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Fatigue and Vibration Parameters Improvement of Steel DIN 41Cr4 by Ultrasonic Shock Peening Treatment

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Abstract

The effects of the ultrasonic peening treatment (UPT) on the rotating bending fatigue behavior and the behavior of the vibrations of alloy steel DIN 41Cr4 were studied. Hardness test, Tensile test, Constant amplitude fatigue tests, and the vibrations measurements have been carried out on the specimens. Also, the fracture surface was examined and analyzed by a Scanning Electron Microscope (SEM). The results of the investigations, e.g. stress to number of cycles to failure (S-N) curves, fatigue strength improvement factor was 7%. The decreasing percentage of maximum Fast Fourier Transform (FFT) acceleration of the ultrasonic peened condition compared to the untreated conditions was 45%.

Keywords: Ultrasonic Peening, Fatigue Life and Fatigue Limit, Alloy Steel DIN 41Cr4.

تحسين متغيرات الكلال, وسلوك الاهتزاز باستخدام تقنية السفع بالموجات فوق الصوتية على سطح الفولاذDIN41Cr4 السبائكي

زينة شاكر محمود ، جمعة سلمان جياد

الخلاصة:

تم دراسة تأثير السفع بالموجات فوق الصوتية على سلوك الكلال الانحنائي الدوار وسلوك الاهتزازات للفولاذ السبائكي DIN 41Cr4. تم إجراء اختبار الصلادة, اختبار الشد, اختبار الكلال ذو السعة الثابتة, و قراءات الاهتزاز على العينات, و فحص سطح الكسر وتحليله بواسطة مجهر مسطح الكتروني (SEM) للفولاذ السبائكي DIN 41Cr4 قبل وبعد السفع بالموجات فوق الصوتية. نتائج الفحص كمنحنيات الإجهاد الى عدد الدورات للوصول الى الفشل(منحنيات S-N)، معامل تحسين مقاومة الكلال حوالي 7%، وتمت مقارنة النسبة المئوية لتناقص تعجيل تحويل فورييه السريع (FFT) قبل وبعد السفع بالموجات فوق الصوتية ويقدر بحوالي 45%.

1. Introduction

The alloy steel DIN 41Cr4 is characterized by their high toughness, good corrosion resistance, and high fatigue strength. Therefore, it's generally used for various components. Most of the structural components are subject to periodic loading during service and are subject to the failure to start the cracks of fatigue from the surface and propagate to the critical length. Several techniques, such as ultrasonic peening treatment (UPT), have been used to modify the surface to improve the fatigue resistance of structural components. Such treatments provide compressive residual stress and also the refinement of the microstructure in the surface area of the components. In comparison with the usual process of shock peening to induce residual compressive stress in the surface area of the component, the ultrasonic peening process induces compressive residual stress at greater depth and also improves the microstructure of the surface area up to the nanoscale [1].

There are three stages of failure. The first is the crack nucleus in small amounts of non-homogenous plastic deformation at the microscopic level. The second is the slow growth of these cracks by cyclic stress. Eventually, an unexpected break occurs when the cracks reach a critical size [2].

Ultrasonic peening treatment (UPT), or ultrasonic impact treatment (UIT), is a promising technique that causes severe plastic deformation and allows rapid structural adjustment and surface layer composition [2]. There are many industrial applications of this technique such as aerospace, ships, marine, automotive, railway, and bridge structures, in which

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materials with very high strength, fatigue life, corrosion and wear resistance are demanded [3].

Vibrations are oscillations of a mechanical or structural system about an equilibrium position. Vibrations begin when the Inertia component is excluded from the equilibrium position because of the energy presented to the system from an external source. Vibrations happen in several mechanical and structural systems. vibration can lead to catastrophic states if the vibrations were uncontrolled. vibrations of machine component can cause improper machining of components. Pumps, compressors, turbomachinery, and other industrial machines with excessive vibrations can stimulate vibrations in the surrounding structure, resulting in inefficient operation of the machines while the resulting noise can cause human discomfort [4]. when the vibration is objectionable, the designer's objective is to control the vibration and to enhance the vibration when it' useful. Although vibrations, in general, are undesirable. undesirable vibrations in a machine lead to loosening of parts, it's malfunctioning or its eventual failure [5].

Arkawa et. al.[6] studied the effect of the USP treatment on the fatigue crack initiation behavior by using Haigh's diagram, and it was obvious that the improvement of the fatigue limit was due to increased resistance to starting fatigue crack caused by compressive residual stress and high hardness generated on the surface by USP treatment. Feng et al.[7] Concluded that longer treatment times led to a significant reduction in fatigue life to levels lower than those of untreated samples. Therefore, extending the UPT times can lead to increased fold defects, so sample failure can occur. Hussain J. Al-Alkawi et al.[8] proved that the percentage increase in mechanical properties reduces gradually as the number of peening line increase. B.N. Mordyuk et al.[9] proved that the enhancement of fatigue characteristics were concluded to be linked with the subsurface crack nucleation accomplished by the following factors: (1) minimized surface roughness and improved integrity of the modified layer; (2) compressive residual stresses facilitated cracks stoppage and closure; and (3) Both the dislocation cell structure and chromium alloying result in substantial superficial hardening, which impedes or postpones plastic deformation, also contributing to the retardation of the crack nucleation. Yanjun Fan et al.[10] Concluded that the formulation of nanocrystal layer on the surface of parts after the use of UPT could prevent the crack initiation and improve fatigue performance, wear resistance and corrosion resistance.

The objective of the present investigation is to study the effect of the hardness, mechanical properties, the improvement of fatigue lifetime, and the vibrations parameters due to ultrasonic peening technique.

2. Experimental Procedures

2.1 Material Selection

A heat-treated steel (alloyed) (DIN 41Cr4) was selected, the material was received as a rod of 16 mm diameter. It's known for its high toughness, good corrosion resistance, and high fatigue strength. It has a wide application for many general engineering applications with low and moderately stressed parts for vehicles, engines and machines where hard, and wear resisting surface is needed.

The chemical compositions were obtained using XRF device of the metal in weight percentage compared by the German standard DIN EN 10083-3[11], which are arranged in the Table 1.

Table (1): Composition of alloy steel (DIN 41Cr4) in Wt.%

El.%	C	Si	Mn	P	S	Cr	Fe
St.	0.37	0.178	0.738	0.0102	0.0217	1.04	Bal.
Exp.	0.38-0.45	Max. 0.4	0.6-0.9	Max. 0.025	Max. 0.035	0.9-1.2	Bal.

2.2 Hardness Test

The Rockwell hardness test was performed at (the State Company for Inspection & Engineering Rehabilitation (S.I.E.R), laboratories and engineering test department, Ministry of Industry and Mineral, Baghdad, Iraq) according to ISO 6580. This test was performed by using TRUE-BLUE II hardness tester as shown in Fig. 1.

Figure (1): Rockwell hardness tester.

2.3 Tensile Test ASTM (E8/E8M-011)

Tensile test was performed by using tensile test machine type UNITED, as shown in Fig. 2, to obtain the mechanical properties like yield and ultimate strength, % elongation, and Young's modulus. The specimens were manufactured according to the American Society for Testing and Materials specifications ASTM (E8/E8M-011) as shown in Fig.3.

Figure (2): Tensile test machine UNITED.

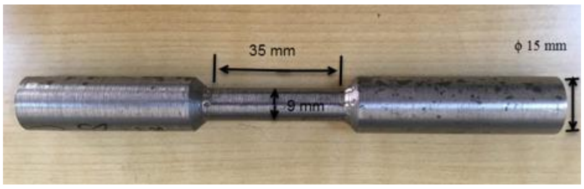


Figure (3): Tensile test specimen.

2.4 Fatigue Test

All fatigue tests at constant amplitude loading were performed by using a rotating bending fatigue machine of type (HI-TECH Limited), which is shown in Fig. 4. The fatigue specimen had a round cross-section while it was subjected to an applied load, which created a constant bending moment.

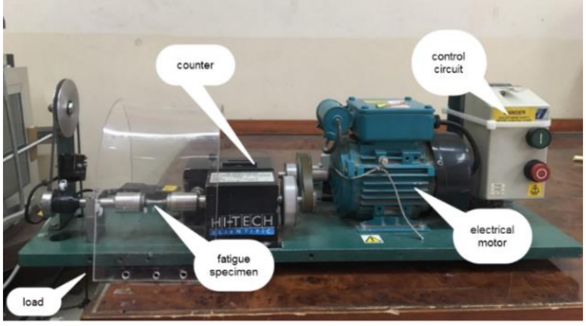


Figure (4): Fatigue testing machine.

- **Fatigue Test Specimen**

The specimens were manufactured by using a programmable CNC lathe machine by writing a suitable program (Mastercam software) from the profile of specimen on a surface of the metallic rod to attain an accurate profile. Then, Shape and dimensions of fatigue sample are manufactured in accordance with the standard specification of (DIN 50113) as illustrated in Fig.5.

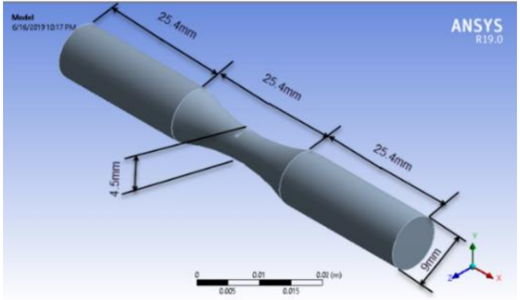


Figure (5): Fatigue test specimen.

2.5 Vibration Test

Because of the importance of the vibration, several mechanisms have been improved to measure the vibration and through employing the computer software, the analyzing of the signals can be performed simply. In this work the device of vibration measurement is:

- **Accelerometer**

A seismic device called accelerometer used to measure acceleration. Most vibration measurements today are performed by accelerometers due to their small size and high sensitivity. The electrical output of the accelerometer can be integrated to obtain the velocity and displacement.

The accelerometer type (ERBESSD Instruments) one end is the Neodymium Magnetic base (connected with the structure to be measured) and the other end a USB outlet joined to a computer to analyze the output signal by EI-CLAC software program as explained in Fig. 6.

Figure (6): ERBESSD INSTRUMENTS accelerometer.

2.6 Vibration measurement procedure

The behavior of maximum acceleration and the maximum FFT acceleration were examined of the fatigue specimen when it was tested on the fatigue test machine under the same condition that was used in the fatigue test by using the accelerometer. The aim of the test is to study the effect of the ultrasonic peening treatment on the maximum acceleration and the maximum FFT acceleration. Where the cable is put on the bearing of the shaft in the fatigue test machine as illustrated in Fig. 7.

The process of the vibration measurement was driven by the computer by using EI-CALC software program. EI-CLAC is an application of real-time vibration analysis with a complete range of spectral analysis tools and comprehensive graphical solutions. The spectral analysis tools in EI- CLAC based on the FFT algorithm. To be easy to measure the required frequencies and root mean square (RMS), the signal from its time-domain description transforming to the frequency-domain description.

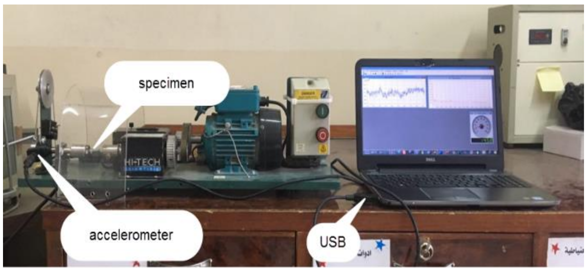


Figure (7): vibration measurement.

2.7 Ultrasonic Peening Treatment

The ultrasonic peening device offers ultrasound energy in the metal through surface impulse contact. This energy is introduced into the metal by converting the resonant, harmonic oscillation of an acoustically tuned body to mechanical pulses on the surface. The ultrasonic peening treatment was performed with one line as the experimental exhibits that the increase percentage in mechanical properties reduce gradually as the number of peening line increase [8]. The main technical parameters of UP device are given below:

Brand Name: HC
Mode Number: HC-S-1
Frequency: 20KHZ, Voltage: 220v, power: 500w
Usage: metal welding, impact treatment tool, relieving of internal stress
Type: portable
Length of gun: 450mm
Weight of gun: 4 kg
System weight: 15kg
Shape of gun: The impact of the needle or impact rod
*The size of generator: 195*270*430 mm*
The weight of generator: 8 Kg
Working mode: impact the surface
Applicable materials: Aluminum alloy, low carbon steel, high strength steel, etc.

The ultrasonic impact treatment is performed by using the ultrasonic device in a fixed position and in various directions, as presented in fig.8. Fig. 9 shows the fatigue specimens before and after the use of ultrasonic peening device.

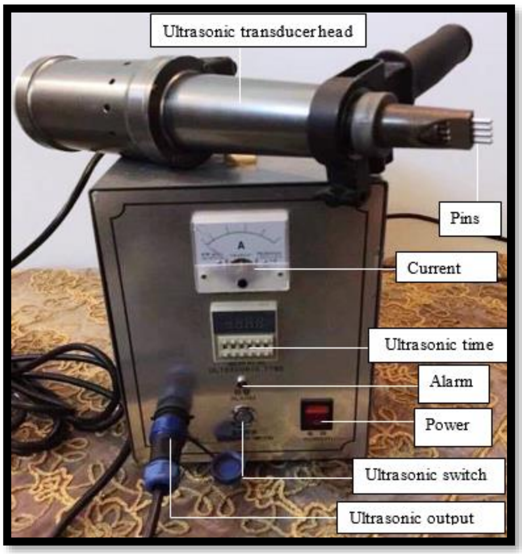


Figure (8): (HC-S-1) Ultrasonic Peening Device.

Figure (9): the fatigue specimens before and after ultrasonic peening treatment.

2.8 Microscopic Examination of The Samples

The broken samples after the fatigue test were examined at (Production and Metallurgical Engineering Department, University of Technology, Baghdad, Iraq) by using scanning electron microscope TESCAN, VEGA 3 LMU with OXFORD EDX detector (INCA XMAW20) device as shown in Fig. 10 to determine the beginning of the crack and its propagation, size, form, and microstructure.

Figure (10): Scanning Electron Device (SEM).

3. Results and Discussions

3.1 Hardness Test Results

Hardness values were measured for all cases in the Rockwell hardness test at (the State Company for Inspection & Engineering Rehabilitation (S.I.E.R), laboratories and engineering test department, Ministry of Industry and Mineral, Baghdad, Iraq) and show the equivalent results in Brinell hardness. The results represented in Table 2.

Table (2): Hardness results in different conditions.

Groups	Specimens	Hardness value Rockwell (HRB)	Hardness value Brinell (HB)
A	Untreated alloy steel	91	187
B	Ultrasonic peened steel	91.5	190

From Table 2, it can be observed that the hardness of steel increases when ultrasonic peened as compared with the value of hardness for un treated steel (187) HB. This is caused by compressive residual stresses from the peening treatment.

3.2 Tensile Test Results

The tensile tests were performed for six specimens at (the State Company for Inspection & Engineering Rehabilitation (S.I.E.R), laboratories and engineering test department, Ministry of Industry and Mineral, Baghdad, Iraq) to explain the influence of ultrasonic peening treatment on the mechanical properties. The results are illustrated in Table 3. and show that the improvement percentage in yield strength about 9.65% and the improvement percentage in ultimate stress about 2.7%.

Table (3): Tensile test results for samples.

Samples	Mechanical Properties		Elongation%	Change in σ_y %	Change in σ_u %
	Yield strength (σ_y) (Mpa)	Ultimate stress (σ_u) (Mpa)			
As received	435	662	30	-----	-----
UPT	477	680	30	9.65	2.7

3.3 Fatigue Test Results

Twenty-four samples were prepared to accomplished the fatigue test under constant amplitude fatigue stress control rotating bending at a stress ratio R=-1 to estimate the S-N curves.

Each series of constant amplitude fatigue tests were carried out for 12 specimens used four stress levels. The results are illustrated in Table 4 and fig. 11.

Basquin law may be utilized to show the relationship between the fatigue strength and fatigue life of the material. This law can be expressed with the following equation [12]

$$\sigma_f = A\, N_f^{\alpha} \qquad \text{....(1)}$$

Where (σ_f) is the cyclic stress amplitude at failure, N_f is number of cycles to failure and (A), (α) are the fitting parameters. The above data are plotted according to Basquin equation in Fig. 11, which illustrates the behavior of fatigue life.

Table (4): Constant amplitude fatigue test results.

Applied stress (MPa)	**N_f Cycles**	**N_f av.**
Raw material fatigue condition		
530	12402,11900,12800	12368
463	54300, 55860,54600	54920
397	310255,326200,297700	311385
331	2570000,2940000,1980000	2496667
Ultrasonic peening fatigue condition		
544	16990,18230,15400	16873
476	72300,69860,68340	70166
408	425000,417600,398200	413600
340	3978613,4185000,3729000	3964204

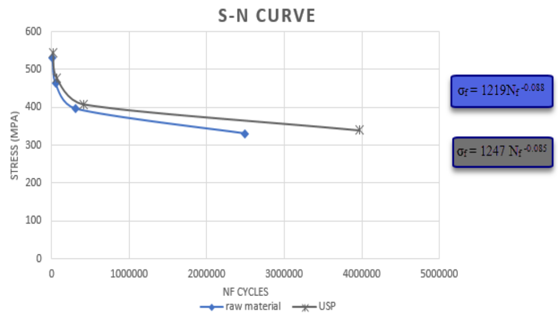


Figure (11): The comparative S-N curve of the fatigue Test with and without ultrasonic peening

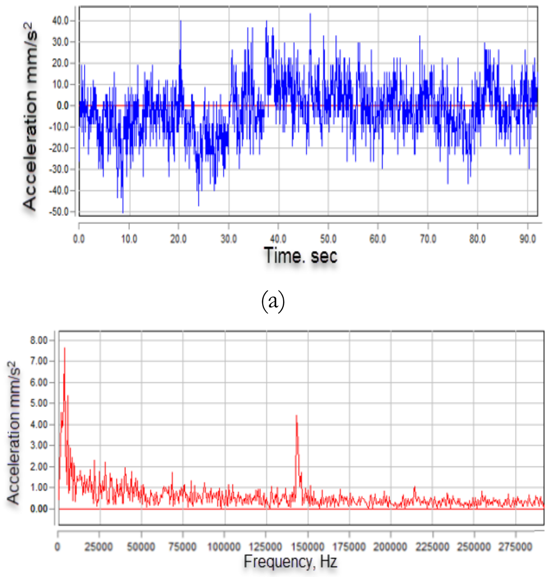
Table (5): Fatigue Strength at 10^6 Cycles and Change Factor.

Condition	**Basquin equation**	**fatigue strength (MPa) at 10^6 cycles**	**Change factor %**
As received	$\sigma_f = 1219 N_f^{-0.088}$	356 Mpa	___
UPT	$\sigma_f = 1247\, N_f^{-0.089}$	381 Mpa	**7%**

Table 5. presents the comparison between the fatigue strengths of ultrasonic peened and as-received material. The improvement in fatigue strength happened due to the beneficial effect of compressive residual stresses represented by metal peening treatments. In ultrasonic peening treatment (UPT), the maximum average residual stress showing (7%) improvement of the fatigue strength.

3.4 Vibrations Results

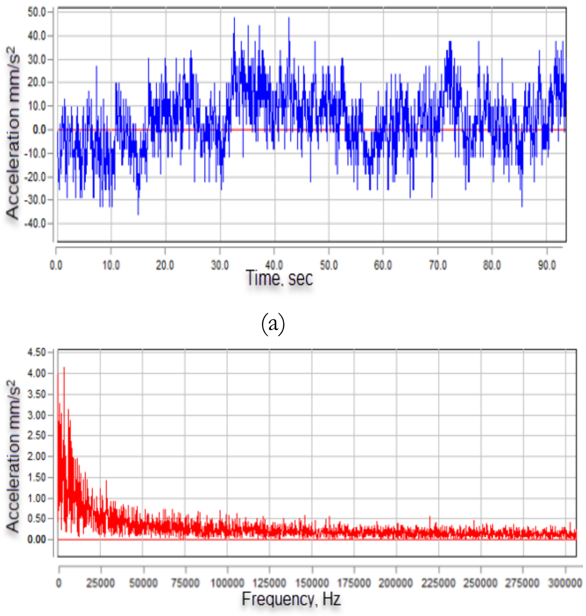
Table 6. illustrates the vibration behavior of the samples before and after ultrasonic peening process. Fig. 12 and Fig. 13 explained the behavior of acceleration associating to time per second, where the decreasing in the maximum FFT acceleration occurred after peening treatments.



(a)

(b)

Figure (12): a. Acceleration of the sample as received before peening treatment.
b. FFT signal of the sample as received before peening treatment.



(a)

(b)

Figure (13): a. Acceleration of the sample after ultrasonic peening.
b. FFT signal of the sample after ultrasonic peening.

Table (6): The vibration result for the samples.

Condition	Max. Acce. (mm/s²)	Min Acce. (mm/s²)	Max. FFT Acce. (mm/s²)	RMS Acce.	Decreasing % of Max FFT
As received	+43	-50	7.6	19	___
UPT	+37	-46	4.14	16	45.5%

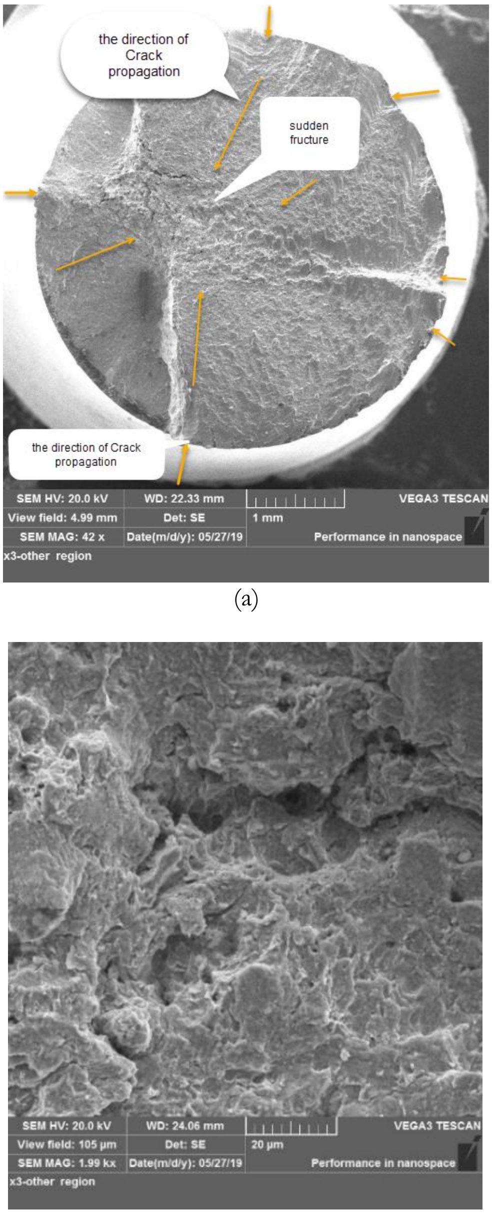
3.5 The Microstructure of the Fractured Fatigue Specimens

The microscopic appearance of fatigue fracture surfaces is strongly affected by the prevailing stress intensity condition at the moving crack tip. These fractures occurred to the specimens after sufficient cycles of the axial load and could be recognized by using scanning electron microscope.

Fig. 14 (a) represents the final fraction of the as-received samples with applied load (397Mpa). The figure explained the crack beginning at the surface which commonly happens by micro surface defects, the cracks propagates towards inside, which are marked by the arrow, propagated through the cross section until the occurrence of the sudden fracture. Fig. 14 (b) explained the grain boundary in the fracture region which is formed as a thick layer due to the crush occurred by the crack propagation.

Fig. 15 (a) showed the fracture region of ultrasonic peened specimen with applied load (403Mpa). The figure showed the crack beginning from the surface resulted from surface defects. The sudden fracture happened due to the crack propagation marked by the arrow.

Fig. 15 (b) defined the microstructure of the cracked ultrasonic peened sample and explained the ferrite and pearlite layers. Each cycle, when it's over, destroyed a grain boundary. When the crack propagates the applied stress increased and therefore the crack propagation increased so each cycle destroys numerous grain boundary and the failure become faster until the final fraction is occurring.



(a)

(b)

Figure (14): a. Micrograph of the fracture region of the as-receive sample.
b. Micrograph of the microstructure of the as-received sample.

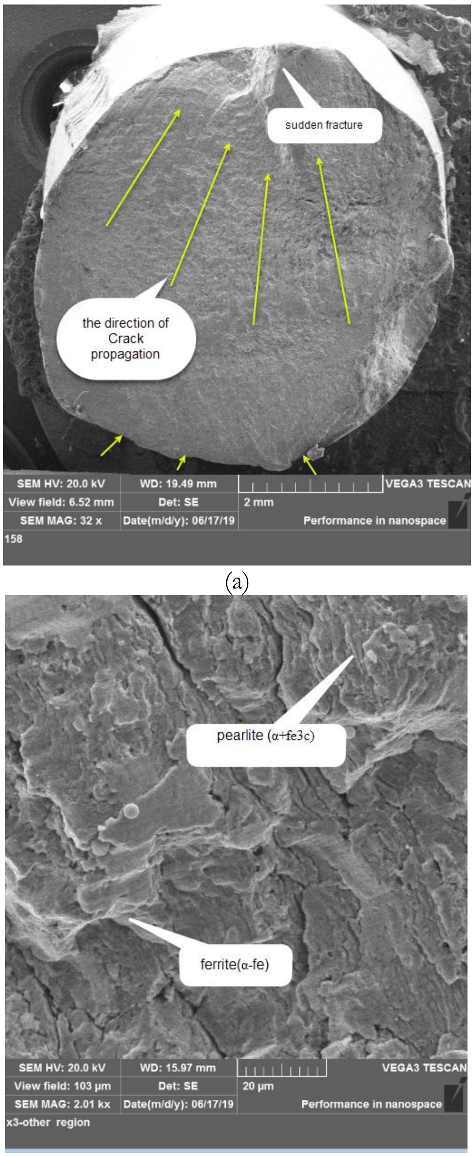


Figure (15): a. Micrograph of the fracture region of the ultrasonic-peened sample.
b. Micrograph of the microstructure of the ultrasonic - peened sample.

4. Conclusions

The main conclusions obtained from the present work can be summarized as follows:

1. Results showed an increase in hardness. This is caused by compressive residual stresses from the peening treatment.
2. The fatigue strength improved by ultrasonic peening in comparison with the as-received material by introducing compressive residual stresses into surface layers of the alloy, decrease in stress concentration and the enhancement of the mechanical properties of the surface layer of the material.
3. The vibration of maximum FFT acceleration for the specimen decreased after ultrasonic peening treatment.
4. The plastic deformations which exists at the surface and treated by ultrasonic peening resist the fracture, and eventually increase the fatigue life.

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