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Evaluation Residual Stress Relaxation Induced by Shot Peening Parameters and its Effect on Fatigue of 2024-T351 Aluminum Alloy

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Abstract

Surface treatment such as shot peening are often used to enhance fatigue life of components. The simulation and experimental work has been carried out under variable amplitude tests to three different shot peening treatments of 2024-T351 aluminum alloy. Experiments were conducted on subjected to three different shot peening intensities which on 4-6A, 6-8A and 8-10A and tested under cyclic loading. The cyclic test for tow applied stress amount, 170MPa and 280MPa, was performed for the 1, 2, 10, 1000, 10000 cycles. The maximum relaxation for load of 170MPa is 45% of the initial residual stress at 10000 cycles for intensities (4-6A, 6-8A) while the maximum relaxation for load 0f 280MPa is 53% at 10,000 cycles for the intensity of 4-6A.This result showing that the redistribution of residual stress depended on the amplitude of applied load and shot peened material. Computer simulation was carried out using finite element method (FEM) by ANSYS software to investigate the residual stresses behavior of 2024T351 aluminum alloy. The simulation results showed a good agreement with the experimental results.

Keywords: *Shot peen, Residual stress, Relaxation, Fatigue, Aluminum*

1. Introduction

Shot peening processes introduce residual stress into mechanical parts, which influences part's fatigue behaviour. Sudden failure of products can be attributed to fatigue failure which is directly affected by the level of residual stress in the components. The presence of residual stress in a component can significantly improve or reduce the fatigue life of a product depending on whether the induced residual stresses are compressive or tensile respectively.

In static loading, the true stress in a

component is determined by the residual and applied stresses. If the static loading is compressive and increased continuously, the residual stress delays the time needed to reach the yield strength. However, it accelerates the time needed to reach the yield strength in tensile loading conditions. In general, compressive residual stress increases the usable material life by preventing the crack initiation and propagation from occurring, whereas the tensile residual stress reduces the material life by accelerating the crack initiation and propagation of the components [1-3].

A residual stress usually exists in different materials without the presence of external stresses. There are many causes of residual stresses, such as mechanical process, thermal process, chemical processes and combined processes [4,5]. There are several surface treatments that are used to induce the residual stresses to improve failure of materials. One of the known processes to improve fatigue life is to induce residual stress by shot peening method which leads to a compressive residual stress on the surface layer of metallic components, making the crack initiation, growth and propagation more difficult [6]. Other methods that can be used to induce compressive residual stress may include toughening of glass, cold expansion of holes and quenching of materials [7]. However, shot peening is the most common, flexible and cheap method that is usually used to produce thin components with complex shapes such as shape wing and fuselage skins, in the aerospace industry. The device factors encompass the infeluenceof shot peening velocity, peening time, mass flow rate, nozzle clearance, shot velocity and coverage as presented in Figure1. This process is accomplished by bombarding on the outer layer of materials component at a high velocity that induce plastic deformation layer. The plastic deformation leads to improve layer residual stress field in the involved area. The layer of compressive residual stress introduced could delay the failure and improves fatigue life under cyclic loading [8,9].

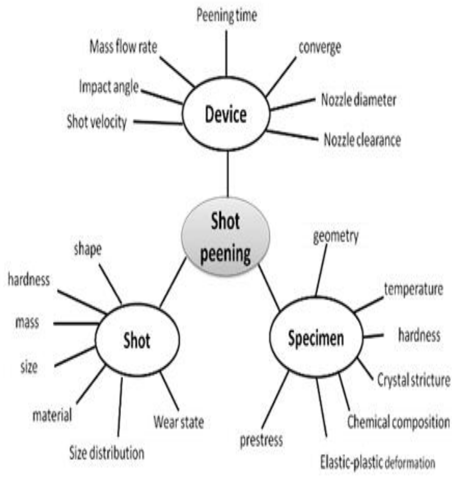

Figure 1: Parameters ofshot peening effecting the performance of shot peening

Many researchers studied the residual stress relaxation under cyclic loading [10-14]. Residual stress relaxation can happen throughout cyclic loading, starting from the first cycle. More relaxation of residual stresses can occur as the cyclic strain range increased until the strain range reaches the elastic strain range.James [15] suggested that there are some form of stress concentration present, such as at grain junctions, dislocation pileups and phase boundaries, which may cause the local stress to exceed the yield point, change the local constraints and thus lead to a stress relaxation. A number of papers [16,17] observed that the long redistribution of the residual stress layer was found in the initial fatigue cycle. Zhou et. al. [18] found a thermal relaxation of residual stress mainly occurs during the initial exposure period (between 10 min to 20 min) for Ti-6Al-4V sheet. Holzapfel et. al. [19] studied shot-peened AISI 4140 steel. The results of the study suggested a proportional relationship between the amount of relaxation and the applied

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stresses.

2. Materials and Methods

This material has been selected for being the standard alloy used to manufacture lower wing panels of the actual generation of large commercial aircraft. This is one of the best known of the high strength aluminum alloy. With its high strength and excellent fatigue resistance, it is used to provide advantage on structures and parts where good strength-to-weight ratio is desired. It is readily machined to a high finish.

This alloy is a solution of heat-treated; control stretched and naturally aged material.

2.1 Experimental Methods

The aluminum alloy specimen was received as 1000 mm in 1000 mm, with thickness of 6.5 mm from Alcoa China in accordance with airbus standard [20], with mechanical properties: material yeid strength of 384 MPa, tensile strength of 448 MPa and an elongation of 2024-T351 aluminum alloy (15%). The chemical compositions of the aluminum alloy specimen asworked are given in Table 1.

Table 1: Chemical Specification of 2024-T351 Aluminium Alloy Specimen (Wt. %)

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

The size of the specimen is with 6.5 mm thickness as shown in Figure2. The samples were cut using low speed cutting progress. The cutting was performed at SN Machinery services. The type of cutting machine used was Computerized Numerical Control(CNC), Electrical Discharge Machining (EDM) wire cut machine, with cutting feed rate 66 m/sec and wire diameter of 25 mm. The precision of the machining was kept at ±0.04 mm

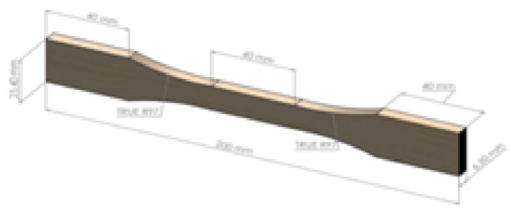

Figure 2: Specimen for fatigue testing (all dimensions in mm)

Shot peening was selected due to its wide use, simplicity, global acceptance and well known process. All specimens were shot peened at GT Industrial PTE LTD; Singapore. The surface flatness of specimens with close tolerance and verified as that shown in Figure 3. The shot peening material treatment applied on surface of specimen depends on a number of factors as size, velocity, shape, angle, and flow rate. The specific steel used for experimental calibration was SAE1070 cold rolled steel and properties are shown Table 2 [21].The relative work done to the surface is called the penning intensity. To measure peening intensity a standard strip called Alemen strip is used in this study.

Table 2: Properties of Shot Peening Steel [21]

Property	**Value**
Maximum tensile strength	640 Mpa
Maximum yield strength	495 Mpa
Modulus of elasticity	201 Gpa
Poison's ratio	0.29
Density	$7.872 *10^3$ kg/m3
Maximum elongation at failure	10%

Figure 1: Image of test specimens after shot peened

It is made from spring steel of carefully controlled quality to a size within close tolerances. It is used in three thickness called strips, the thickest strip is 2.38±0.02 mm and thinnest strips is 1.30 ±0.02 mm. An intensity range was selected since it is S110 cast steel shots to 4-6A, 6-8A and 8-10A Almen intensities. A constant specimen distance from the nozzle of around 120 mm was maintained. Impact angle was 900 and surface coverage was set to 200% and shots diameters were 0.356 mm for three intensities. The velocities were set to 29 m/s, 42 m/s and 60 m/s for intensities 4-6A, 6-8A and 8-10A respectively.

Using XRD to measure the initial and residual stresses after each cyclic load at the longitudinal orientation in middle of the gage length on the width direction at surface of specimens. In addition, measuring the X-ray diffraction residual stress was carried out using a two-angle sine squared- method [18]. This was according to SAE HS- 784 that uses the X-ray diffraction of chromium K-alpha peak from (FCC) structure of the (311) planes of the specimen. The samples were shocked during range of ± 1.50 around the mean psi angles though measurement of the residual stress intensity over more grains structure tominimise the influence of the grain size.

Diffractometer fixturing are parameters shown in Table 3. Moreover, previous the amount of the x-ray elastic constant determination, which is needed for convert from the strain measured the macroscopic residual stress at normal to the (311) planes of peened and unpeened 2024-T351 aluminum alloy.

Table 3: X-Ray Diffraction Residual Stress Measurement Parameters

Item	**Condition**
Incident beam divergence	1.0 deg
Detector:	Scintillation set for 90% acceptance of the chromium K-alpha energy
Power	25 kV and 25 mA
Psi rotation:	10.00 and 50.00°
Plane (Bragg Angle)	(311) set of planes. (Bragg angle: 159°)
Irradiated Area	0.20in×0.20 in (5.1×5.1) mm

2.2 Residual Stress Simulation Procedure

In this section, a finite element method (FEM) was employed to shot peened material which is 2024-T351 aluminium alloy. An FEM-based computer modelling package, ANSYS Parametric Design Language (APDL) was employed for the analysis. Basically, the code is developed by combining many of analytical solution to executed data of shot peening to the finite element model in ANSYS Mechanical APDL. The mesh format of 3D-FEM is set-up to 6356 elements and 28762 nodes as shown as shown in Figure 4. The mechanical properties of shot peening material and aluminum material as shown in Table 4.

The specimen was subjected to a fully developed shot peen and then a constant surface pressure will be applied to the part putting the surface layer in tension. In order to prevent rigid body motion and to obtain a deformed shape having two symmetry planes, the following multiple point's constraints were

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implemented along (z) = (0, w/2, 0), where L = 200 mm, w = 14 mm. The initial stress and nodal displacements obtain from program were transferred to displacements simulation model.

Table 1: Mechanical Properties Of Shot Peen And Specimen Material

Property of shot peen material	**Value**	**Property of specimen material**	**Value**
Density of the steel shots S110 (ρs)	7872 kg/m3	Density (ρt)	2800 kg/ m3
Modulus of Elasticity (E)	201 GPa	Elastic Modulus (E)	210 GPa
Poisson's ratio	0.29	Poisson's ratio	0.31
Yield Strength (ρy)	495 MPa	Yield Strength (ρy)	379 MPa

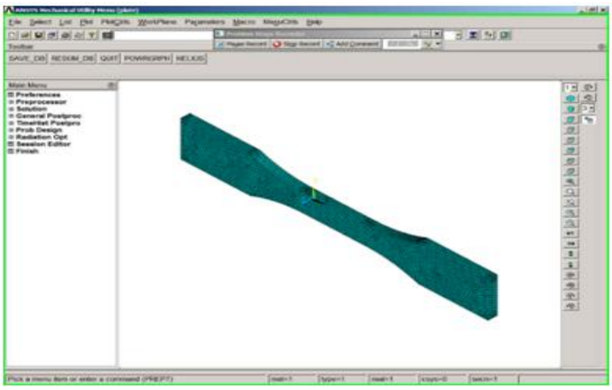

Figure 2: 3D of shot peening specimen meshing

Then, the model was subjected to three velocities $\upsilon 1$ = 20.32 m/sec, $\upsilon 2$ = 22.86, $\upsilon 3$ = 25.4 with S110 steel shots (D = 0.356 mm) and coverage 100%.

3. Results and Discussion

Result of finite element simulation of fatigue shot peened and unpeened of aluminium alloy 2024-T351 is presented. The Figure 5[(a) and (b)] shows the simulation results of the specimens which is loaded under maximum stress of 500 MPa. From results considerable improvement in the fatigue life of 8-10A peened component was observed. Fatigue life improved of peened specimens its reached 28% of 8-10A shot peening intensity with compered with unpeened specimens. It can be said that the shot peening process is able to improve fatigue life of the material by creating the beneficial residual stress at all sides on specimen. The material improvement that's depended on shot peening condition. However, higher shot peening parameters (shot material, velocity, size) resulting high compressive residual stress to improve fatigue life. From this result, it can be said that the shot peening process is able to improve the fatigue life of the material by creating the beneficial residual stress at all sides on specimens.

To simulate residual stress relaxation, three initial values of axial residual stress at the surface were chosen as same as in the specimen, was evaluated by X-ray measurements which on, -166±10 MPa, of 4-6A, -180±12 MPa for 6-8A and -195±13 MPa for 8-10A.

For an applied stress of 170 MPa observed the compressive residual stress exhibited redistribution of 33% after the initialcycle.Usingthe intensities of 4-6A, 6-8A and 8-10A of was observed that the residual stress relaxation reduce to 55.35MPa (33%), 58.05 MPa (32.24%) and 55.77 MPa (28.59%) respectively after the first cycle as shown in Figure 6.

For an applied stress at experimental result of 170 MPa, it was observed that the residual stress exhibited relaxation of -59 MPa (35%) after the first cycle. This is in comparison to the early compressive residual stress observed under intensity of 4-6A.

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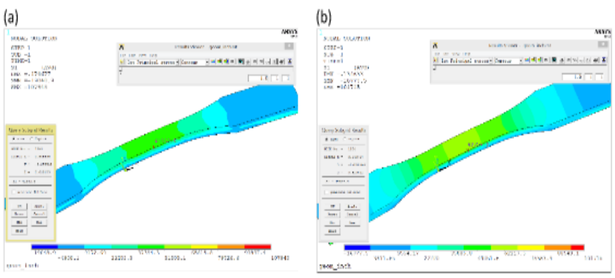

Figure 3: The maximum stress develops in the 3D FEM after applied stress of 72519 Ib/in2: (a) 3D FEM unpeened specimen and (b) 3D FEM peened specimen

After 2 cycles, it was observed that the initial residual stress relaxed by -63 MPa (37%), -67 MPa (37%), and -72 MPa (36%) given the shot peening intensities of 4-6A, 6-8A, and 8-10A, respectively. Upon measuring on the 10 cycle, it was observed that the residual stress relaxed at levels of -65 MPa (39%), -70 MPa (38%) and -74 MPa (37%), given the shot peening intensities of 4-6A, 6-8A, and 8-10A, respectively.

At the 1000 cycles, it was observed that the initial residual stress relaxed by -70 MPa (42%), -75 MPa (41%), and -80 MPa (39%) given the shot peening intensities of 4-6A, 6-8A, and 8-10A, respectively. Initial residual stress for 10000 cycles, was observed to have relaxed by -75 MPa (45%), -82 MPa (45%), and -85 MPa (43%) for shot peening intensities of 4-6A, 6-8A, and 8-10A, respectively.

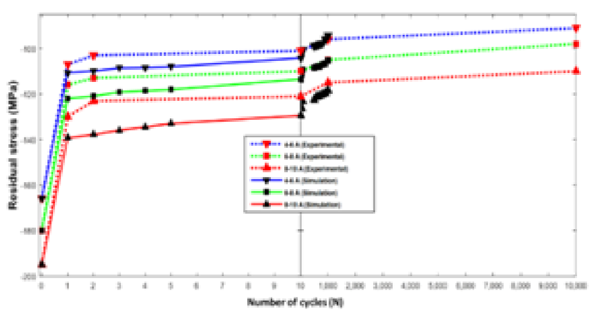

Figure 6: FE prediction and experimental result of residual stress relaxation with different number of cycles for applied stress 170 MPa

and three different shot peening intensities (4-6A, 6-8A, and 8-10A)

At simulation result, after initial fatigue cyclic load, redistribution of compressive residual stress for 280 MPa applied stress reached -98.65 MPa (46% ± 7) of first compressveresidual stress for intensity of 4-6A and -108.74 MPa (44% ± 6) and -120.34 MPa (43% ± 6) for shot peening intensities 6-8A and 8-10A respectively as shown in Figure 7.

At experimental result, after initial fatigue cyclic load, redistributionof residual stress for 280 MPa applied stress reached -66 MPa (39%) of first compressveresidual stress for a shot peening intensity of 4-6A, -66 MPa (36%) for shot peening intensity of 6-8A, and -78 MPa (40%) for shot peening intensity of 8-10A.

For the shot peening intensity of 4-6A, the initial relaxation of residual stress reached to be at -73 MPa (43%), -80 MPa (48%), -86 MPa (51%), and -88 MPa (53%) for cyclic loads of 2, 10, 1000, and 10000, respectively. The initial relaxation of residual stress relaxation for the medium intensity of 6-8A is -70 MPa (38%), -81 MPa (45%), -88 MPa (48%) and -95 MPa (52%) for the cyclic loads of 2, 10, 1000, and 10000, respectively.

The initial residual stress relaxation for the specimen intensities of 8-10A is -84 MPa (43%), -88 MPa (45%), -92 MPa (47%), and -97MPa (49%) for the cyclic loads of 2, 10, 1000, and 10000, respectively.

The large relaxation induced after first cycle when applied high load (280 MPa) with low intensity 4-6A reached 40% of initial residual stress. After second cycles the relaxation talked liner relation between the applied maximum stress of (170 MPa and 280 MPa) with certain number of cycles (after second cycles) of three shot peening: 4-6A, 6-8A and 8-10A.

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The relaxation value for three intensities with applied two loads from second cycles loading to 10,000 loading cycles was found to be in the range of 5–8% of the initial compressive residual stress. From each intensity, one specimen was made to cycle up to failure. After failure, residual stress measurements were performed on the tested specimens.

This was done in an area that was far enough from the fracture surface (about 3.5 mm). Doing so helped to avoid the alteration of the residual stress field. The result indicated that the relaxation had a slight variation compared to the value obtained at 10000 cycles. Residual stress redistribution follows when the superposition of the applied strain and compressive residual stresses to be exceeds the yield stress. Greatest the redistribution of the shot peening for two cyclic loads (170 MPa and 280 MPa) obtained in initial cycle. It was found that the redistribution at cyclic load of 280 MPa was larger than the redistribution at cyclic load of 170 MPa. Thus, the redistribution of compressive residual stress that followed in the initial loading cycle improved with improving load due to quasi-static redistribution results.

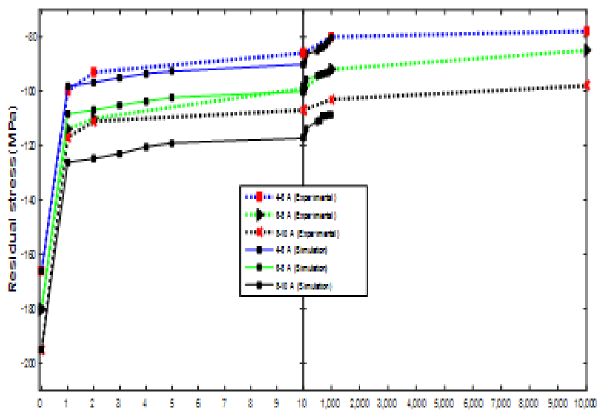

Figure 4: FE prediction and experimental result relaxation of residual stress with different cycles number of cycles for applied stress 280 MPa and three different shot peening intensities (4-6A, 6-8A, and 8-10A)

4. Conclusions

This study presented the residual stress relaxation in 2024T351 aluminium alloy that was to investigate experimentally and numerically by varying specimen intensities owing to cyclic loading. In this study, the relaxation was divided into two stages, the first few cyclic and the subsequence cycles. This was induced by various shot peening intensities due to cyclic loading.

The simulation and experimental results increased fatigue strength after shot peening treatment due to the compressive residual stress ability to influence fatigue crack initiation.

For the first cycle load relaxation, the experimental maximum relaxation was found to be 39% of the early residual stress that was measured after the initial cyclic load, given an applied load of 280 MPa and shot peening intensity of 4-6A. Later, the first cyclic load, however, the minimum compressive residual stress relaxation among the three different intensities (4-6A, 6-8A, and 8-1A) was found to be 33% of initial residual stress. This was under a given applied load of 170 MPa and a shot peening intensity of 8-10A.

The good agreement result measured by the X-ray method for all residua stress specimens at two loads (170 MPa and 280 MPa) and three shot peening intensities with predicted result established in this study indicates that the application of residual stress analytical prediction methods to finite element analysis was successful.

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