UDC 669
DOI: 10.15587/1729-4061.2021.243391

DEVELOPMENT OF MECHANICAL AND FATIGUE PROPERTIES OF AA7001 AFTER COMBINED SP WITH DEEP CRYOGENIC TREATMENT AND UIP WITH DEEP CRYOGENIC TREATMENT

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Al alloys have long been of interest to the aerospace community, due to their modest specific strength, ease of manufacture, and low cost. In recent years, with the rapid development of weaponry, 7XXX ultra-high strength aluminum alloys used increasingly in military fields. Chemical analysis of the AA7001 is supported out at The Company State for Engineering, Rehabilitation and Inspection (SIER) in Iraq. Strengthening the surface (shot penning) is beneficial to delay crack nucleation and extend life. The test samples (tensile and fatigue) are subject to the SP process by using ball steel with the parameters (Pressure=12 bars, Speed=40 mm/min, Distance=150 mm, Shot size==2.25 mm, Coverage=100 %). The ultrasonic impact treatment (UIP) machine is used for enhancing the surface properties. For the Deep Cryogenic Treatment (DCT), the samples have been placed in the cooling chamber. A standard tensile test specimen is prepared in a round section with the dimensions chosen according to ASTM (A370-11). Tensile and fatigue of rotating bending with R=–1 have been conducting, after the effect of deep cryogenic treatment (DCT), combined shot peening (SP+DCT), and ultrasonic impact peening (UIP+DCT) of AA7001 have been examining. The maximum improvement percent in ultimate tensile strength (UTS) due to (DCT), (SP+DCT), and (UIP+DCT) were about 3 %, 8.27 %, and 6.25 %, respectively. The rise in the yield stress due to (DCT), (SP+DCT), and (UIP+DCT) were 9.5 %, 14.6 %, and 13.14 %, respectively. The ductility reduced by constituents of 8.57 %, 12.5 %, and 11.42 % sequentially. The improvement in fatigue strength in a high cycle regime is 16 % for (SP+DCT) due to combined effects, it is an 8 % increase in the endurance limit on fatigue behavior due to inducing compressive residual stress (CRS)

Keywords: AA7001, deep cryogenic treatment, ultrasonic impact, shot peening, tensile and fatigue properties

Received date 08.09.2021
Accepted date 20.10.2021
Published date 29.10.2021

How to Cite: *Alhamdany, A. A., Khenyab, A. Y., Mohammed, Q. K., Alalkawi, H. J. M. (2021). Development of mechanical and fatigue properties of AA7001 after combined SP with deep cryogenic treatment and UIP with deep cryogenic treatment. Eastern-European Journal of Enterprise Technologies, 5 (1 (113)), 62–69. doi: https://doi.org/10.15587/1729-4061.2021.243391*

1. Introduction

Aluminum alloy such as 7xxx series of wrought aluminum alloys and has the highest strength in commercial heat treatable aluminum alloys and is the strongest of the forging alloys. Furthermore, it has fair corrosion resistance. This alloy is in high demand by aircraft production companies for structural parts and for other highly stressed applications.

Ambient temperature mechanical property improvement of metals by different heat-treating techniques has been established for many years. The performance of well-known metals, regarding effective heat treatments, has been categorized in different books. Cryogenic treatment of metals to develop their mechanical properties and wear characteristics is a relatively new engineering field. A little information about this treatment in tool steels has been reported but there is a dearth of information on how the technique operates and the degree of effectiveness of its application.

The idea of improving the properties of steel by exposure to low temperature is very old. Some industries have taken advantage of a subzero cold treatment for improving the serviceability of parts or tools for a long time. It is believed that old Swiss watchmakers were improving their watch components by burying them in snow during harsh winter temperatures. Toolmakers also stored the raw materials in freezer cabinets before using them for the same purpose. However, because of the unpredictable behavior experienced by many when using this treatment and a lack of understanding in its working principle, it did not find a main place in the production line, unlike conventional heat treatments.

The cryogenic process typically involves slowly cooling a mass of parts to –196 °C, holding them at this temperature for a period, and later tempering them. The idea for steels is to rid the structure of austenite, the soft, ductile phase in steels. Generally, the complete transformation from austenite to martensite is desired. Martensite resists plastic deformation much better than the austenitic structure. Therefore, the studies of this process is scientific relevant.

2. Literature review and problem statement

Aluminum alloys 7xxx series are using in many engineering applications, such as aerospace and aircraft structures and recently in the military field [1, 2]. Alloy 7001 is an alloy, with zinc as the primary alloying element; it has high mechanical and corrosion resistance and excellent fatigue life due to precipitation hardened.

Several difficulties happen during the service of machines due to external and internal defects. Defects are the sources of initiation cracks; they are growing during the time until it reaches a certain length a catastrophic failure produce [3], to prevent such issue and reducing the cost of repairing or maintaining the damaged parts, which require to spend a fortune every year. The surface treatments play a role in enhancing mechanical and fatigue properties; such treatments are cheap, easy to use, and traditional like shot peening (SP) and ultrasonic impact peening (UIP). Ultrasonic impact peening (UIP) or shot peening (SP) are the methods to improve the fatigue strength of examined material.

Fatigue life is defined as the number of cycles to fracture at specific stress. It is the most common failure of materials present in structures when materials are subjected to dynamic and fluctuating stresses. The material may be fracture at a stress level below the tensile strength. Enhance the fatigue strength of an alloy by introducing compressive residual stress on the surface. Shot peening enhances mechanical properties and fatigue life by producing compressive residual stress on the surface of a material and hardening it. The treated object with SP has high compressive residual stress, dislocation density, which affects texture and crack on the surface layer. Controlling the process of shot peening has been reviewed [4]. Ultrasonic peening is also used to improve properties but unlike the SP. Such a method's main feature could give a smooth surface compared to SP due to using a polished ball. Furthermore, it can provide much energy in a short time due to a high frequency [5].

The deep cryogenic treatment (DCT) was starting using the tool steel. It has been operating on ferrous alloys and non-ferrous alloys years ago. The use of cooling liquid at a temperature below (–196 °C) to strengthen the metals, i.e., tool steel, was an early application dated back to the 1930s. A way to enhance mechanical properties and fatigue life using deep cryogenic treatment (DCT) is because it affects the entire structure of the material, not only the surface [6, 7]. This study is concerned about Aluminum alloy 7001, due to its good properties. Compounded surface treatments with DCT have been examined in order to enhancing the mechanical and fatigue properties.

So, it is needed to improving the mechanical and fatigue properties by using compound surface treatments, and give an image about how the dual treatment can effective on the fatigue life and strength.

Many studies have concentrated on improving the mechanical and fatigue properties of Al alloy using different surface treatments. A review study has been done on the shot peening effects on different materials [8]. This review will help the researchers and readers to better understand the several benefits and applications of shot peening. The review of shot peening process is focused on the latest development and pushes the readers towards the on-going research in this classic process.

The high cycle fatigue performance of 7050-T7451 aluminum was investigated for untreated asmachined, laser peened, and shot peened conditions. Constant amplitude, smooth fatigue tests were conducted in four-point bending at a stress ratio of R=0.1 [9]. Results showed that laser peening induces a layer of compressive residual stress more than three times deeper than for shot peening. Both treatments significantly increase fatigue performance. At a moderate level of stress, peened specimens outlast as-machined specimens, by a factor of 7.9 for laser peening and 2.9 for shot peening. At higher stress, life improvements are lower, a factor of 3.3 for laser peening and 2.1 for shot peening. At a 100,000-cycle lifetime, fatigue strength of laser peened specimens is 41 % higher than as-machined specimens and the fatigue strength of shot peened specimens 30 % higher than as-machined. A form of pitting was noted on the laser peened surfaces and follow-on tests assessed the effects of the pitting on fatigue performance. Results indicated that the pitting does not significantly influence fatigue performance. Others have examined the influence of (DCT) on the properties of aluminum alloys, [2] have investigated the improvement in hardness, toughness, wear resistance, and fatigue life on an extruded plate of high strength Al 7A99 alloy using (T6) treatment (The T6 thermal cycle consists of a solution heat treatment followed by a water quenching and then an age hardening (or precipitation hardening) then by (T6+DCT) treatment. After the T6 (peak ageing) method. It was found in this study that the tensile strength was 705MPa, yield strength was 678 MPa, and elongation was 14 %. With (T6+DCT) treatment, there was a refinement in the grain size to less than 1,000 nm. It has noticed a homogenous distribution of the precipitations, which leads to improving the alloy's mechanical properties [10] have provided a brief study about the Cryogenic treatment and have explained which the process plays on enhancing the mechanical properties of various alloys.

The Cryogenic treatments increase the resistance to stress corrosion. Finer grains were observed after subjecting the material to (DCT), which affects the material properties. [11] have investigated the formability of cryocooled AA7075 alloy and its mechanical properties. A sheet with a 30 % reduction in thickness has been used in this study. Cryogenic treatment was performed on the sheet samples of AA7075 to improve their mechanical properties. A noticeable improvement in the Ultimate tensile strength has been seen after deep cryogenic treatment, while 20 % of the elongation reduced after rolling processes. The hardness has been increased by 13 %, and the wear resistance has been increased after deep cryogenic treatment.

[12] have been processing and optimizing the treatment parameters for getting the best combination of hardness and surface roughness after the cryogenic treatment of 7075 aluminum alloy, with the effect of the soaking period on this alloy, using design of experiments by Taguchi and optimization by gray relational analysis. [13] have been using Al alloy (Zn-Mg-Cu) treated by (DCT) to investigate the changes in the microstructure to improving the mechanical properties. They used high-resolution transmission electron microscopy to examine the microstructure change. [14] have been concluded that cryogenic treatment influences AlSi10Mg alloy, which increases tensile strength, compressive

strength, and hardness. A transition in the alloy from ductile to brittle has been observed was mainly due to the precipitation of second phase particles. [15] tribological studies have been conducted for evaluating the wear resistance of the most used various Aluminum alloys at cryogenic temperature and subjected them to (CT) for 64 hrs. The wear test in treatment was reported for the first time available. It was observed from the wear data that the slide wear resistance and the coefficient of friction evaluated superior wear resistance for the load application of 40N and 50N. Lower friction levels for the spacemen subjected to sliding at cryogenic temperature and the samples (DCT) compared to the untreated ones; the results were proved using SEM technique.

3. The aim and objectives of the study

The aim of the study is about improving the mechanical and fatigue properties by using compound surface treatments, and give an image about how the dual treatment can effective on the fatigue life and strength.

To achieve this aim, the following objectives are accomplished:

– measure the mechanical properties (Ultimate strength, Yield strength, Ductility, and Young's modulus);

– find the S-N curve for three different surface treatments (DCT, SP+DCT and UIP+DCT) on Al alloy 7001-0 at RT.

4. Materials and methods

The chemical composition of the aluminum alloy is presented in Table 1. Chemical analysis of the AA7001 is supported out at (The Company State for Engineering, Rehabilitation and Inspection (SIER) in Iraq.

Table 1

Chemical composition of 7001-0 Al alloy examined at the state company for standard and measured in wt. %

Elements wt. %	Zn	Si	Fe	Cu	Mn	Mg	Cr
Standard [16]	6.8–8	0.35	0.4	1.6–2.6	0.2	2.6–3.4	0.18–0.35
Experimental	6.1	0.33	0.4	1.85	0.18	3.1	0.27

Strengthening the surface (shot penning) is beneficial to delay crack nucleation and extend life as shown in Fig. 1. The test samples (tensile and fatigue) are subject to the SP process by using ball steel with the parameters mentioned in Table 2 at 10 min. Table 2 has listed all the required parameters for the experiment work.

Fig. 1. The SP device

Table 2

Shot peening process parameters

Parameters	Values
Pressure	12 bars
Speed	40 mm/min
Distance	150 mm
Shot size	2.25 mm
Coverage	100 %

The ultrasonic impact treatment (UIP) machine shown in Fig. 2 is used for enhancing the surface properties. High power ultrasonic drive impact tool has more than twenty thousand times per second frequency impact on a metal surface, make the metal surface produces a larger plastic deformation. The specimens were subjected to 35 sec (one line) ultrasonic peening. The main technical requirements are listed in Table 3.

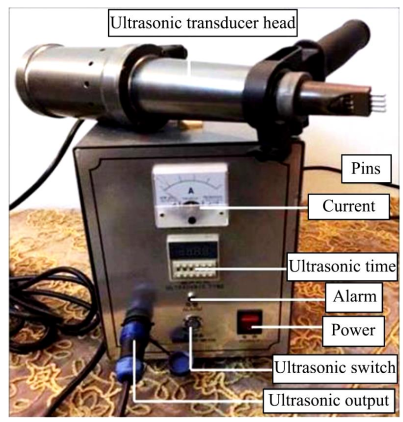

Fig. 2. The UIP device

Table 3

The UIP requirements

Main technical parameters	Materials
Power supply: 220V, frequency: 50Hz 5 A. (AC) Operation frequency: 20 kHz (output frequency) Maximum power: 500 W (output power) Adjustable (10 –100 %) Size of gun: length 450 mm Gun weight: 4 kg	applicable materials: Aluminum alloy, low carbon steel, high carbon steel, etc.

For the Deep Cryogenic Treatment (DCT), the samples have been placed in the cooling chamber, as shown in Fig. 3. The slow cooling procedure was applied to prevent the thermal shock possibility. For slow cooling, the liquid nitrogen was fed to the cooling chamber with a speed of 1 L/h until it reaches –184 °C. The samples were kept inside the cooling chamber for 24hours. This cooling process was according to ISO 21011-2013 listed in Table 4.

A standard tensile test specimen is prepared in a round section with the dimensions chosen according to ASTM (A370-11), as shown in Fig. 4. The tensile tests have been performed using tensile test rig type (WDW-50), as shown in Fig. 5. The tensile test was performed on the machined samples; 15 specimens were tested, 3 specimens for each test conducted at (RT).

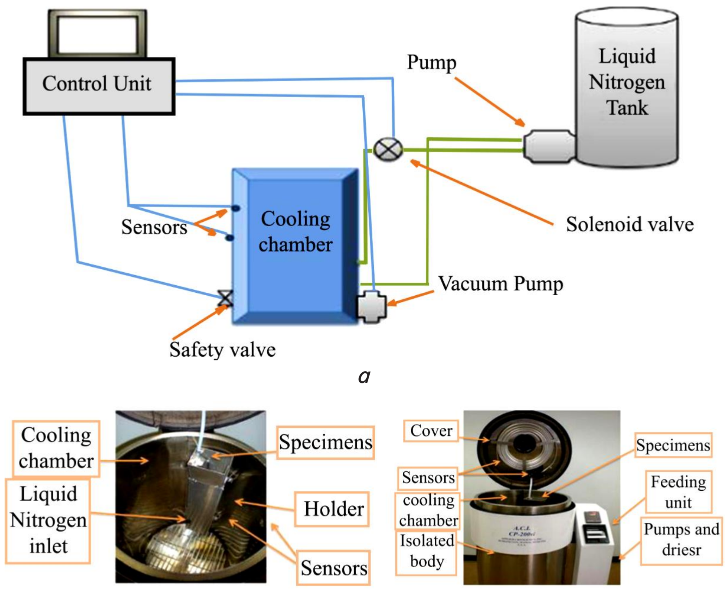

Fig. 3.The deep cryogenic treatment processes: *a* — Schematic diagram of DCT process; *b* — Specimens in cooling chamber; *c* — Cooling chamber and its accessories

Table 4

The DCT requirements according to ISO 21011-2013

Requirements	
Nitrogen feeding speed initial temperature of nitrogen	1 litter hour
Holding time for (–184 °C) environment sequence	–184 °C 1-day vacuum 24 hours

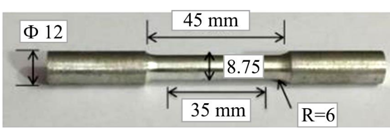

Fig. 4. The dimensions of the sample are given from the standard ASTM (A370-11) standard specification

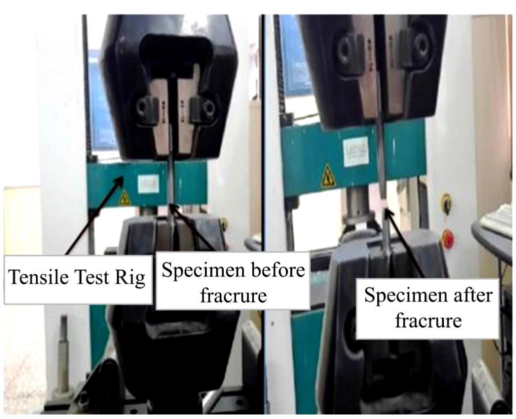

Fig. 5. Tensile test machine WDW-50

The fatigue samples were machined according to ASTM E 466-07, as shown in Fig. 6 [17]. The samples have been grinding and polished in order to prevent any surface geometrically. The fatigue tests have been performed using the (Schenck product) type.

The fatigue test machine is a rotating bending type, as shown in Fig. 7.

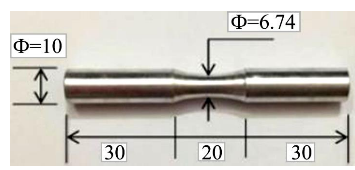

Fig. 6. The fatigue sample with its dimensions in mm ASTM (DIN 50113)

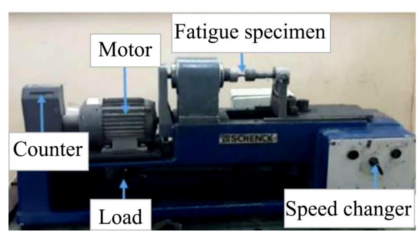

Fig. 7. Fatigue Rotating Bending Machine

Fatigue stress has been calculated using (1). The load subjected on the specimen was applied load to the side, and it was perpendicular to the longitudinal axis of the specimen. This setting will develop the bending moment.

Therefore, the surface of the specimen is under tension and compression stress when it rotates:

$$\sigma_b = L \cdot \frac{32P(N)}{\pi d^3}, \quad (1)$$

where L is the moment arm=125.7mm, σ_b is the bending stress in (N/mm^2), P is the load in (N), and d is the sample minimum diameter in (mm).

5. Results of research of mechanical and fatigue properties by using compound surface treatments

5. 1. Mechanical Properties Measurement

The tensile tests were performed to measure the mechanical properties (Ultimate strength, Yield strength, Ductility, and Young's modulus) for as received and the three different treatments (DCT, SP+DCT, and UIP+DCT) as shown in Fig. 8. The stress strain carves for these different treatments will increase till values between (5-10) then decreases. The Mechanical properties for as received have compared with the literature [18] and summarized in Table 5.

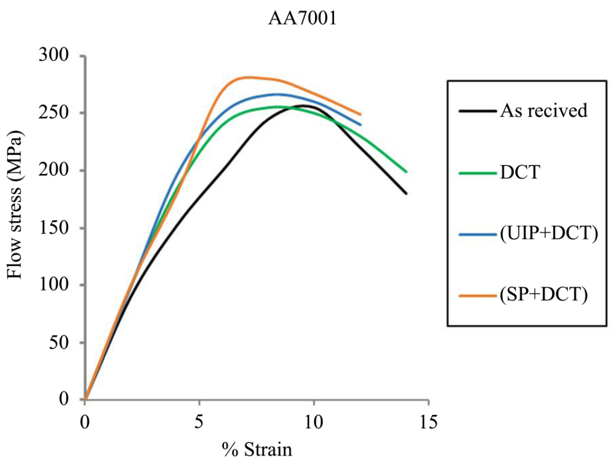

Fig. 8. The stress strain carves for different treatment on AA7001

As shown in Fig. 9, the (UTS) increased by 8 MPa for DCT, 23 MPa for (SP+DCT), and 17 MPa for (UIP+DCT) treatments. It has shown slight improvement in the UTS after DCT, that is maybe due to second phase precipitation in nonferrous metal as described in the study of [19], and the cryogenic treatment has the potential to alleviate residual stress without sacrificing tensile strength [20], along with surface integrity and dimensional stability. The second reason may be to the crystal defects are lessened, resulting in crystal homogeneity due to the decline of vacancies inside the crystal lattice, refining the grain size, and precipitate with 30–40 nm on the Guinier-Preston (GP) zones which little improves the properties of alloy as demonstrated in Li Chun-mei et al. study [13].

The UTS gets the maximum increasing after the SP+DCT then the treatment with UIP+DCT because both SP and UIP processes are methods to generate the compressive residual stress (CRS) at the surface every shot striking the material acts as a tiny peening hammer, imparting to the surface a small indentation or dimple. Below the dimple, a hemisphere of hardening or cold-worked that highly stressed. SP and UIP have proved to enhance mechanical properties and fatigue life. It has been reported that the (CRS) values are at least as high as 50 % of the UTS of the material [21].

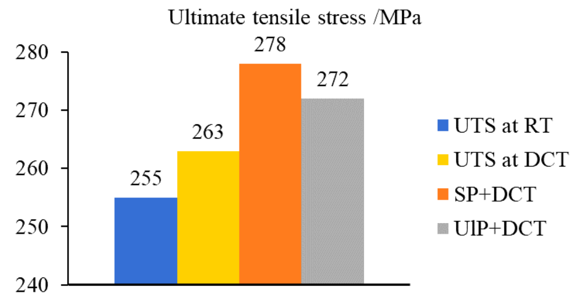

Fig. 9. The values of the tensile strength for as received and three different treatments (DCT, SP+DCT and UIP+DCT) on Al alloy 7001-0

Fig. 10 shows the (YS) values as received, DCT, SP+DCT, and UIP+DCT samples. It was found that the yield stress increases up to 11 %, 17 %, and 15 % respectively. The maximum increase percentage was 17 %, the same reason as mention before.

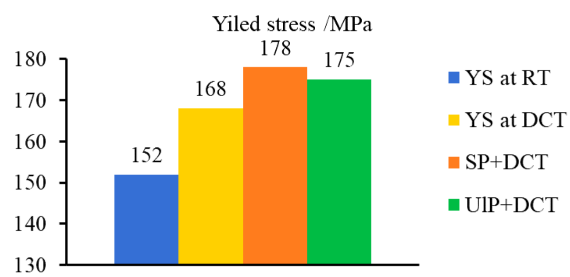

Fig. 10. The values of the yield tensile strength for as received and three different treatments (DCT, SP+DCT and UIP+DCT) on Al alloy 7001-0

Table 5

Mechanical properties of 7001 Al alloy tested compared with the standard

7001 Al	Ultimate Tensile stress (UTS) MPa	Yield stress (YS) MPa	Ductility %	Modulus of Elasticity GPa
Standard [18]	255	150	14	71
Experimental (RT)	255	152	14	70
Experimental (DCT at –184 °C)	263	168	12.8	71
Experimental (SP+DCT)	278	178	12.2	71.5
Experimental (UIP+DCT)	272	175	12.1	71.3

Fig. 11 shows the ductility of as received, DCT, SP+DCT, and UIP+DCT samples were decreasing with 8.57 %, 12.85 %, and 11.42 %, respectively, which is fundamental because of an increase in strength of metal after treatments.

Fig. 12 shows that Young's modulus values are 70, 71, 71.5 and 71.3 GPa. The maximum Young's modulus is 71.5 GPa after SP+DCT treated it; it is reasonable after increasing tensile and yield strength.

In general, the effect of DCT is relatively small compared with the SP or UIP techniques is the cause in improving the mechanical properties by work hardening on the top layer of the sample by roughening the surface and generation of the compressive residual stress. All these factors expected to affect both mechanical and fatigue properties [22].

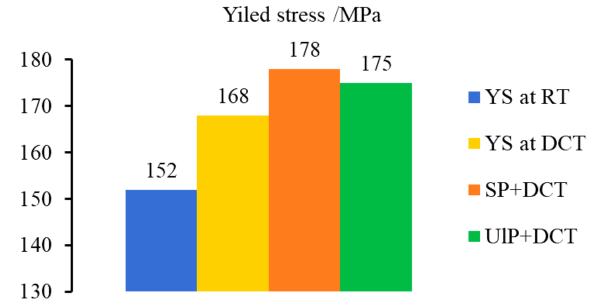

Fig. 11. The values of the ductility for as received and three different treatments (DCT, SP+DCT and UIP+DCT) on Al alloy 7001-0

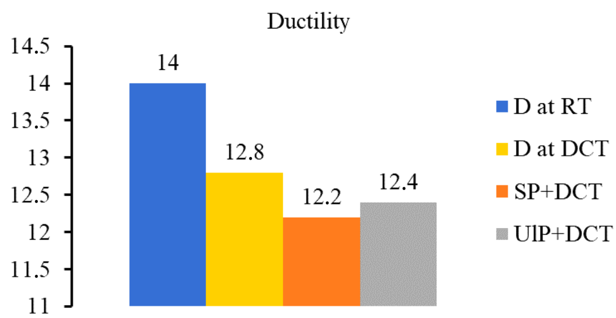

Fig. 12. The values of the Young's modulus for as received and three different treatments (DCT, SP+DCT and UIP+DCT) on Al alloy 7001-0

5. 2. S-N curve for Al alloy

The Fatigue Property Results. The rotating bending fatigue test was performed to establish the S-N curves for the four cases (AR, DCT, SP+DCT, and UIP+DCT) to understand the development in fatigue life of A7001 alloy. The fatigue test was conducted under constant fatigue stresses $R=-1$ at room temperature (RT). The results are listed in Table 6, and the S-N curve is shown in Fig. 13.

The fatigue life of tested samples after treated by DCT, SP+DCT, and UIP+DCT are slightly higher than the life of as received results. The three treatments used in this work have a beneficial effect on fatigue behavior due to the creation of compressive residual stresses (CRS) and the grain refinement strengthening on the surface layer.

Table 6

The S-N curve results of Al 7001 alloy average of three values treated, with different treatments

Stresses (MPa)	Average N_f (AR)	Average N_f (DCT)	Average N_f (SP+DCT)	Average N_f (UIP+DCT)
200	26300	32000	34800	30600
180	65933	71800	88800	79500
160	14933	13300	168600	141000
120	32933	400000	45600	40700

There is about a 3 % increase in fatigue strength for all three treatments in the low cycle regime, while in the high cycle regime, it is increasing by16 %. These confirm that surface treatments play an essential role in high cycle fatigue which impedes in nucleating the cracks.

It is evident from Fig. 13 there is no fatigue limit in AA7001 alloys. At large N_f, the lifetime is dominated by nucleation. Table 7 shows the best-fit equation and its correlation coefficient for each power case.

From Table 7, the best fit equation which accurately describes the behaviour of the metal and to fine the endurance limit stress in the Basquin formula is used in (3) and tabled in Table 8:

$$\sigma_f = aN_f^b, \tag{2}$$

where a and b are material properties, produced from the S-N carve fitting [23].

It has shown that the endurance limit of the treated sample with SP+DCT is increasing by 8 % from as received. These are due to factors such as grain size, dislocation, strain hardening, and CRS as reported in the literature [24, 25].

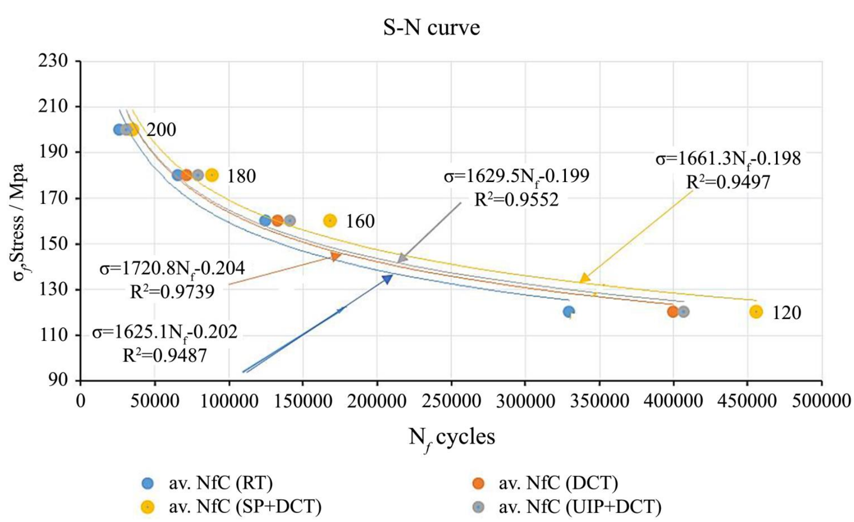

Fig. 13. The S-N curve for as received and three different surface treatments (DCT, SP+DCT and UIP+DCT) on Al alloy 7001-0 at RT

Table 7

The equations with correlation factor for A7001 alloy

The Equation and correlation coefficient	
As received (RT)	$\sigma_f = 1625.1N_f^{-0.202}$ $R^2=0.95$
Treatment (DCT)	$\sigma_f = 1720.8N_f^{-0.204}$ $R^2=0.97$
Surface treatment (UIP+DCT)	$\sigma_f = 1629.5N_f^{-0.199}$ $R^2=0.96$
Surface treatment (SP+DCT)	$\sigma_f = 1661.3N_f^{-0.198}$ $R^2=0.95$

Table 8

The endurance stresses using the Basquin formula when the number of cycles is 10^7

$\sigma_{E.L}$	
As received (RT)	63 MPa
(DCT)	64 MPa
(UIP+DCT)	66 MPa
(SP+DCT)	68 MPa

Grain size can affect fatigue behavior; decreasing grain size increases strain hardening as per the Hall-Petch relationship. It is explained based on the Hall-Petch formula [26, 27]:

$$\Delta\sigma_{GB} = \sigma_0 + kd^{-\frac{1}{2}}, \tag{3}$$

where $\Delta\sigma_{GB}$ is grain boundary strengthening, σ_0 is lattice friction stress, d=grain size, and k is constant (0.04 MPa $m^{1/2}$). The process of peening increases the value of σ_0 and reduces the magnitude of grain size resulting in high $\Delta\sigma_{GB}$.

Minimizing the grain size after (SP+DCT) resistance to crack initiation increases. Additionally, decreasing grain size increases the frequency of crack encounters boundaries, which provides more resistance to crack growth.

6. The discussion of the experimental results of mechanical and fatigue properties

Analysis of the results obtained (Fig. 9–12) allows to make such an interpretation. To have low fatigue crack growth, the surface residual stress should be as high as possible [28]. When the sample treated by (UIP+DCT) and (SP+DCT), hardening or plastic deformation at the sample surface was produced. It has been proved that CRS prevents crack growth. Nevertheless, surface roughness accelerates the crack initiation while cold work retards it [29].

The strain hardening effect, caused due to dislocation nucleation and pile-up, increases the hardness but decreases the material's ductility. Several researchers have reported that the influence of strain hardening still ambiguous on fatigue life and this study.

Some techniques like SP cause desired features on the specimen surface. Compressive residual stress compensates the tensile stress generated due to the applied load that reduces crack initiation possibilities on the surface. Compressive residual stress and stress inclination throughout the depth is useful for fatigue life as they can provide high protection towards both crack initiation and propagation mechanism. This study supports the influence on the high magnitude of compressive residual stress is beneficial for high fatigue performance. Recorded that even though the treated samples with SP underwent high CRS, the fatigue endurance limit was lower than that of the as-received samples due to high surface roughness.

The limitations of this study may be related to the range of technological processing modes. Investigation of the mechanism of hardening processes, including for extended ranges of input variables of the technological process, constitutes areas of further research.

7. Conclusions

1. It has improved among all the three processes, deep cryogenic treatment combined with SP got better results in tensile strength, yield strength, and Young's modulus with 278 MPa, 178 MPa, and 71.5 GPa, respectively.

2. There is about a 3 % increase in fatigue strength for all three treatments in the low cycle regime, while in the high cycle regime, it is increasing by 16 %. These confirm that surface treatments play an essential role in high cycle fatigue which impedes in nucleating the cracks.

Acknowledgments

The authors would like to acknowledge the support of the University of Technology (Iraq) and special thanks go to Asst. Prof. Dr. Hosham Salim (Head of Electromechanical Engineering Department) for providing the experimental support with the equipment.

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