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ORIGINAL ARTICLE

Steel 7225 surface ultrafine structure and improvement of its mechanical properties using surface nanocrystallization technology by ultrasonic impact

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Abstract In ultrasonic nanocrystalline surface modification (UNSM) technology, ultrasonic energy is used as a method to apply severe plastic deformations on metal surfaces. Therefore, the surface structure of the metal, which is micro in its normal state, is transformed into a nanostructure up to a certain depth. This method results in mechanical improvements such as hardness, fatigue, yield stress, and surface smoothness. In this research, by designing and manufacturing a vibrating tool and a required fixture for the operation, the effect of UNSM process on steel 7225 was studied. SEM analysis showed that the nanostructure was created at the surface of steel 7225. It showed that the fatigue life and yield stress of processed steel 7225 workpiece increased greatly when compared to those in its similar crude specimen, revealing the efficacy of these operations in increasing fatigue life. Ultimately, the relationship between the number of passes for the application of a number of equal impacts and surface smoothness, as well as the effect of the number of impacts on the hardness of steel at different depths were studied.

Keywords Grain refinement · Fatigue · Nanostructured materials · Ultrasonic · Hardness · Roughness

1 Introduction

The short life of pieces is among the different problems in using metals faced by industries today. In this regard, different operations including surface and heat treatment have been employed to increase the life time of pieces [1–3]. Today, these operations are not cost-effective since there are problems such as work force conditions and expensive spaces for furnaces and materials used [4–6]. Such problems revealed the need for a review in the principle of production of crude materials for metals from melting stage and alloying to cold and hot working, in order to produce optimal products for the market [7]. Nanostructuralism of metals is one of the operations that increases the life of industrially produced metals. On the other hand, nanostructuralism does not scientifically prevent cracks, and its being time-consuming and the difficulty in the operation are its disadvantages. Its high cost compared to the saved cost resulting from nanostructuralism has kept these innovations at university and laboratory levels, preventing them from being industrially produced [8]. Combining nanostructuralism with surface operations led to a method called surface nanostructuralism, one of whose application methods is the severe plastic deformation at the surface [9]. After the Second World War and with the discovery of ultrasonic transducers, this choice was considered very suitable for plastic deformation at the surface and established the ultrasonic nanocrystalline surface modification (UNSM) strategic technology or production of nanostructure at the surface of a metal by using ultrasonic waves. In addition to life increase through grain refining by this technology, other mechanical properties such as surface hardness, surface smoothness, and yield stress are also improved [10].

This research was devoted to the study of UNSM. At first, the vibrating tool was designed, and it was later installed on the fixture. In this study, the aforementioned operation was implemented on steel 7225, and the effect of the number of passes on the application of equal number of impacts on surface smoothness was studied. Furthermore, observation of surface fine graining up to nano-scale by SEM, fatigue and

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tension tests were also carried out. Moreover, the effect of the number of impacts on surface smoothness and hardness, and hardness measurement for different depths for the mentioned metal were also studied.

2 UNSM technology

In this method, an ultrasonic horn designed by software is connected to an ultrasound transducer. The whole set connected to the designed fixture is installed on a lathe support. The UNSM technique employs the ultrasonic vibrating energy, inflicting several thousand impacts per second on the area unit of the matter. These impacts are influenced by a constant pressure generated with the pneumatic unit and can be interpreted as the micro cold forging, which leads to severe plastic deformation at the surface layer creating a nanocrystalline surface.

In this technology, the static load, which is the agent of constant pressure on ultrasonic equipment, and a dynamic load equal to $P_{dy}=P\sin 2\pi ft$ at the surface of the workpiece are applied, and the total load of impact (F) in UNSM represented as:

$$F = P_{st} + P_{dy} = P_{st} + P\sin 2\pi f t \quad (1)$$

Where P_{st} is the static load applied to the tool and P is the amplitude of the dynamic load. The dynamic energy is usually 2.5 to 5 times, as much as that of the static energy.

Figure 1 depicts the UNSM configuration equipment consisting of the following components: an ultrasonic generator generating electric ultrasonic frequency, an air compressor keeping the ultrasonic unit at a constant pressure (the factor producing static load), a piezoelectric transducer, a booster reinforcing the vibrations, a horn which transfers ultrasonic vibrations and also a reinforcement, and a ball-tip installed at the end of the horn.

The ultrasonic waves are generated by the piezoelectric transducer and reinforced when passing through the booster. The dimensions of the horn provide vibration in the range of 10–30 μm generating a homogenous frequency behavior on the surface. The energy generated by these high frequency pulses along with $F=P_{st}+P_{dy}$ force was applied on the surface and exerted 20,000 to 40,000 impacts on every square millimeter according to Eq. 2, which is the severe plastic deformation generating nanostructure [11, 12].

Many parameters, which might be controlled and optimized precisely and excellently by numerical control/computer numerical control (NC/CNC) machines or by UNSM unit, affect the behavior of UNSM. The surface layer thickness of the nanostructure depends on factors like the nature of the raw material, number of impacts, and UNSM process parameters such as the size of the ball-tip tool, amplitude, pneumatic pressure, feeding speed, and the speed of the NS/CNC machine spindle. The relation between the number of vibration impacts (N) and the applied ultrasonic frequency is presented in Eq. 2. In this equation, $N = \frac{60 \times f}{S \times V}$, V is the linear velocity based on one turn of the workpiece $\left(\frac{\text{mm}}{\text{s}}\right)$, S is the feeding for the main axis of ultrasonic equipment $\left(\frac{\text{mm}}{\text{rev}}\right)$, and f is the resonance frequency for the set of vibrating tool (horn) [13]. ($V=\pi dn$, (d is specimen diameter (mm) and n is spindle speed (rpm))):

$$N = \frac{60 \times f}{S \times V} \quad (2)$$

The schematic UNSM process is depicted in Fig. 2.

It is worth mentioning that the relation between the depth of nanostructuralism after UNSM and the number of vibration impacts is not purely linear.

3 Process preparation

3.1 Design and manufacture of the vibrating tool

Ultrasonic vibrations are divided into three types: (1) linear, (2) torsion, and (3) bending. Since the goal is to study the effects of impacts on metals in this research, there is a need for linear ultrasonic vibrations. The goal of the design and manufacture of the vibrating tool is to obtain the material, geometry, and dimensions of the tool resonated in the frequency generated by the ultrasonic transducer without wasting the generated energy, which led to the intensification of impacts on the surface. To prevent vibration energy loss, the vibrating

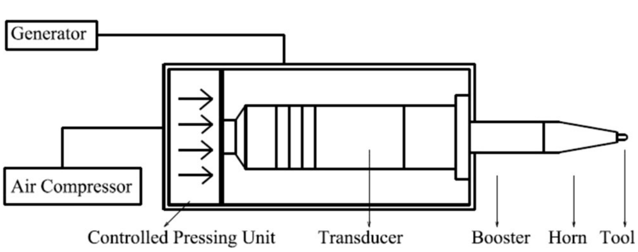

Fig. 1 UNSM configuration equipment

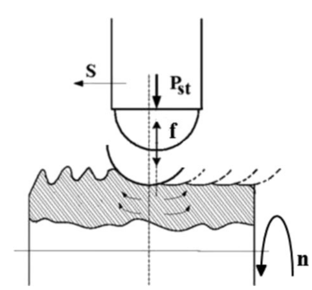

Fig. 2 UNSM process

tool should be of a material with minimum damping, which is easily intensified in the desired type of vibration and frequency transferring the waves. In this article, the vibrating tool is selected as Al 7075, on which T6 heat treatment was performed and is the best material with the best heat treatment for the transfer of vibrations. A ball-tip made of hardened steel was attached to the end of the vibrating tool. As a result of the need for the concentration of vibrating energy for severe plastic deformation, the diameter of the concentrating tool should be reduced by moving it away from the transducer. Other dimensions and sizes should be selected, such that the vibrating tool enjoys a linear vibrating mode at or close to the frequency of 20 kHz. Table 1 shows the specifications of Al 7075 and hardened steel. By applying these specifications in ABAQUS 6.11 software, the modal analysis for attaining the just mentioned frequency was performed and the final dimensions of the tool were obtained.

Figure 3 depicts the resonance frequencies for the tool after modal analysis by the software (Fig. 3a) and vibration of the tool at the desired linear frequency (Fig. 3b). The frequency of 19,771 Hz is the linear resonance frequency; that is, the resonance frequency before it is in a torsion mode (14,228 Hz) and after it is in a bending mode (23,960 Hz).

3.2 Equipment and test devices

In the next step, the aforementioned tool was connected to a set of 20-kHz piezoelectric transducers, and a 3-kW ultrasonic generator (MPA Company) generates and controls the transducer vibrations. Figure 4 shows the tool (a), the transducer and its component (b), and the ultrasonic generator (c).

The set of tool and transducer, assembled inside the UNSM fixture, was placed on the lathe support. Figure 5 shows the UNSM fixture assembled on the TN50A lathe.

4 Tests and results

All hardness tests in this study were carried out by HVS-1000B microhardness machine (made in China) with a force of 10 kg in 10 s, and all surface smoothness tests were carried out on MAHR machine (GmbH.G ttingen, Germany).

The UNSM process can be prepared for the tests by assembling the fixture on the lathe as shown in Fig. 6.

Table 1 Al 7075 and hardened steel specifications

	Density	Young's modulus	Poisson's ratio
Al 7075	2740 (kg/m^3)	70 GPa	0.3
Hardened steel	7800 (kg/m^3)	200 GPa	0.3

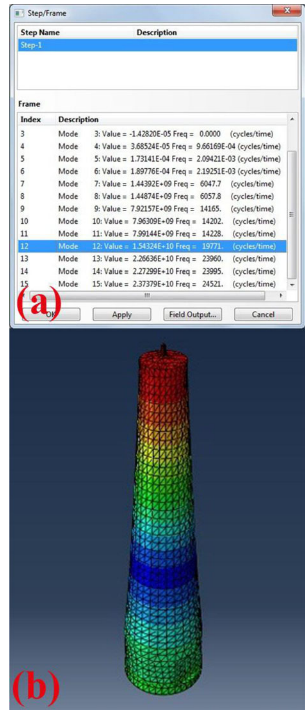

Fig. 3 The resonance frequencies for tool (**a**) and vibration of the tool in linear resonance mode (**b**)

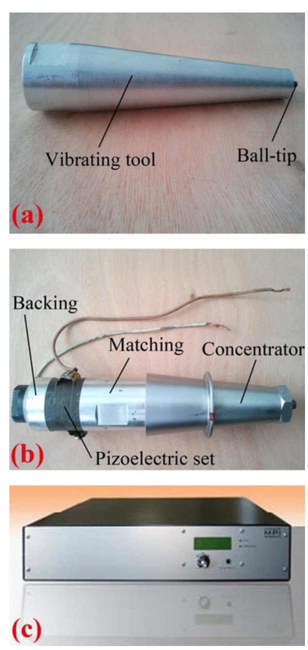

Fig. 4 Tool (**a**), transducer (**b**), and generator (**c**)

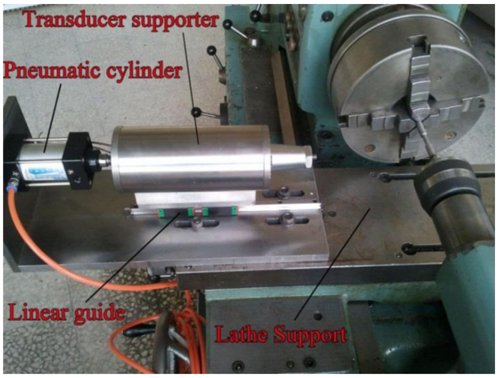

Fig. 5 UNSM fixture assembled on TN50A lathe

This figure was taken from a set consisting of a fixture and a tool during operations performed on the fatigue specimen.

As mentioned earlier in this research, the UNSM operations were performed on steel 7225, and mechanical tests were carried out on this metal to study its properties.

4.1 Effect of the number of passes on the application of equal number of impacts on surface smoothness

In the beginning, the steel 7225 shaft, placed between two chucks, was lathe cut up to a diameter of 10 mm. UNSM operation was carried out on both sections of this piece with the goal of applying 20,000 impacts per square millimeter on each section with different numbers of passes. The conditions of operation in the first, second, and the crude (machined) sections and also the number of impacts applied on the first and second sections were calculated according to Eq. 2, along with the number of passes operations applied to reach 20, 000, impacts as presented in Table 2. Since the vibration frequency in the ultrasonic tools is greater than/equal to 20,000 Hz, the conditions and parameters existing in Eq. 2 should be selected such that utmost

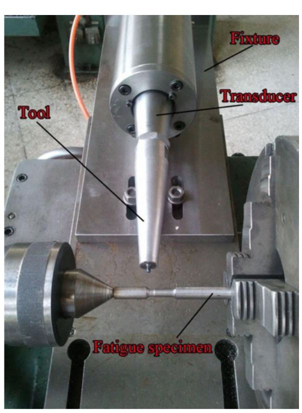

Fig. 6 UNSM operations performed on the fatigue test specimen

Table 2 The effect of the number of passes on the application of 20,000 numbers of impacts on the roughness in steel 7225

Conditions for the application of 20,000 impacts on area unit	First section	Second section	Lathe cut sections
Spindle speed (rpm)	250	90	1000
Feeding speed (mm/cycle)	0.08	0.08	0.08
Number of passes	11	4	0
Roughness (R_a)	2.101	0.551	2.604

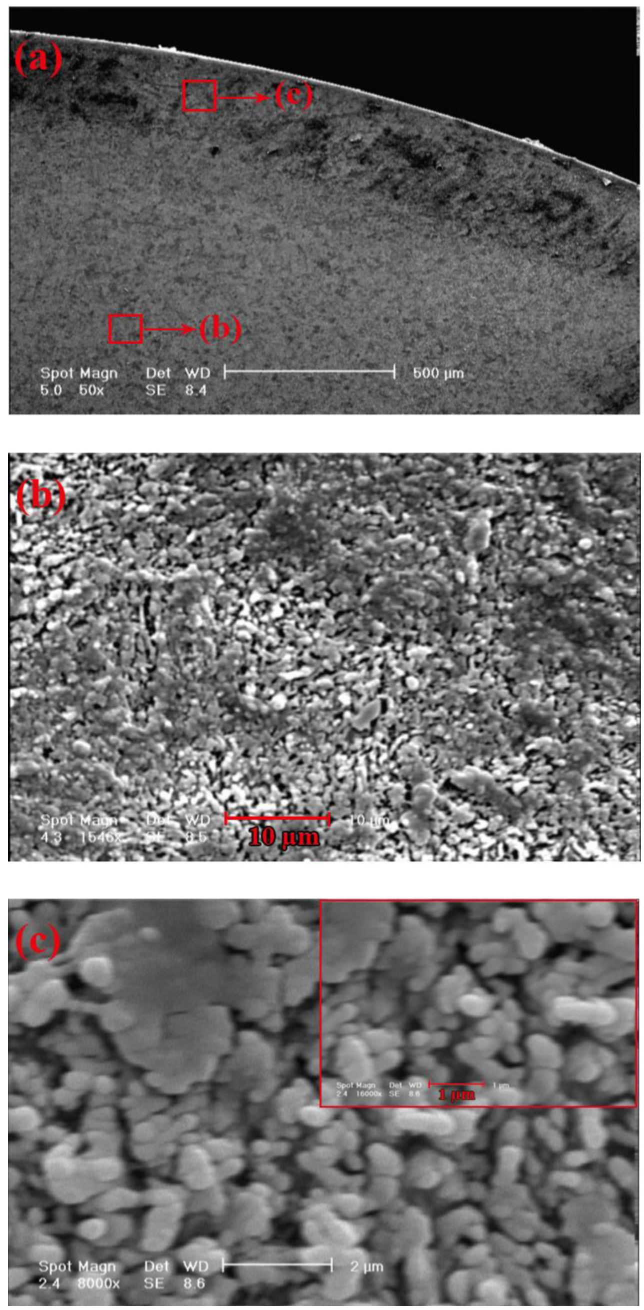

Fig. 7 SEM image ((**a**) cross-section of treated specimen, (**b**) structure of treated specimen core, (**c**) structure of treated specimen surface)

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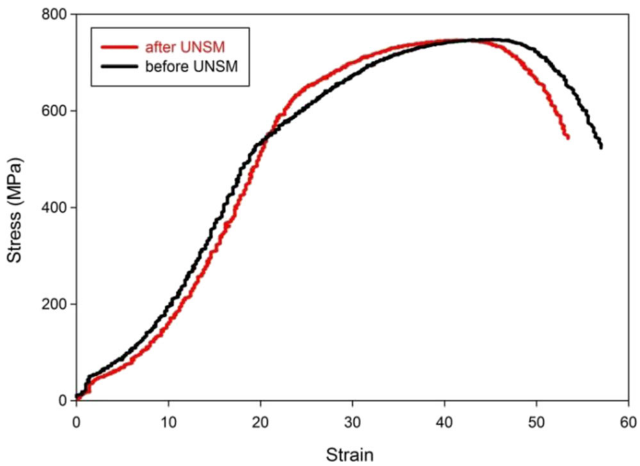

Fig. 8 Stress and strain diagram (after and before UNSM)

advantage is taken of the resonance frequency of the tool, and the maximum numbers of impacts applied to the area unit and severe plastic deformation is obtained. The conditions for the application of the process on the first, second, and the crude section; the number of the process application passes of the application of the process; and the results of surface roughness are presented in Table 2.

It was understood from the aforementioned results that roughness has a direct relationship with the number of applied passes for the production of a number of equal impacts. Hence, the higher the number of applied passes for the number of equal impacts, the rougher the surface will be. On the other hand, the quality of the machined surface on which no UNSM operation is carried out is R_a=2.604 in steel 7225, showing that if the passes of UNSM process for this metal go beyond a specific number, the surface produced by the operation will probably be even rougher than that produced by the machining process.

Table 3 The effect of the number of impacts on the roughness in steel 7225

	First specimen	Second specimen	Third specimen
Number of impacts	4000	8000	10,000
Roughness (R_a)	0.772	0.548	0.488

4.2 Workpiece surface SEM image for the exhibition of ultrafine structure

Microstructural observation was performed using SEM (Phillips XL 30: Eindhoven, The Netherlands). Cross-section SEM sample was prepared by mechanical polishing with 60–2400 grid SiC paper in water and then buff-polished with 0.3 μm Al_2O_3, followed by etching with 87.5 % methanol and 12.5 % sulfuric acid. Figure 7 shows the images prepared from the core and the surface edge by SEM.

It is clear that due to the UNSM process, the core of the specimen has maintained its microcrystal structure while the structure of the surface of the specimen is transformed from micro to ultrafine structure (at nano-scale in some parts) up to a depth of several microns.

4.3 Tensile test

Tensile tests of UNSM treated and untreated samples were carried out by an electronic universal test machine (STM-150 SANTAM, Iran). The stress-strain curves of samples are shown in Fig. 8. It can be seen that the materials yield stress increases from 520 MPa before UNSM to 610 MPa after UNSM.

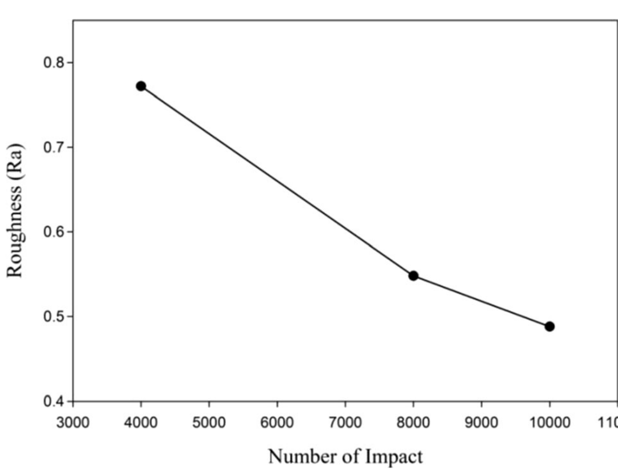

Fig. 9 Number of impacts–roughness

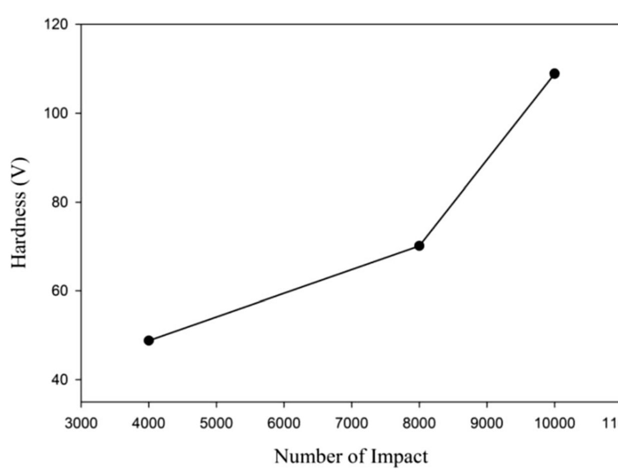

Fig. 10 Number of impacts–hardness

Table 4 The effect of the number of impacts on the hardness in steel 7225

	First specimen	Second specimen	Third specimen
Number of impacts	4000	8000	10,000
Hardness (HV)	48.8	70.1	108.9

4.4 Effect of the number of impacts on roughness and hardness

UNSM operation at two, four, and six passes were performed on three steel 7225 specimens with a diameter of 10 mm at 250 rpm spindle speed and feeding speed of 0.08 mm per cycle. The number of applied impacts per square millimeter on each specimen with two, four, and six passes is 4000, 8000, and 10,000 times, respectively. The roughness of the surface of the specimens with 4000, 8000, and 10,000 impacts was measured to be R_a=0.772, R_a=0.548, and R_a=0.488, respectively. This fact shows that the higher the number of impacts applied on the area unit, the more the smoothness of the surface, and the better the quality of the surface. Figure 9 and Table 3 show the earlier mentioned results.

The hardness of the aforementioned specimens was also measured. For the specimen with 4000 impacts, the hardness is 48.8 HV; for that with 8000 impacts, it is 70.1 HV; and for that with 10,000 impacts, it is 108.9 HV, indicating that an increase in hardness was directly proportional to an increase in the number of impacts applied on the area unit. Figure 10 and Table 4 show hardness according to the number of impacts.

UNSM technology, inflicting repeated impacts on the metal surface led to the microstructuralism of the surface and is itself a type of cold forging. Obviously, hardness will increase by microstructuralism, and the reason for the decrease in surface coarseness is inflicting several thousand impacts in the time unit per square millimeter on the surface, and this decreases the surface coarseness.

4.5 Fatigue test

Figure 11 shows the dimensions of the specimen used for the fatigue test in this research. Fatigue test machine made by P.P.I was used to carry out this test, and the load applied on the specimens was 15 kg equivalent to 150 N during the test.

According to these dimensions, eight specimens of steel 7225 were prepared, two of which were tested as crude specimens. The remaining six specimens underwent UNSM operation in three groups each with two specimens. In all the tests, the spindle speed was 250 rpm and the feeding speed was 0.08 mm per cycle. The goal of performing an operation on the first two specimens was to impose 4000 impacts on the area unit. Therefore, one pass was applied on a 6-mm diameter, and two passes were applied on a 10-mm diameter. In the second dual-group, the goal was to apply 8000 impacts on an area unit. Hence, four passes were applied on the 10-mm diameter and three passes were applied on the 6-mm diameter with regard to the conditions of the spindle speed and feeding speed, in order to attain these impacts. The last dual-group was surface-treated at a 10-mm diameter and at a 6-mm diameter with six and four passes, respectively. The number of impacts applied on area unit in this group was 10,000.

The fatigue test was performed on each of the earlier mentioned groups, and the fatigue life of each group was obtained by the mean life of the two specimens of that group. The obtained results are presented in Fig. 12.

$$\begin{array}{ll} \text{Crude specimens} = 10,407 \text{ and } 12,930 \text{ cycles} & \text{mean} = 11,668.5 \text{ cycles.} \\ \text{Specimens with 4000 impacts} = 19,140 \text{ and } 17,868 \text{ cycles} & \text{mean} = 18,504 \text{ cycles.} \\ \text{Specimens with 8000 impacts} = 29,002 \text{ and } 22,744 \text{ cycles} & \text{mean} = 25,873 \text{ cycles.} \\ \text{Specimens with 8000 impacts} = 48,006 \text{ and } 42,325 \text{ cycles} & \text{mean} = 45,165.5 \text{ cycles.} \end{array}$$

By comparing the fatigue life of the earlier mentioned items, it was concluded that the higher the number of impacts, the longer the fatigue life.

Fatigue means the creation of cracks on the metal surface, and its growth towards the depth was created as a result of alternative loads. UNSM technology makes the metal surface microstructural and does not make any change in the structure dominating the metal depth. In other words, in UNSM technology, the structure of the metal surface has been microstructured to a nano-scale while the structure of

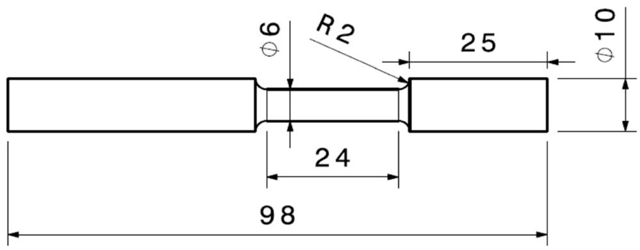

Fig. 11 The specimen used for the fatigue test

the metal depth remained in large grains. Since the creation of cracks decreased by microstructuralism and the growth of cracks decreased by the structure remaining in large grains, this technology multiplies the fatigue life. The results obtained in this manuscript are the proof for this claim.

4.6 Measurement of hardness for several different depths and their comparison

The hardness of steel 7225, on whose area unit 20,000 impacts were applied in four passes, was measured at different depths by a microhardness tester. Figure 13 shows the results:

Hardness at surface : 304.7 HV;
Hardness at the depth of 20 microns : 287.3 HV;
Hardness at the depth of 60 microns : 83.9 HV;
Hardness at the depth of 80 microns : 76.5 HV;
Hardness at the depth of 100 microns : 72.8 HV;

By comparing the values of depth and measured hardness, it was concluded that hardness decreases with an increase in depth. Also, the values of hardness up to a depth of 25 microns relatively higher than the metal hardness are at deeper depths, indicating that the

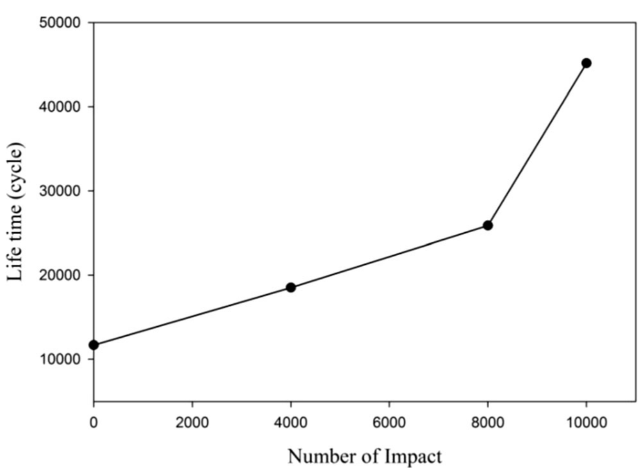

Fig. 12 Number of impacts–fatigue life based on cycle

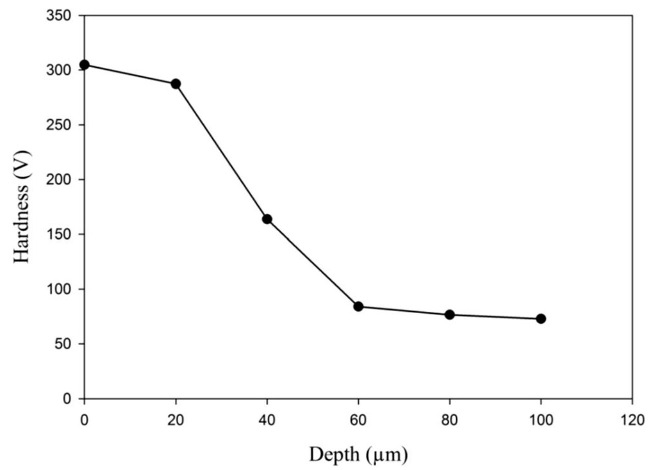

Fig. 13 Microhardness at different depths

structure of the metal up to a depth of 25 microns gets finer, and that at more depths, the structure becomes larger than the metal surface, so that by approaching the sample core, we approach the microstructure.

5 Conclusions

In this research, the UNSM process was applied on steel 7225. The effect of the process on the improvement of specific features of this metal was studied, and the results are as follows:

1. SEM analysis showed that the surface structure of steel 7225 became finer at nanometer scale due to the application of UNSM technology.
2. The fatigue life and yield stress of the treated steel 7225 piece increased greatly relative to the similar crude specimen, in a manner that the yield stress in this metal increased to 610 MPa from the 520 MPa present in the crude specimen. In addition, the fatigue life of the treated specimen in comparison to the crude specimen increased by approximately four times showing the efficacy of UNSM technology for life increase.
3. The higher the number of passes in the application of the number of equal impacts, the coarser the surface; and the higher the number of impacts, the smoother the surface will be. In other words, the best surface smoothness in UNSM technology is obtained when the number of impacts is the highest and the number of passes required for the application of these impacts is the lowest.
4. With an increase in the number of impacts, the surface hardness also increased. At different depths, it was found that with an increase in depth, the

hardness resulting from the operation was reduced in a manner that it was 304.7 V at the surface of the specimen, and 72.8 V at a depth of 100 microns. With regard to its depth, the change in the values of hardness shows that a specific depth of the surface (about 25 microns) is nanostructured by UNSM.

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