with the Hall-Petch equation. By increasing the grain size, the acoustic parameters were increased and this increase in acoustic parameters is much more noticeable compared to samples without heat treatment and fully annealed samples. In fact, in the yielding area, a large number of dislocations begin to move, creating a lot of AE.

In all samples, the amplitude is approximately between 30-40 dB, which is related to the deformation of the ferrite, and the maximum rise time in these samples is about 700-800 microseconds. In all specimens, the Sentry Function is ascending after yielding, indicating that the ratio of the AE energy released during the traction process is less than the strain energy and the results showed that performing a full annealing operation reduces the amount of the sentry function. The ferrite phase deformation has a frequency range of about 175 kHz that was obtained by the FFT method and it is noteworthy that performing a full annealing operation and different temperatures of this operation did not have a significant effect on this frequency range.

6. References

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