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Effect of Ultrasonic Nanocrystal Surface Modification on Residual Stress and Fatigue Cracking in Engineering Alloys

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Abstract

The effects of Ultrasonic Nanocrystal Surface Modification (UNSM) on residual stresses and fatigue crack initiation were investigated in various engineering alloys. It was found that higher contact force and smaller pin in UNSM produced higher compressive residual stresses at the surface and subsurface of the alloys. The compressive residual stresses were found to be higher in high yield strength alloys. A deeper compressive residual stress field was observed in alloys with higher elastic modulus and strain hardening exponent. Fatigue crack initiation was found to occur subsurface in the material where the effect of UNSM hardening was saturated. It was concluded that deeper UNSM hardening produces higher fatigue life.

Keywords: Residual Stress, Finite Element Analysis, Ultrasonic Nanocrsytal Surface Modification, Fatigue Life Improvement

Nomenclature

$UNSM$	Ultrasonic Nanocrystal Surface Modification
σ	Flow Stress
A	Yield stress at room temperature
B	Strain factor
ε_p	Effective plastic strain

n	Strain hardening component
C	Strain rate sensitivity factor
ε_0	Reference plastic strain rate
T	Effective temperature
T_{room}	Ambient temperature
T_{melt}	Melting temperature
$Life_{UNSM}$	Fatigue life after UNSM Treatment
$Life$	Fatigue life before UNSM Treatment
m	Material constant

1- Introduction

The use of mechanical work to transfer energy into materials is used widely for improvement of the surface properties and fatigue life [1–7]. Surface treatment processes such as laser shock peening, shot peening, ultrasonic shot peening and ultrasonic nanocrystal surface modification (UNSM) are now used for improvement of the fatigue, wear and surface properties of materials [4-7]. The plastic deformation of the surface in these treatments produces compressive residual stresses in the material up to a significant depth, which, combined with beneficial modification of the microstructure, delays fatigue cracking and improves the life of materials. Higher fatigue life is obtained when the surface treatment produces higher compressive residual stresses and a deeper refined microstructure layer [3-4].

The compressive stress that will develop in surface treatment gradually decrease down in the subsurface of material. A balancing tensile stress in the subsurface is observed to maintain the equilibrium in the material. The subsurface tensile stress promotes the crack initiation. Therefore, the subsurface cracking is common in surface treated engineering components. The higher and deeper hardening and compressive residual stresses in combination enforce the crack initiation deep in the subsurface to improve the fatigue life. The optimal hardening and residual stress beneficial for fatigue life improvement is achieved by different combinations of surface treatment process parameters in different materials. The hardening and residual stresses are controlled by the elastic modulus, yield stress and strain hardening exponent of the target material.

UNSM is a novel surface treatment process for improvement of the fatigue characteristics and wear rate of engineering materials. In comparison to shot peening, laser shock peening and other techniques, the lower cost, better control, and ease in application of UNSM make it an ideal choice for surface treatment of engineering alloys [1-4]. It is a cold working process which decomposes the surface microstructure into a nanostructured layer and hardens the target material. In the UNSM process, the material is impacted with a hard rigid pin moving with ultrasonic frequency, typically 20 kHz. The impact deforms the surface of the target material and converts its microstructure into nanocrystals. The plastic deformation produces a 1-2mm deep compressive residual stress field in the material. The surface deformation, nanostructured layer and compressive residual stresses, in combination, delay fatigue crack initiation and improve fatigue life [3-4]. The elastic–plastic properties of the target material and process parameters of UNSM control the surface deformation, hardening, depth of the refined nanocrystal layer and the residual stresses.

UNSM has been applied by for improvement in wear and fatigue properties. Pyoun *et al.* [1] applied UNSM on various engineering alloys and improved their surface roughness and fatigue properties. Cao *et al.* [2], Suh *et al.* [3], and Wu *et al.* [4] used UNSM on steel alloys for improvement of their fatigue strength. It has been found in these studies that the fatigue life improvement by UNSM depends on the elastic–plastic properties of the target material and its microstructure. The UNSM pin diameter and impact force also affect the fatigue life improvement [8-10]. The complex interaction of material properties and UNSM process parameters for fatigue improvement make the selection of optimum parameters very challenging. Different process parameters of UNSM produce different hardening and residual stresses, affecting the fatigue life of the material. The process parameters that will produce higher fatigue life improvement in one alloy show no relevance to other alloys. Hence, UNSM application without considering the interaction of material properties and process parameters may show adverse effects on the fatigue performance. A lower compressive stress, shallow refined layer or a higher balancing tensile residual stress may result in lower fatigue life in the target material by promoting premature fracture [10].

Whilst the effectiveness of surface treatment is widely acknowledged, the fatigue life improvement potential of engineering alloys is not completely understood. The dynamic nature of surface treatment processes deforms the materials with very high strain rate which makes the direct observations of residual stress and refined layer very difficult. There have been numerous studies on surface treatment of engineering alloys and fatigue life improvement [8-12], and whilst empirical selection of process parameters are used to show improvement in fatigue life for the different techniques [9, 11], the trial-and-error approach that is often deployed improves the fatigue life without finding the maximum potential for fatigue life improvement [12]. In some cases, process parameters produce excessive plastic deformation or disadvantageous stress fields and reduce the fatigue life [10]. Unfortunately, there is no mathematical method to predict the accurate residual stresses and depth of refined layer in the material.

Finite Element (FE) simulations of surface treatment processes have been used for investigations of the relationship between surface treatment process parameters and fatigue performance of engineering alloys [15-17]. Experimental and FE studies of UNSM on hardening and residual stresses of various engineering alloys are still scarce [8, 13].

This study aims to develop a better understanding of the interaction of UNSM parameters with fatigue life improvement of various alloys. The optimization of the most critical material properties which control the elastic residual stresses, hardening, and fatigue life improvement was carried out. Finite element simulations were used in this study to model the deformation, stress and strain fields in different engineering alloys and compared with fatigue testing data. It was found that smaller diameter pin and high impact forces in UNSM produce a higher magnitude of compressive residual stress. The UNSM develops more hardening and compressive residual stresses in alloys with higher yield strength. A deeper compressive stress is obtained in alloys with higher elastic modulus and strain hardening exponent. It was found that UNSM treatment result in higher fatigue life in alloys where higher and deeper hardening is developed.

2- Theoretical Background

In the UNSM process, a sinusoidal electric field is generated by an ultrasonic wave generator to excite an ultrasonic transducer. The transducer is attached to a horn to amplify the signal and produce mechanical energy. A rigid pin is connected to the horn, and a static contact force is used to bring the pin into contact with the target material. Fig. 1 (a) shows the schematic representation of UNSM equipment. The movement of the pin at ultrasonic frequency generates kinetic energy and applies dynamic force to the material. The static contact force and kinetic energy of the pin in combination produce high impact energy, which deforms the near surface region plastically. The microstructure of the material deforms to a nanostructure and a beneficial compressive residual stress in the material is produced. Fig. 1 (b) shows a schematic representation of the deformed microstructure of the material after UNSM treatment.

The total pin force on the surface of material can be written as:

$$Force = Static\ Force + Dynamic\ Force$$

$$F_{total} = F_{static} + F_{Dynamic}$$

$$F_{total} = F_{static} + F_a \sin(\omega t)$$

Where F_{total} is the total force applied by the pin on the material, F_{static} is the static component of the force, $F_{Dynamic}$ is the dynamic component of force applied by with ultrasonic frequency, F_a is the amplitude produced by the ultrasonic generator, and ω is the cyclic frequency ($\omega = 2\pi ft$) driving the pin. Hence the dynamic force produced by UNSM is equivalent to $F_a \sin(2\pi ft)$. It can be said that the dynamic component of force was always constant and total force of the pin can be varied by changing the static component of the force.

The high frequency pin impact in UNSM deforms the material with high strain rates. The Johnson-Cook model accurately describes the deformation behaviour of the material at high strain rate [18]. It is a strain-rate-dependent empirical model which uses the effects of strain hardening, strain-rate hardening and thermal softening of the material during deformation. The hardening of the material in the model is defined by the yield stress from equation (1).

$$\sigma = (A + B)\left(1 + Cln\frac{\varepsilon^p}{\varepsilon_0}\right)\{1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\} \quad (1)$$

Where σ is the flow stress, A is the yield stress at room temperature, B is the strain factor, ε_p is the effective plastic strain, n is the strain hardening component, C is the strain rate sensitivity factor, $\varepsilon_p/\varepsilon_0$ is the effective plastic strain normalized with reference plastic strain rate, T is the effective temperature, T_{room} is ambient temperature, T_{melt} is the melting temperature, and m is the temperature exponent. The parameters $A, B, C, n,$ and m are material constants for the Johnson-Cook strain-rate-dependent yield stress. The material constants A, B, C, m, and n are extracted from the Split Hopkinson Pressure Bar (SHPB) test. It is a high strain rate deformation test where a pulse of compression travels down and compresses the incident bar through a striker bar where alloy specimen is attached. The applied displacement and load are converted into stress-strain equation and the plastic curve is fitted by $\sigma = A + B(\varepsilon^p)^n$. For determination of material parameter m, quasi-static experimental tests are carried out at room and elevated temperature and corresponding plastic strain ε^p are obtained. The dynamic stress strain curves are used to determine the strain rate effect (C). The Johnson-Cook parameters of different alloys investigated in this study are shown in Table 1.

The equation 1 uses various materials constant for expression of flow stress of the material when subjected to the high strain rate deformation. The equation has three components, separated by different brackets. The terms in the first bracket gives stress as a function of equivalent plastic strain. The terms in the second bracket gives the stress as a function of strain rate, while the terms in the third bracket gives stress as a function of temperature. The model for flow stress used in equation 1 is more user friendly for computations. The high strain rate deformation can be described by more complicated models however; the computational packages cannot readily incorporate complicated and diverse models.

3- **Finite Element (FE) Simulations of UNSM**

The simulations were performed in the Dynamic Explicit mode of commercial FE package ABAQUS, using a deformable axisymmetric material and a rigid pin. A model size of 50 mm × 50 mm was constructed in two parts: a plate as the target material and a sphere as the impact pin. The target material was modelled as a deformable material using eight-node linear brick, reduced integration, hourglass control C3D8R elements. The pin was modelled as a rigid element with four-node 3D bilinear rigid R3D4 elements. The contact between the plate and pin was enforced by defining the pin as 'master' and the target plate as 'slave' surfaces. A static component of the force was used to bring the pin in contact with the target plate. The dynamic component of the force was constant in all simulations; hence variation in static component of force component was used for deeper penetration of the pin into the target plate. Only the master surface was allowed to penetrate into the slave surface. The coefficient of friction between the pin tip and the specimen surface was set to zero, assuming no significant effect of friction on the deformation process. The pin strikes the target surface for a very short duration of time in each cycle with extremely high frequency of 20kHz and given the spherical shape of the pin with carbide tip which is a material known to provide lower friction characteristics, the negligible effects of friction on UNSM simulation are justified.

The reaction force was recorded on the top surface of the pin in each step of pin displacement. Loading and unloading stages were simulated with periodic amplitude. In the simulation, the rigid pin penetrated the sample up to the maximum depth and then returned to the initial position. The target impact region was very small compared to size of the model, hence a fine mesh size was used around the contact regions. The simulation was carried out for 1×10^{-3} s on each target location, resulting in 400 strikes on the material surface. After 1×10^{-3} sec, the pin was translated horizontally 250 and 500µm away from its initial position and then simulation was performed on the new target region after each translation. The Johnson-Cook yield criterion was used for deformation of the target material. Fig. 2 (a) shows the schematic representation of the finite element model.

The residual stress profile in the material after UNSM treatment can be characterized with six distinct parameters which include compressive stress at the surface, maximum stress in the subsurface of material, maximum tensile residual stress, depth of maximum compressive stress, depth of transition of compressive to tensile residual stress, and depth of maximum tensile stress. Fig. 2 (b) shows the schematic representation of a typical residual stress curve obtained after UNSM treatment.

4- Results and Discussion

4.1- Residual Stresses

The experimental measurements of UNSM residual stresses with a 2.4mm diameter pin and 15N contact force in various alloys are shown in Table 2. The residual stress measurements were carried out with X-ray diffraction and Hole Drilling methods. The details of the measurements are reported elsewhere [19-22]. The residual stress measurement techniques use different areas to average the residual stress over that region. The minimum mesh size in the FE simulations was kept as 30 to 60um, which was different than the area used for averaging experimental stress measurements. Hence, the comparison of residual stress at the surface, which is usually high gradient, was not made in this study. However, the comparison of FE simulations using Johnson-Cook material model with experimental results of maximum residual stresses in the subsurface showed very good agreement with each other.

4.1- Effect of Pin Diameter

The effects of pin diameter on the material deformation and residual stresses in UNSM were investigated by process simulations with various pin diameters. The simulations were performed with 1.2, 2.4 and 3.6mm pin diameters on AISI 304 alloy. A static contact force of 15N was used in the simulations. Fig. 3(a) shows the variation in impact profile with different pin diameters. It was found that the size of the residual impact increased with diameter of the pin. The larger diameter pin produced a wider impact area and larger plastic deformation of the target location in the material. The larger UNSM pin, owing to its higher mass, transfers more energy and produces larger deformation of the target surface [8-9].

Fig. 3 (b) shows the variation in residual stresses with different pin diameters. It can be seen that compressive stress on the surface of material was similar for all pin diameters. However, the maximum compressive stress in the subsurface of the material was higher for a smaller diameter pin. The depths of maximum compressive stress and transition of compressive to tensile stresses were lower for the smaller diameter pin. Therefore the smaller diameter pin produces a sharper residual impact and higher subsurface compressive stresses in the material, but a relatively shallow residual stress field overall.

4.2- *Effect of Static Force*

The effects of static force on the material deformation and residual stresses in UNSM were investigated by process simulation with various static forces. The simulations were performed with 15, 20 and 30N static force on AISI 304 alloy. A pin diameter of 2.4mm was used in the simulations. Fig. 4(a) shows the variation in impact profile with different static forces. It was found that the size of the residual impact increased with static contact forces in the UNSM simulation. The depth and width of the residual impact in the target material increased with increase in the magnitude of static force. The depth of the residual impact increased by 12, 24 and 30% for 15, 30 and 45N static forces, respectively. A higher UNSM static force therefore transfers more energy and produces deeper plastic deformation in the material.

Fig. 4 (b) shows the variation in residual stresses with UNSM static force. The surface residual stress was 100MPa when no static force was used in the simulation. The surface residual stress increased with contact force [13], by 100, 115 and 130% for 15, 30 and 45N static forces, respectively. There was no significant effect of static force on maximum subsurface stress and depth of transition of compressive to tensile stresses.

Fig. 4 (c) shows the variation in equivalent plastic strain in the target material with static force. The equivalent plastic strain shows combined effect of all plastic strain components. Simulation without static force showed 15% plastic strain on the surface of material. The plastic strain in the material increased continuously with increase in the static force. It was found that the effect of static force was higher on the surface of material. The surface plastic strain increased by 25, 33 and 40% for 15, 30 and 45N static forces, respectively. The highest static force used in simulation produced 45% higher plastic strain of the surface of material. A higher static force in UNSM therefore increases the area of residual impact, residual stresses on the surface and plastic deformation of the material.

4.3- *Effect of Material Properties*

The effects of material properties on the impact profile and residual stresses were also investigated.

The UNSM simulations were performed on alloys Al 6061-T6, AISI 304, Ti6Al4V and Inconel 718. These alloys are commonly used in fatigue loading in various aerospace and power plant applications. The simulations were performed with a 2.4mm pin diameter and 15N static force. Fig. 5(a), (b) and (c) show the variation in residual impact, plastic strain and residual stress in different alloys. The same process parameters produced different effects in different alloys. A deeper impact was observed in aluminum and steel compared to titanium and Inconel. Previously work in aluminium alloys found material pile-up at the edge of an indentation [23]. A higher surface plastic strain was seen in alloys with lower yield strength. The aluminum and steel alloys showed 20-23% surface plastic strain which was 75% higher than the titanium and Inconel alloys. However, a higher compressive residual was seen in the titanium and Inconel compared to the aluminum and steel.

4.3.1 Effects of Yield Strength on the Residual Stress

Fig. 5 (c) shows the variation in residual stress for different alloys. It can be seen that high yield strength alloys showed higher and deeper residual stresses. The variations in residual stress were in agreement with the Hertz Contact Mechanics Theory which describes the stress under a spherical indenter as a function of elastic modulus and yield strength of the material [24]. Alloys AISI 304 and Inconel 718 have a similar elastic modulus but different yield stress: the yield strength of Inconel 718 is three times higher than the AISI 304. It was found that the residual stress at the surface and subsurface of Inconel 718 was 2.5 times higher than the AISI 304. However, the depths of maximum compressive stress, and transition of compressive to tensile stress were found to be 1.3 times higher in AISI 304 than the Inconel 718. The UNSM produces higher surface and subsurface residual stresses in high strength alloys. However, the compressive stress in these alloys converts into balancing tensile stress at lower depths.

4.3.2 Effects of Elastic Modulus on the Residual Stress

The depth of maximum compressive residual stress was higher in alloys with higher elastic modulus. The residual stresses in alloys AISI 304 and Al 6061-T6, with similar yield strength but different elastic modulus, were compared. The surface residual stress was found to be higher in the Al alloy with lower elastic modulus, as shown in Fig. 5(c). However, the maximum subsurface compressive stress was found to be higher in the AISI 304 alloy with the higher elastic modulus. Similarly, the depths of maximum compressive stress and transition of compressive to tensile stress were found to be higher in AISI 304 alloy. No effect on the magnitude of maximum tensile stress was found. The UNSM produce higher surface stress in alloys with lower elastic modulus. However, a higher and deeper subsurface compressive stress is produced in alloys with higher elastic modulus.

4.3.3 Effects of Strain Hardening on the Residual Stress

The effects of strain hardening exponent of the alloys on the variation in residual stress were studied by UNSM process simulation on alloys Al 2024-T351 and Al 6061-T6. The strain hardening exponent of alloy Al 2024-T351 is higher than Al 6061-T6. Fig. 6 shows the modelled residual stress profiles for the alloys. The changes in strain hardening exponent showed no effect on the surface stress; however, the alloy with higher strain hardening exponent showed a higher and deeper maximum subsurface stress.

Table 3 shows the summary of effects of material parameters on the residual stress profile features in UNSM treated alloys.

4.4- Residual stress from UNSM Overlapping

The UNSM coverage is increased by moving the impact pin across the surface of the target material. After several strikes on one location the USNM pin translates and strikes on a new location. The translation displacement is used in way that no part of the target material is left untreated. Hence, a small fraction of the initial target location is treated again in the treatment of the new location. The locations of overlapped treatment acquire a new residual stress state. The effects of UNSM overlapping were investigated in the simulations by moving the pin across the target material. The simulations were performed on alloy AISI 304 with 2.4mm diameter UNSM pin and 15N contact force.

Initially the simulation was performed on the first target location. The impact width on the surface was found to be 400 µm. Later, the pin was translated to distance equal to 50 and 100% of width of residual impact obtained in initial treatment. After each translation, the simulation was performed again and variation in residual stress before and after translation was obtained.

Fig. 7 shows the variation in residual stress before and after pin translations. It can be seen that the initial residual stress profile varied with treatment after pin translations. The maximum compressive stress region in the subsurface of material followed the spherical pin movement [9]. Fig. 8 shows the variation in residual stress in the alloy before and after pin translations at locations x= 0, 300 and 600 µm where x=0 is the initial target region underneath the center of pin. The UNSM treatment with center of pin at initial region at x=0 showed a higher subsurface maximum compressive stress than surface stress. However, the UNSM impact after translations of pin changed the earlier residual stress profile of the first target location. The UNSM overlapping resulted in stress state of first target location with similar surface and subsurface stress. The residual stress profiles at locations x=300 and 600 showed that conventional "hook shape" residual stress profile with maximum compressive stress in the subsurface of material moved with the pin movement. The location underneath the pin center developed a higher stress in the subsurface than surface. The locations away from the pin center showed similar stress at surface and subsurface of material. The UNSM pin translations showed no effect on the tensile residual stresses and the depth of transition of compression to tensile stresses. It can be said that UNSM impact coverage on large areas brings the material in a stress sate with hook shape residual stress profile for region under the pin. The regions away from the pin acquire similar surface and subsurface stress.

5.1-Fatigue Crack Initiation

The FE simulations of UNSM process on various alloys were used for comparison of fatigue characteristics of UNSM treated AISI 310 and Ti6Al4V alloys. The experimental investigations of fatigue life improvement, crack initiation depths, and full field residual stresses would have been very time consuming and expensive. Hence, results of only two alloys, AISI 310 and Ti6Al4V, have been compared with simulations. The UNSM treatment was performed on both alloys with a 2.4-mm-diameter carbide-tip pin and 20N static force on hourglass-type fatigue specimens. The UNSM treated specimens were cyclically-loaded at load ratio $R = -1$ with 20 kHz ultrasonic frequency. More details of the specimen geometry and fatigue testing are reported elsewhere [1, 13].

Fig. 9 shows the variation of hardness on the UNSM-treated cross-sections. It can be seen that UNSM treatment increased the surface hardness of the specimens. The hardness increase gradually decreased in the subsurface towards the bulk material hardness at around 300 µm depth. The percentage increase in the surface hardness and depth of hardness saturation was different for the different alloys. The specimens showed 20 and 14% increase in surface hardness for AISI 310 and Ti6Al4V, respectively. The difference in surface hardness increase was in agreement with the UNSM simulations where similar increase in surface plastic strain was obtained for both alloys. The hardness increase in the alloys is obtained when energy of surface treatment forms the nanocrystals. It has been found in earlier studies that equivalent plastic strain of around 8 gives indication of nanocrystal grains in the material [4]. The depth of percentage plastic strain 8 or higher was found to be 250 µm in Fig.5 (b). This was in agreement with hardness variation shown in Fig. 9 where the depth of hardness saturation in the subsurface was found as 300 µm for AISI 310 and 170µm for Ti6Al4V. This showed that similar UNSM process parameters developed different plastic deformation in the different alloys.

The UNSM impact force develops dislocations and nanocrystalline grain layers on the surface of material [8]. The density of dislocations and depth of nanocrystalline grain layers increase the hardness of the materials [8, 10, 13]. The hardness of the surface and the depth of the hardened layer depend on the plastic properties of the target material.

The fatigue testing of UNSM-treated specimens showed increase in the fatigue life of both alloys. The fatigue crack initiation was found to be in the subsurface of the specimens for both alloys. The fatigue life improvement and crack initiation depth were found to be higher in AISI 310 than Ti6Al4V. Fig. 10 (a) shows the variation in fatigue crack initiation depth for alloys with loading stress normalised by yield strength. It can be seen that the specimens that initiated cracks from deeper in the material were found to have higher failure cycles. The crack initiation depth was found to be 300-400 µm and 180-230µm for AISI 310 and Ti6Al4V, respectively. Fig. 10 (b) shows the S-N curves of both alloys before UNSM treatment. Fig. 10 (c) shows the correlation between UNSM fatigue life improvement in specimens and crack initiation depth. It can be seen that specimens with higher fatigue life improvement found to have deeper crack initiation in the subsurface of alloys.

The crack initiation depths in the alloys were found to be similar to the depth of hardness saturation and equivalent plastic strain in the alloys. Fig. 11 shows the fracture surface of both alloys. The AISI 310 specimen was tested at 550MPa and failed at 4.09×10^7 cycles while Ti6Al4V specimen was tested at 650MPa and failed at 9.3×10^7 cycles. The material composition at crack initiation region was found to be Al, Ti, Mn, Ni etc. however, for Ti6Al4V it was found to be Cr, Mo, Zr, Sn etc. which eas similar to the specimens without UNSM treatment for both alloys. It can be said that cracks initiated from subsurface depth where the hardness increase was saturated. Specimens loaded with lower stress showed deeper crack initiation and showed higher fatigue life than those loaded at higher stress.

The UNSM treatment of alloys AISI 310 and Ti6Al4V improved their fatigue life. However, the fatigue life improvement in both alloys was found to be different. It can be said that compressive residual stress at the surface of alloys results in improvement of the fatigue life of alloys however, the comparative improvement of fatigue life can be assessed by comparison of the magnitude and depth of maximum subsurface residual stress, hardening of the material, and depth of crack initiation. The UNSM treatment of Ti6Al4V alloy showed a higher and deeper compressive stress than AISI 310. However, higher fatigue life improvement and deeper crack initiation were observed in AISI 310. The better fatigue characteristics of AISI 310 than Ti6Al4V can be attributed to the higher and deeper plastic deformation and hardening in the alloy. The crack initiation depths for both alloys were found to be at the depths where the effect of hardness increase was saturated. In Ti6Al4V, a considerably higher compressive stress was found at the crack initiation location. However, the compressive stress was found to provide limited effect against resistance to crack initiation. It can be said the crack initiation takes place from subsurface depth where the effect of plastic deformation of the material saturates. The alloys with higher elastic modulus show deeper hardening and show higher fatigue life improvement potential in UNSM treatment.

It was concluded that smaller diameter pin and high contact force in UNSM produce deeper plastic deformation of the material. The materials with deeper hardening potential when targeted with a smaller diameter pin and higher static force produce higher fatigue improvement in the materials. The favourable location of crack initiation is the subsurface of material where hardening and compressive stress effect is found minimum.

6- Conclusions

Finite element simulations were used to investigate the residual stress evolution mechanism due to UNSM treatment in engineering alloys. It was found that a smaller diameter pin produces a higher magnitude of compressive residual stress at the surface and subsurface of the material. The higher static contact force produced a higher compressive residual stress in the material. It was found that UNSM produce higher compressive stress in materials with higher yield strength. A deeper residual stress field was observed in materials with higher elastic modulus and strain hardening exponent. The fatigue crack initiation was found in the material subsurface where the effect of UNSM hardening was saturated. It was concluded that deeper hardening of alloys produce higher fatigue life improvement. The alloys with higher elastic modulus possess a higher potential of fatigue life improvement.

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