مجلة جامعة بني وليد للعلوم الإنسانية والتطبيقية
Bani Waleed University Journal of Humanities and Applied Sciences
تصدر عن– جامعة بني وليد – ليبيا
Website:https://jhas-bwu.com/index.php/bwjhas/index
المجلد التاسع ـ العدد الخامس ـ 2024 ـ الصفحات (324 -332)
ISSN3005-3900

تأثير الأحمال الدورية على عمر الكلال ونمو التشققات لسبيكة الألمنيوم T3512024

فرج سعيد علي[1*]، عبدالقادر الزرقاني منصور[2]، عبدالسلام علي أحمد[3]
[1]قسم الهندسة الميكانيكية، كلية التقنية والعلوم بني وليد، بني وليد، ليبيا
[2]قسم الهندسة الميكانيكية، المعهد العالي لتقنيات الهندسة، بني وليد ، بني وليد، ليبيا
[3]قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بني وليد، بني وليد ،ليبيا
faragpodina@yahoo.com

Effects of Shot Peening Cyclic Load on Fatigue Crack Propagation Life of 2024T351 Aluminum Alloy

Fareg S Ali [1*], Abdulghadar A. M Awheda [2], Abdussalam A Ahmed [3]
[1] Department of Mechanical Engineering, College of Technical and Sciences Bani Walid , Bani Walid , Libya
[2] Department of Mechanical Engineering, Higher Institute of Engineering Technologies, Bani Walid, Bani Walid , Libya
[3] Department of Mechanical Engineering, Faculty of Engineering, Bani Waleed University, , Bani Walid , Libya

تاريخ الاستلام:15-10-2024 تاريخ القبول: 18-11-2024 تاريخ النشر: 06-12-2024

الملخص:
تعتبر مشكلة التعب المعدني أحد أهم التحديات التي تواجه الصناعات الهندسية، حيث يؤدي إلى فشل مفاجئ للمكونات المعدنية وتسبب خسائر اقتصادية فادحة. تهدف هذه الدراسة إلى تحسين أداء سبائك الألومنيوم 2024-T351من خلال تقنية المعالجة السطحية بالقصف بالكرات الفولاذية (A10-8 و A8-6 و A6-4). حيث تم تطبيق مستويين مختلفين من الأحمال 170 ميقا باسكال و280 ميقا باسكال لعدد دورات متفاوته من 1 إلى 10000 دوره. وتعتمد هذه التقنية على قصف سطح المادة بكرات فولاذية عالية السرعة لتوليد إجهادات متبقية تعيق نمو الشقوق وتزيد من مقاومة التعب. وتم إجراء تجارب معملية ومحاكاة عددية لتقييم تأثير هذه التقنية على عمر الكلال لسبائك الألومنيوم المدروسة. ويمكن استنتاج تقدير عمر التعب للسبائك من منحنى SN بناءً على الحد الأقصى للضغط الذي تتعرض له العينة. وأظهر عمر الكلال للعينات المعالجه سطحيا زيادة في عمر الكلال بنسبة 28%. وأثبتت نتائج المحاكاة بآنه يوجد توافق وثيق مع النتائج التجريبية.
الكلمات المفتاحية: القصف بالكرات، الحمل الدوري، عمر الكلال، الصلادة، الاجهادات المتبقية.

Abstract:
Surface treatments like shot peening are frequently employed to bolster the fatigue resistance of components. This study entails simulation and experimental investigations conducted on 2024-T351 aluminum alloy specimens subjected to three distinct shot peening treatments. The experiments involved subjecting specimens to varying intensities shot peening categorized as 4-6A, 6-8A, and 8-10A, followed by cyclic loading tests. Two different stress levels, 170MPa and 280MPa, were applied during cyclic tests for varying cycle counts ranging from 1 to 10,000 cycles. The enhanced fatigue life of peened specimens exhibited a notable increase of 28%, contingent upon the shot peening parameters. Specifically, employing higher shot peening parameters such as material of shot peen,

peening velocity, and size led to greater layer of residual stresses, thereby improving fatigue life. These beneficial effects serve to impede crack initiation and propagation on component surfaces, consequently retarding crack propagation rates. Fatigue life estimation for the 2024-T351 aluminum alloy can be derived from the S-N curve based on the maximum stress experienced by the specimen. Notably, simulation results closely aligned with experimental findings.
Keywords: Shot peen, Cyclic load, Fatigue life, intensity, Residual stress.

1. Introduction:

In the aerospace industry, 2024 T-351 aluminum alloys are extensively utilized due to their remarkable attributes including high strength [1-3], exceptional toughness [4-6] and superior corrosion resistance [7-8]. This particular alloy is categorized as a heat-treatable, precipitation-strengthened variant [9-10]. Wherein the morphology and dispersion of intermetallic phases play pivotal roles in determining its mechanical and corrosion properties [11-12]. Heat treatment emerges as a potent technique for modulating the morphology and distribution of these intermetallic phases, with solid solution treatment being a prevalent method. Notably, dissolution stands out as the primary phase transformation process during solid solution treatment. Coarse phases containing S and Fe are common in 2024 T-351 aluminum alloys, and their presence significantly compromises both mechanical and corrosion properties [13].

In a study conducted by Mattson & Coleman (1954) [14] the relationship between residual stress compressive layer and fatigue life was explored using leaf-spring samples subjected to shot peened. The findings elucidated a direct relationship between fatigue life and residual stress surface treatment induced by shot peening. Zaroog et al [15] examined the redistribution of residual stress surface in aluminum alloy during fatigue cyclic load. The process was observed to occur in stages: initial redistribution due to top layer surface yielding in the first cyclic load, followed by gradual redistribution in subsequent cycles. These stages demonstrated a significant decrease in residual stress related to samples undergoing no fatigue cycles, a result also corroborated [16]. The investigation focused on the 2024-T351 aluminum alloy, which serves as the standard material for manufacturing lower wing panels in contemporary large commercial aircraft. Renowned for its high strength and exceptional fatigue resistance, this alloy offers a superior strength-to-weight ratio, making it ideal for structures and components requiring such characteristics. Notably, it possesses excellent machinability, allowing for precision finishing, and can be easily formed in its annealed state before undergoing subsequent heat treatment [17].

2. The Aim of Study:

This study is a simulation and validate with experimental and study on the effect of shot peening on fatigue life of 2024T351 Aluminum alloy. Moreover, to investigate the relaxation of compressive residual stresses as well as the reduction of the hardness and cold work in the same material. The axial fatigue test is done on hour glass specimens complying with ASTM E 384. The investigation of compressive residual stress experimentally of three shot peened intensity with tow loads under yield strength at certain number of cycles.

3. Materials and Methods:

Aluminum alloy (2024-T351) is classified as (a copper-magnesium) founded age-hardenable alloy. The inclusion of copper facilitates strengthening through the age-hardening process, while magnesium mitigates the embrittlement effects caused by iron impurities [18]. This alloy is a combination of heat-treated, controlled stretched and naturally aged material. Wrought aluminium alloys comprise two principle groups known as non-heat-treatable alloys and heat-treatable [19,20]. The first group of alloys cannot be strengthened by heat treatment. Achievement of the primary strength of these alloys is attributed to the hardening impact of the alloying components such on manganese, silicon (Si) and magnesium.). Further hardening of these alloys is modify by cold work (strain hardening). Examples of such non-heat-treatable alloys are 1xxx, 3xxx, and 4xxx and 5xxx series. These non-heat-treatable alloys are also described as ductile and moderately strong based on the alloying elements concentration [21]. Their common applications are found in industrial deep drawn components, wire, tubes, sheets, extruded parts, and pressure vessels. However, the second group, the heat-treatable alloys, can be strengthened by heat treatment. Achieving the initial strength of these alloys is due to the hardening influence of the alloying components such on copper (Cu), silicon (Si), magnesium [22,23] and zinc (Zn). Subsequently solubility of these elements (or intermetallic) compounds designed from these elements in solid aluminium relies on the temperature, there is a possibility for this group of alloys to get hardened by the heat treatment, a process called precipitation hardening (age hardening). Alloys of 2xxx series are described as heat-treatable alloys. Such alloys are also used for manufacturing airplanes components and structures, welded structures, automotive body panels, part of machines.

The raw material, sourced as a sheet from Alcoa China, was 1 meter by 1 meter in size and 6.5 millimeters thick. It had a tensile strength of 484 MPa, a yield strength of 348 MPa, and an elongation of 15%. The chemical compositions of the tested material are listed in the attached Table 1. The fatigue samples were scaled according to Airbus standards [24]. The specimen was cut at SN Machinery Services using a slow cutting process with a dimension shown in Figure 1. The type of cutting machine used was a Mitsubishi RA9 CNC wire EDM machine with a diameter of 0.25 mm and a wire feed speed of 1.1 m/min. Wire cutting was used to reduce the temperature generated during the cutting process. The cutting temperature was kept in the range of room temperature ($25-30\ ^{o}\mathrm{C}$) by extensive cooling, and to ensure the temperature did not exceed the range a thermometer was used. In addition, the precision of the machining was maintained at $\pm 0.04\,\mathrm{mm}$.

Table 1: Specific chemical composition of Al alloy 2024-T351 (wt. %)

Component Element	**Ratio wt.%**	**Component**	**w t.%**	**Component**	**wt.%**
Al	93.50	Si	0.50	Fe	0.50
Cr	0.10	Ti	0.15	Mg	1.20-1.8
Cu	3.80-4.90	Zn	0.25	Mn	0.030-0.9
Ni	0.05	Zr	0.20	Pb	0.05

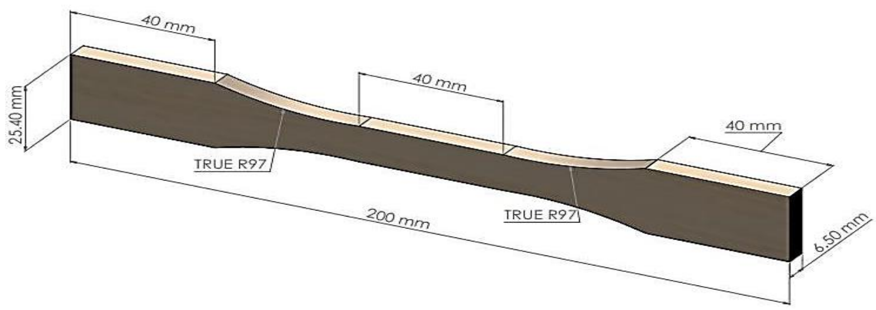


Figure 1: Shape of fatigue test sample

The chosen technique for cyclic testing involved tension-tension loading using hourglass-shaped specimens, conforming to Airbus standards. Ensuring the smoothness of the hourglass shape was imperative to avoid stress concentrations that could potentially affect test results adversely. At room temperature, a constant sinusoidal load at a frequency of 30 Hz was applied using an Instron 8874 unit with hydraulic grips, as shown in Figure 2. This unit, featuring a fully digital servo-hydraulic controller, offers automatic calibration for all compatible transducers.

Figure 2: Specimen loaded to the fatigue test machine

The selection of the load source was contingent upon various factors including required frequency, magnitude of forces, and available control systems. A minimum to maximum load ratio of 0.1 was opted for primarily to maintain a consistent total tensile cyclic stress and to mitigate potential adverse effects. The mechanical system of the 8874 servo-hydraulic testing apparatus boasts advanced functionalities, incorporating software such as Bluehill for static and dynamic tests, along with WaveMatrixTM for cyclic block loading. Tests were conducted at ambient temperature to preempt any failure arising from undesired mechanisms. Specimens were subjected to cyclic loads of 1, 2, 10, 1000, and 10000 cycles, encompassing both high and low loads, across the three shot peening intensities.

4. Fatigue Simulation:

After extensive review of the literature, it has been identified that ANSYS Parametric Design Language (APDL) stands out as one of the solvers capable of predicting fatigue life in materials treated and untreated via shot peening processes. Utilizing a 3D finite element model, fatigue analysis is performed. Upon successful verification and validation of the APDL code, it becomes evident that APDL is an effective tool for conducting fatigue analysis within a 3D finite element framework. The fatigue analysis entails simulation using a 3D finite element model to assess the fatigue life of materials subjected to shot peening treatment and untreated materials under external loading. Mechanical properties of the fatigue specimens are kept consistent with those employed in the shot-peened section. In particular, different mesh sizes are used to examine mesh sensitivity in the treated area. With increasing mesh size, the obtained results exhibit increased stability, corresponding to an increased gap between experimental and numerical compressive residual stress profiles observed.

The specimen dimensions depicted in Figure 3 remain consistent throughout the analysis. A total of 6356 elements and 28762 nodes are generated for meshing purposes. Boundary conditions entail the application of varying loads on the surfaces of two specimens—one treated with shot peening at intensity 4-6A, and the other in an unpeened state. External loads are applied to the 3D finite element model (FEM), as illustrated in Figure 3 with red arrows denoting the direction of external pressure or load. The shot peening coverage is fixed at 100%, aligning with standard practices.

Parameters for the shot-peened specimen (4-6A) include a velocity of 60 m/s, shot radius of 0.356 mm, nozzle angle of 90°, and shot peening coverage of 100%. Cyclic loading is administered longitudinally, with a maximum applied stress of 72519 Ib/in^2 and a stress ratio of 0.1. The resulting maximum stress induced on the FEM surface is recorded for both the shot-peened and unpeened models. This process is iterated with different external loading conditions applied to the FEM. Determination of material strength is facilitated by correlating the maximum stress with the standard S-N curve corresponding to the specific material.

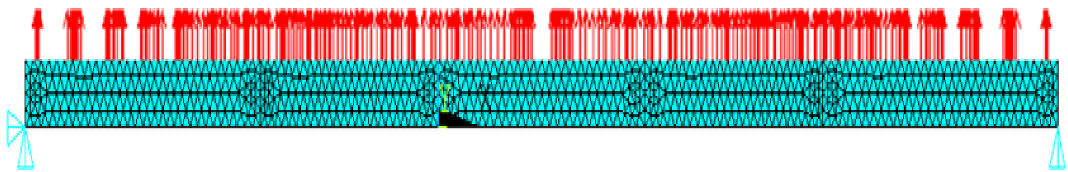


Figure 3: 3D FEM Boundary Condition Applied

5. Result and Discussion:

The shot-peening treatments significantly improved the fatigue life of the samples, as shown in Figure 4, which shows the S-N curve of shot-peened 2024-T351 samples compared to untreated material. This graphical representation clearly shows the improvement in fatigue life achieved by shot peening. In particular, higher shot peening intensities lead to correspondingly higher levels of residual compressive stress. The observed improvement in the fatigue life of shot-peened samples can be attributed to the plastic deformation caused by shot-peening, which subsequently creates a layer of compressive residual stresses on the sample surface. This compressive stress has proven to be advantageous because it effectively reduces the alternating stress acting on the component. This increases the fatigue strength of the sample. The S-N curve that specifically evaluates the fatigue life of samples shot peened at an intensity of 8–10A is shown in Figure 4. This intensity results in the lowest residual stress, suggesting that other intensities have comparable effects on fatigue life due to their higher residual stress compared to the 8–10A intensity. This section presents the results of finite element simulation conducted to assess the effect of shot peening on the fatigue life of aluminum 2024-T351.

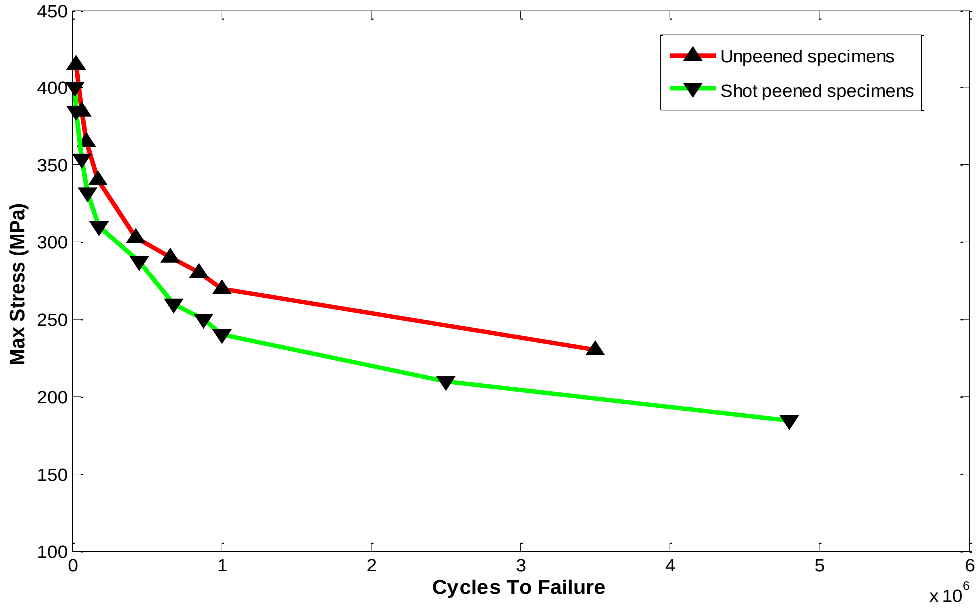
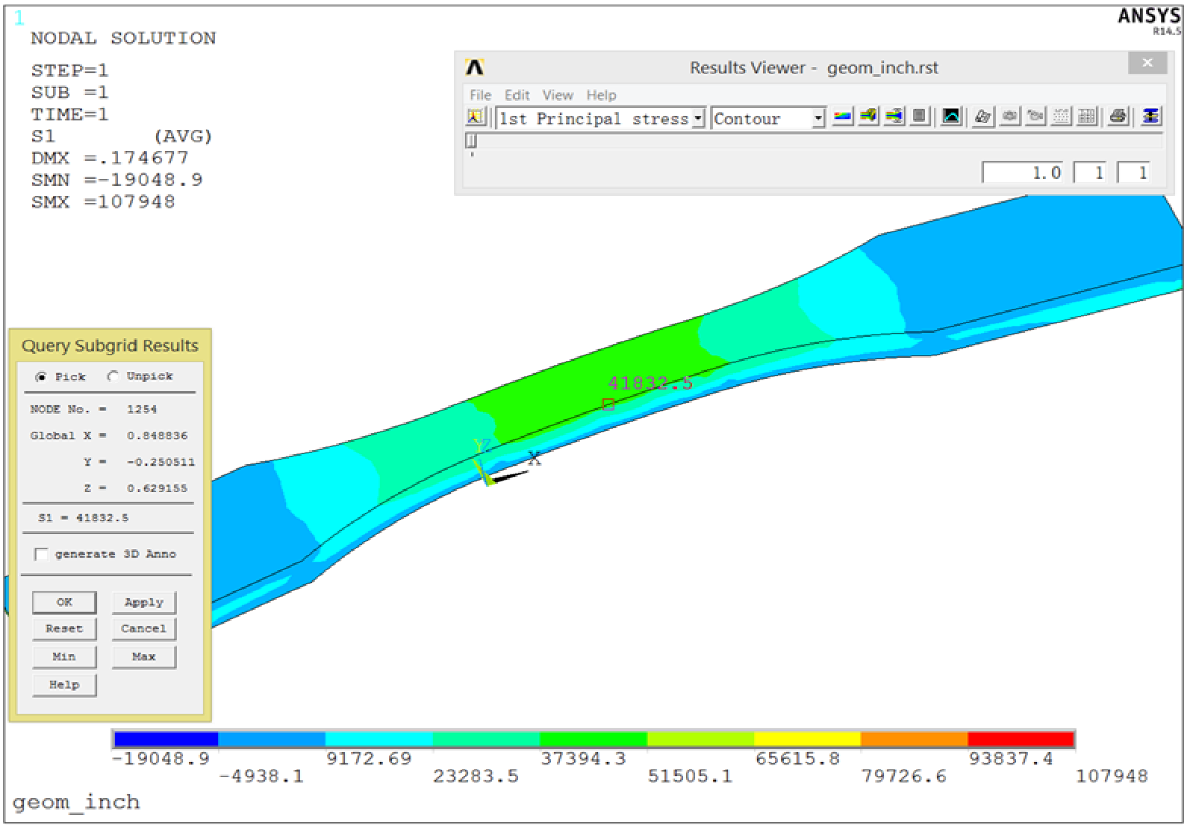


Figure 4: S-N curves for experimental fatigue result for unpeened and shot peened intensity (8-10) specimens with maximum stress 430 MPa for 2024 T-351 aluminum alloy Aluminium Alloy.

A comparative analysis between shot-peened and unpeened materials under identical loading conditions was performed to evaluate stress performance on the material surface. Various pressure levels were applied as external loading in the negative normal direction on the shot-peened surface. Figures 5 (a) and (b) show the simulation results of samples loaded with a maximum stress of 500 MPa. In particular, Figure 5 shows a significant improvement in the fatigue life of the 8-10A blasted component. The fatigue life of peened specimens showed a remarkable improvement of 28% compared to unpeened specimens. This result highlights the effectiveness of the shot peening process in improving material fatigue life by generating beneficial residual stresses throughout the specimen. This beneficial stress serves to impede and delay the initiation or propagation of crack growth on the component surface, consequently decelerating crack propagation rates. Furthermore, the fatigue life of aluminum alloy 2024-T351 can be determined from the S-N curve, which correlates fatigue life with the maximum stress developed on the specimen.

Figure 6 illustrates a notable enhancement in the fatigue resistance of the 8-10A shot-peened specimens compared to the untreated material. The influence of shot peening on the surface resulted in an improvement relative to the untreated material. Under applied cyclic loading, residual stress tends to decrease until failure, with a slight improvement observed in this regard. However, for medium and high cycles, shot peening treatment led to an increase in fatigue life. Overall, under the conditions examined, the shot peening process represents an improvement in the fatigue limit of more than 15% compared to the base material. This improvement is contingent upon the parameters of the shot peening process, with higher parameters such as blasting material, speed and size, which leads to higher compressive residual stress and thus an increase in fatigue life.

(a)



(b)

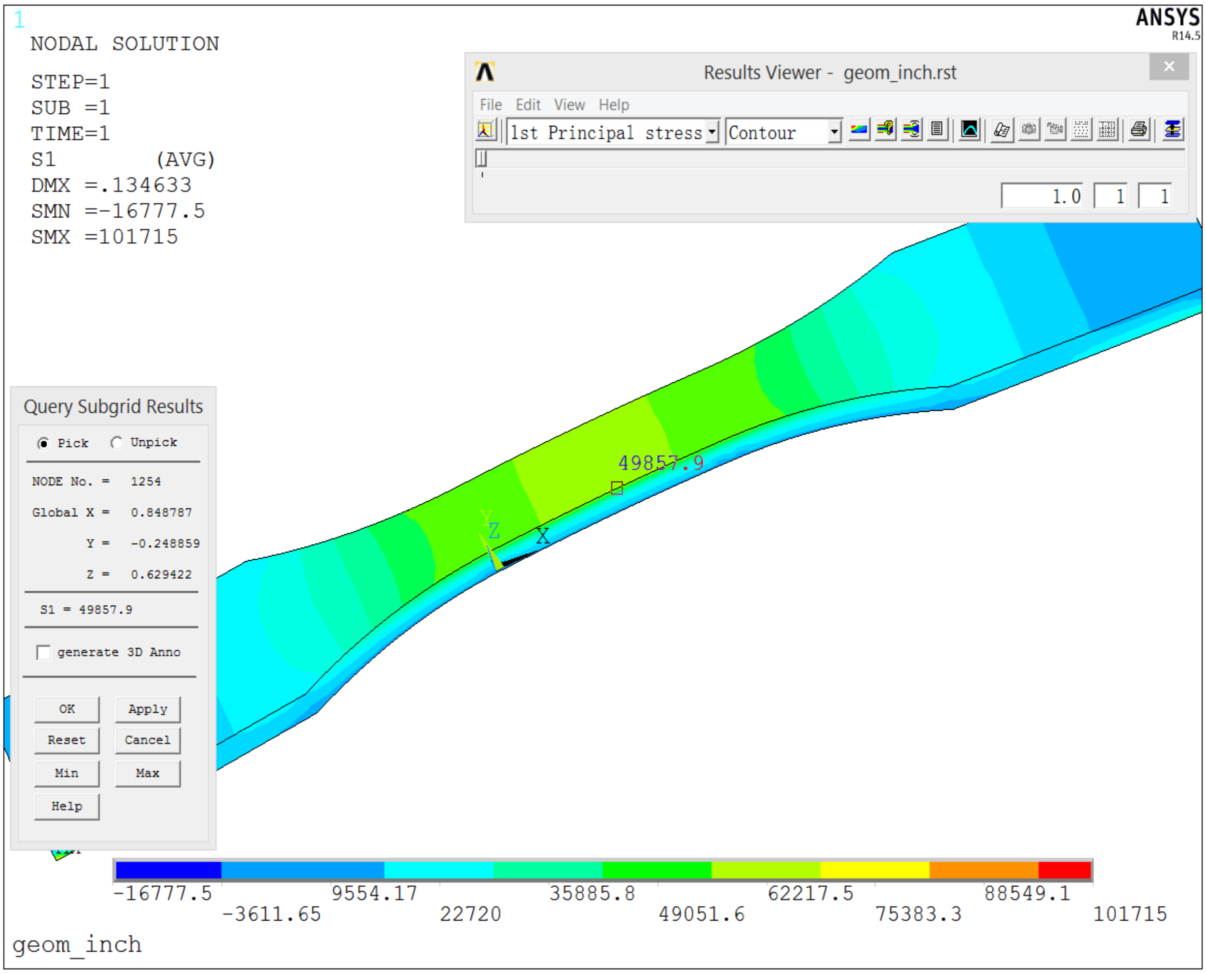


Figure5: The maximum stress develops in the 3D FEM after applied stress of 72519 Ib/in^2: (a) 3D FEM unpeened specimen and (b) 3D FEM peened specimen.

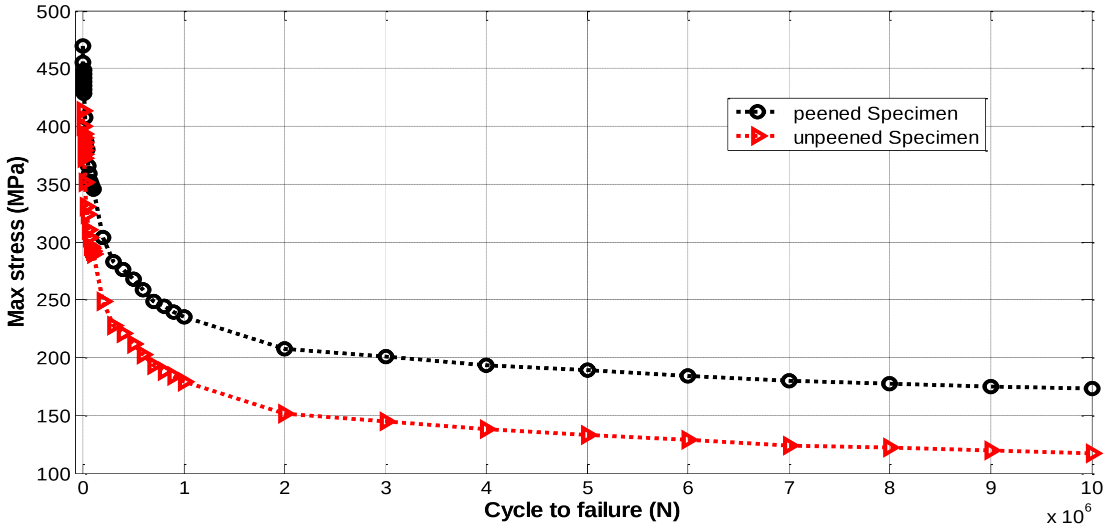


Figure 6: S-N curves for simulation fatigue result for unpeened and shot peened intensity (8-10) specimens with maximum stress 470 MPa for 2024-T351 Aluminium Alloy.

6. Conclusion:

A three-dimensional finite element model was used to simulate the shot peening process, which takes multiple shot impacts into account. In this simulation, a shot peening material model was assigned to the workpiece material, which accounted for the differing shot peening behaviour during initial and cyclic deformation stages. Notably, fatigue crack initiation in unpeened coupons consistently manifested at the specimen surface, whereas in peened coupons, initiation sites were consistently subsurface, likely within regions experiencing compensatory tensile stress. The enhanced resistance to plastic deformation and the presence of residual stress profiles contributed to the closure of fatigue cracks. The compressive residual stress layer also caused the fatigue crack area to be driven deeper beneath the surface. This observation was supported by comparing residual stress profiles obtained from simulations using three different shot peening intensities and cycle load models with corresponding experimental values. Notably, this comparison revealed a high degree of agreement in residual stresses at the specimen surface, validating the simulation results.

References

1. Li, H. X., Bai, Q. L., Li, Y., Du, Q., Katgerman, L., Zhang, J. S., & Zhuang, L. Z. (2017). Mechanical properties and cold cracking evaluations of four 7××× series aluminum alloys using a newly developed index. *Materials Science and Engineering: A*, *698*, 230-237.
2. Pongen, R., Birru, A. K., & Parthiban, P. (2019). Study of microstructure and mechanical properties of A713 aluminium alloy having an addition of grain refiners Al-3.5 Ti-1.5 C and Al-3Cobalt. *Results in Physics*, *13*, 102-105.
3. Zhou, P., Song, Y., Hua, L., Lu, J., Zhang, J., & Wang, F. (2019). Mechanical behavior and deformation mechanism of 7075 aluminum alloy under solution induced dynamic strain aging. *Materials Science and Engineering: A*, *759*, 498-505.
4. Chen, S. Y., Chen, K. H., Dong, P. X., Ye, S. P., & Huang, L. P. (2014). Effect of heat treatment on stress corrosion cracking, fracture toughness and strength of 7085 aluminum alloy. *Transactions of Nonferrous Metals Society of China*, *24*(7), 2320-2325.
5. Chausov, M., Zasimchuk, E., Maruschak, P., Khyzhun, O., Pylypenko, A., Prentkovskis, O., & Brezinová, J. (2021). Influence of impact-oscillatory loading on fatigue life of aluminium alloy 2024-T351. *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering*, 1-10.
6. Han, N., Zhang, X., Liu, S., Ke, B., & Xin, X. (2011). Effects of pre-stretching and ageing on the strength and fracture toughness of aluminum alloy 7050. *Materials Science and Engineering* 528(10-11), 3714-3721.

7. G. da Silva Savonov, M.G.G. Camarinha, L.O. Rocha, M.J.R. Barboza, G.V. Martins, D.A.P. Reis, (2023). Study of the influence of the RRA thermal treatment and plasma nitriding on corrosion behavior of 7075-T6 aluminum alloy, *Surf. Coating. Technol*. 374 736-744.
8. Ye, Z., Liu, D., Zhang, X., Wu, Z., & Long, F. (2019). Influence of combined shot peening and PEO treatment on corrosion fatigue behavior of 7A85 aluminum alloy. *Applied Surface Science*, 486, 72-79.
9. Azarniya, A., Taheri, A. K., & Taheri, K. K. (2019). Recent advances in ageing of 7xxx series aluminum alloys: A physical metallurgy perspective. *Journal of Alloys and Compounds,* 781, 945-983.
10. Chobaut, N., Carron, D., Arsène, S., Schloth, P., & Drezet, J. M. (2015). Quench induced residual stress prediction in heat treatable 7xxx aluminium alloy thick plates using Gleeble interrupted quench tests. *Journal of Materials Processing Technology*, 222, 373-380.
11. Ma, J., Wen, J., Li, Q., & Zhang, Q. (2013). Electrochemical polarization and corrosion behavior of Al–Zn–In based alloy in acidity and alkalinity solutions. *International Journal of Hydrogen Energy*, 38(34), 14896-14902.
12. Ma, J., Qin, C., Li, Y., Ren, F., Liu, Y., & Wang, G. (2019). Properties of reduced graphene oxide for Mg-air battery. *Journal of Power Sources*, 430, 244-251.
13. Davis, J. R. (1993). Aluminum and aluminum alloys. ASM international.
14. Mattson, R. L., & Coleman Jr, W. S. (1954). Effect of shot-peening variables and residual stresses on the fatigue life of leaf-spring specimens. *SAE Transactions*, 546-556.
15. Zaroog, O.S., A. Ali, B. Sahari and R. Zahari (2009), Relaxation of compressive residual stress. Part 1: Relaxation of stage I. *Journal of Scientific & Industrial Research,*. 68(12): p. 1035-1037.
16. Torres, M. A. S., & Voorwald, H. J. C. (2002). An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel. *International Journal of Fatigue*, 24(8), 877-886.
17. Story, J., G. Jarvis, H. Zonker and S. Murtha, (1993). Issues and trends in automotive aluminum sheet forming, *SAE Technical Paper*.
18. Yuan, T., Dou, M., Liu, L., Li, L., Sun, S., & Hu, C. (2023). Improving high temperature fretting fatigue performance of nickel-based single crystal superalloy by shot peening. *International Journal of Fatigue*, 171, 107-563.
19. Meng, X., Leng, X., Shan, C., Zhou, L., Zhou, J., Huang, S., & Lu, J. (2023). Vibration fatigue performance improvement in 2024-T351 aluminum alloy by ultrasonic-assisted laser shock peening. *International Journal of Fatigue*, 168, 107-471.
20. Hu, Y., Cheng, H., Yu, J., & Yao, Z. (2020). An experimental study on crack closure induced by laser peening in pre-cracked aluminum alloy 2024-T351 and fatigue life extension. *International Journal of Fatigue*, 130, 105232.
21. Zhang, M., Li, J., Song, H., & Zhang, S. (2024). Comparative study on the fatigue properties and dislocation evolution of three kinds of aluminum alloys. *International Journal of Fatigue*, 178, 108001.
22. Qin, Z., Li, B., Zhang, H., Wilfried, T. Y. A., Gao, T., & Xue, H. (2022). Effects of shot peening with different coverage on surface integrity and fatigue crack growth properties of 7B50-T7751 aluminum alloy. *Engineering Failure Analysis*, 133, 106010.
23. Kuyucak, S., & Sahoo, M. (1996). A review of the machinability of copper-base alloys. *Canadian Metallurgical Quarterly*, 35(1), 1-15.
24. ASTM, E. (2007). Standard practice for conducting force controlled constant amplitude axial fatigue tests of metallic materials. *West Conshohocken*