International Journal of Pure and Applied Mathematics
Volume 118 No. 24 2018
ISSN: 1314-3395 (on-line version)
url: http://www.acadpubl.eu/hub/
Special Issue
http://www.acadpubl.eu/hub/

Experimental and finite element modeling of residual stress relaxation under cyclic load of aluminium alloys: Review

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March 30, 2018

Abstract

The compressive residual stresses, which were induced as a result of the shot peening techniques, increased the fatigue life of the component. The initial residual stress was relaxed during the components operational life and considering the stress relaxation within the design, is very important. Particularly, the cycle-dependent fatigue stress was influenced by the component residual stress. Therefore, an accurate monitoring of the stress would help in maintaining safety and for predicting the repair duration and the product life. Residual stress in the subsurface of the material can be determined with the help of non-invasive and popular methods like the X-ray diffraction technique. When the residual stress relaxation trends were compiled for different materials, it was observed that the highest relaxation occurred at the end of the first cycle with small amounts occurring for the subsequent cycles.

***Key Words*:**Shot Peening; Surface Treatment; Residual Stress; Relaxation; Aluminium Alloy; X-ray Diffraction; Fatigue.

1 Introduction

The fatigue resistance can be considerably improved by the shot peening technique which imparts better compressive residual stresses in the material subsurface to reduce the nucleation and the propagation of the fatigue stress cracks(1, 2). The shot peening technique is a surface impact technique that is repeated multiple times. In this process, hard spherically shaped shots are air-blasted against the surface of the components critical surface(3, 4). This caused an indentation on the surface which is due to the local elastic plastic deformation that occurs on the material surface.

The formation of indentations by shot peening depends on several factors like the nozzle pressure, hardness, size, and the shot angle against the specimen layer. These process variables or factors are integrated to constitute the Almen Intensity (5-8). The shot intensity is estimated by the Almen strips and the Almen gage. These strips are manufactured from SAE1070 spring steel and they have been classified based on their thickness into three types - "N" strips for lower intensity, "A" strips are for an average intensity and the "C" strips for higher shot intensity. These strips are the basic standards for quality control. The residual stress refers to the stress that is present in the structure of the component without the application of external loads(9-11). In the case of the surface treated materials, the residual stress is self-equilibrating and the residual stress profiles depend on the type of material and the treatment method that is applied. However, the favourable compressive residual stress that is imparted by the shot peening method is generally exposed to the mechanical and the thermal loads, hence, the stress gets partially or completely relaxed during the fatigue life(12-21). The distribution of the residual stress is affected by several factors of the mechanical surface treatment like changes in the SP parameters, which include material hardness (Hm), shot hardness (Hs), shot velocity (V) and the coverage (C), which have been depicted in Fig.1. Technically, the residual stresses are relaxed if the superposition of the applied and the residual stress reach the material yield point. Several reports have stated that the relaxation of residual stress is a very complicated process that depends on the interaction of parameters like the loading mode, amplitude of applied cyclic stress, the cycle number, material characteristics and surface finishing procedure. As the stress relaxation is related to the dislocation motion, it is associated with the accumulation of plastic strain with the cycle number. Generally, most of the stress relaxation occur in the initial few cycles and is followed by the minimal relaxation for the successive cycles (22-26).

In a published report, the authors measured the residual stresses and the cold work distribution using an automated X-ray diffraction method Prevey et al.(27). This technique helped in the measurement of the residual stress by measuring the peak shift in the X-ray diffraction profile, which results in the changes in the material lattice space which are present as a result of the residual elastic strains (or stress). Additionally, this technique measures the widening of the X-ray diffraction peak for quantifying the degree of the cold-work present in the matter.

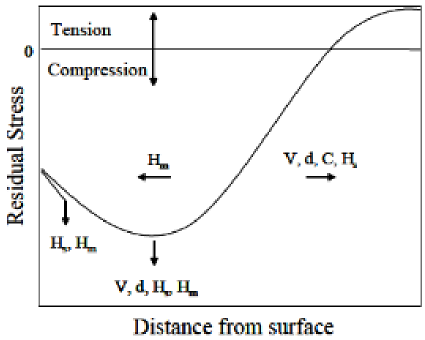

Figure 1. Shot peening parameters vs. residual stress distribution (28) (V = shot velocity, d = shot size, C = coverage, Hs = shot hardness, Hm = material hardness).

2 Literature Review

2.1 Shot peening

Many researchers have published their reports regarding the numerical and analytical study of the single shot impact on the components. Though there has been an increase in understanding the basics of shot peening, the impact of single shots on the component is still not understood. Moreover, the factors and the residual strain features are also not understood clearly.

The process of shot peening causes a plastic local deformation in the surface of the layer, which introduces residual stress in the layer (29-31). Many reports have stated the increase in fatigue strength for the shot peened parts (32-36). This depends on the process variables like nozzle pressure, shot size, shot flow rate, impingement angle, and the distance of the nozzle from the surface of the specimen. These variables are incorporated in the Almen intensity. Studies (30, 31, 37-40) have illustrated the benefits of the shot peening process on the various grades of the aluminium alloys.

Several studies have been reported in the literature which measured the fatigue life, residual stress distribution, and the shot influence, along with the component and the process factors. Some experiments focus on the impact of the single shots on the components(3, 41). In his study, Al-Hassani(42) carried out the dynamic tests and tests for measuring the single steel ball static indentation. Also, Mori et al(41). Conducted dynamic analytical tests by shooting single shots from a particular height on a metallic plate. The diameter and the impact speed of these balls were 40 mm and 12.2 m/s in the study by Mori et al. and 50 mm and 6.3 m/s in the study by Kobayashi et al(3). Mahagaonkar (43) stated that the shot peening technique induced a plastic local deformation in the surface of the exposed layer and hence, introduced compressive residual stress, in the layer. His study also described an improvement of the fatigue strengths for the shot peened parts. This depended on the process variables like nozzle pressure, shot size, shot flow rate, impingement angle, and the distance of the nozzle from the surface.

Hiroji and Etuichi (44) studied the impact of the different peening conditions on the fatigue strength of the carburised steel. They conducted their experiments on the SCr420H material. Shot peening was carried out on the steel by varying the shot velocity, projection density, hardness and they observed that the fatigue strength varied between 113- 141 % when compared to the unpeened material.

In their report, Kobayashi et al(3) stated that the shape of the indentations and the residual stress distributions that were caused by the static compression differed from those that were caused by the dynamic impacts. The parameters applied in (3, 41, 45), are different from the actual peening factors and the observed results could not be compared directly to the shot peening applications. Miao et al(46) examined the quantitative relationship between the surface coverage, saturation, and roughness in relation to the shot peening time using the aluminium Al2024 strips. He observed that the compressive residual stress have a positive effect and improve the component fatigue life after shot peening, but the surface roughness had a negative effect(47, 48).

In their study, Ali et al(34) reported that by using the shot peening technique, they were successful in improving the fatigue life of an aircrafts friction-stir welding joints made from the 2024-T 351 aluminium alloy. However, he stated that the major problem was that the first residual strain field which was inherent or incorporated in the final product would become unstable during the components operational life.

Kirk and Abyaneh (49) conducted a study for explaining the variation of the coverage for the shot-peened specimens with respect to time and the multiple impacts. They deduced that the small areas present near the dimples which are not affected by shot peening did not indicate that they were the 'weak points' present in the peened surface i.e. they stated that the not dimples, but the deformation zones below or surrounding the dimples generated the compressively stressed areas. Mylonas et al(50) also studied the treated or the shot peened materials and developed a 3-D numerical model. He carried out his analysis using a high strength AA7449-T7651 Aluminium alloy plate for carrying out the shot peening. The author conducted the multiple shot study for his analysis. After validating the numerical models, the author carried out a parametric test for creating a residual stress database that would help in the selection of process parameters for different types of shot peening materials. This database helped to develop the numerical model which stimulated the distortions of the thin sheets. He carried out the parametric study by using the previously presented shot patterns, which included 4 types of shots (S110, S230, S330 and S550), with varying shot velocities which ranged between

20 - 100 m/s and the shots were fired from two different impinging angles of 75° and 90°. Fig. 2 describes the maximal compressive stress that was calculated for these four types of shots and the two impinging angles plotted against the shot velocity. It can be observed that the maximal residual stress increased with an increase in the shot velocity for all of the studied cases. The test results depicted that the residual strain also increased with the shot size but was not affected by the angle of impingement.

In Fig.3, we have described the residual profiles which have been predicted numerically and compared them to the experimental data using a common stainless steel and aluminium alloy of the 2000 series. In their experimental study, Yu-Gao et al(51) studied the Compressive Residual Stress Field (CRSF) which was induced by the shot peening technique on the 40Cr steel. Initially, they prepared the specimen samples of ϕ 30 mm $\times$ 50 mm, which they tempered at the temperatures of 200°C, 400°C, 550°C and 650°C for 2 hours. The shot peening technique was conducted using an air-blasting machine using the cast steel shots having a hardness of 50-60 HRC. In their study, the authors used around 60 different heat treatments and peening settings. They applied the strain diffractor meter and used the Cr Ka radiation and the sin2Ψ method. An air pressure ranging from 0.2-0.6MPashot diameter of 0.5-1.10 mm, and a shot peening coverage rate ranging from 100-600 pct, was used in the study. According to their results, they stated that the maximal CRSF for any material is similar despite the various shot peening methods used and the surface residual strain values depend on the materials mechanical properties and the shot peening factors used for the study.

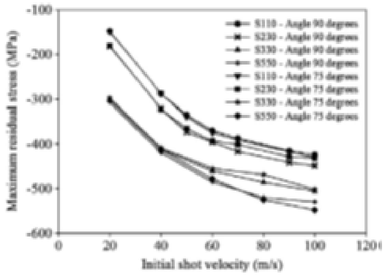

Figure 2. Maximum compressive residual stress computed for different velocities; shot types S110, S230, S330 and S500, and

impinging angles of 75° and 90°.

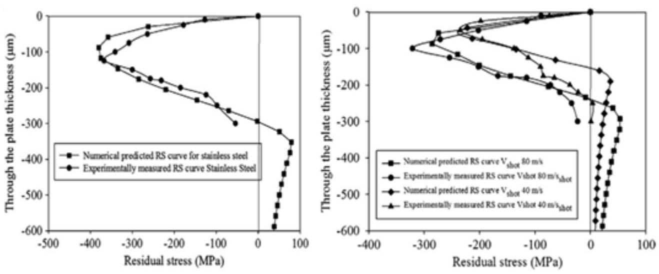

Figure 3. Numerically predicted RS curves versus experimental for stainless steel and aluminium alloy 2xxx series.

2.2 Residual stress measurement

There are numerous methods for determination of the residual stress like X-ray diffraction(52, 53), neutron diffraction(54-58), surface and deep hole drill(59-61), boring(62, 63), slicing(64-66), and magnetic techniques(67). Out of these techniques, the neutron diffraction method is able to establish the stress present in the components interior in a non-destructive manner. The non-destructive technique has the advantage of conducting a fatigue study on the samples, which have been measured for their residual stress. Moreover, any introduction of the residual stress in the life of the material can be measured after re-estimating and conducting further experiments(68, 69). The technique of X-ray diffraction(70)is another non-destructive method which allows for the determination of the residual stress near the surface layers of any material. The X-ray beam probes the sub-surface of the matter, which is ten micrometers thick. Hence, this technique is ideal to determine the residual stresses present in the thin steel plate surfaces. Kodama(22) examined the residual strain relaxation on the shot peened surfaces using the X-ray diffraction methods. He suggested the linear logarithmic reduction relationship between the residual stresses and the load cycles after the initial cycle was similar to the logarithmic law(19, 71, 72).

According to Han et al.(73), when the residual stress present in the 0.7-mm-thick and 0.03%C cold-rolled steel plates, was measured using the Cr-K characteristic X-rays, then, the 2-sin2Ψ diagram exhibited good nonlinearity. This decreased the accuracy and reliability of the residual stress calculation by using the X-ray diffraction technique. Additionally, Shiraiwa et al(74). observed that when the 0.08%C cold rolled steel plate, with a thickness of 4-mm, underwent elastic strain, then, the 2-sin2Ψ diagram which was obtained using the Cr-K X-rays characteristics displayed nonlinearity resulting due to material anisotropy. In their study, Kurita et al(75) suggested the stress measurements for the textured materials using X-rays. The 2θ -sin2Ψ diagrams obtained by the X-ray estimations made 7 Ψ angles by using the Cr-Kα X-ray characteristics. The gradients of the 2-sin2Ψ diagrams along with the X-ray stresses are estimated using the least squared method and complex statistical techniques(76, 77) Hence, this technique requires several Ψ values and complex processing of data. Hong(78) proposed the numerical model and studied the relation between the shot peening factors and the residual stress by using the finite element study. Frija(79) discovered a good relationship between the residual stresses that were observed by the X-ray diffraction technique and the FEM model.

2.3 Residual stress relaxation

The redistribution and relaxation of the residual stresses take place when the sum of the residual and the applied stress values resulting from the mechanical loads exceed the material yield condition(80-83).The residual stress behaviour during the fatigue is of wide interest to the researchers. Numerous material and load combinations have been studied and relaxation models are proposed. Several years ago, Mattson and Coleman(84) had observed the cyclic residual stress relaxation, as depicted in Fig.5. In spite of the limited compressive residual stress relaxation, the authors observed some beneficial effects of stress relaxation on the fatigue life of the component. They stated that the values for the fatigue lives were lesser than the predicted values if the residual stress relaxation is not considered. In Fig. 6, a schematic diagrammatic representation for the tensile (stretching) cold working effects on the total yield strength has been depicted. It can be seen that though the increase in the tensile cold working effect leads to an increase in the tensile yield strength, the initial local compressive yield strength is actually decreased. It is seen that, the higher the tensile cold working, the lesser the compressive yield strengths. This is called as the Bauschinger effect. As the compressive yield strength gets lowered, the tendency to cyclically reduce the primary compressive residual stresses increases.

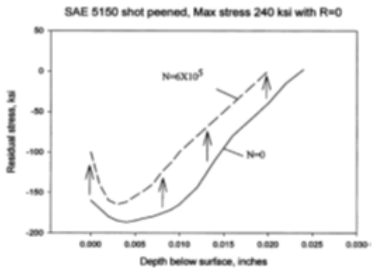

Figure 4. Residual stress relaxation before and after cyclic loading(84)

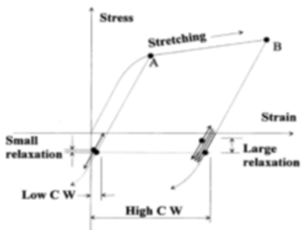

Figure 5. High/low cold work effect on residual stress relaxation

Then, after many years, in his report, Walker et al.(85) stated the residual strain and the dislocation density progression on the rolled mild steel EN3b (Fig. 6). It can be observed from these studies that there is a relation linking the residual strain relaxation activity to the material microstructure/dislocation density. Furthermore, Han et al.(86) discovered that the residual strain relaxation for the initial loading cycle was quite large and this value decreased for the successive loading cycles. Moreover, Morrow and Sinclair (87)developed a relation between the load cycle and the mean stress which is dependent on the stress-controlled fatigue analysis. A similar exponential function was also suggested by Jhansale and Topper (88).

In his study, Al-Obaid (89), evaluated the residual stress distribution in the material and suggested several theoretical expressions for the process variables that were dependent on a novel model for the spherical cavity expansion. He concluded in his study that there was a huge amount of knowledge which is yet to be discovered and scientists have only entered the research area of the shot peening mechanics. James (90) suggested a model for studying the relaxation of stress based on the effectual shear stress which acts on the primary slip planes that are oriented with an angle to the surface. Iida and Takanashi(91) discovered that the relieved strain which was resultant of the repeated cyclic loadings had a higher value than the stress caused due to reversed cyclic loadings. Kodama (22) stated that the relaxation of residual stress in the case of the annealed mild steels linearly varied to the log of the fatigue cycle whereas the relaxation rate was observed to be proportional to the strain amplitudes. Also, Farrahi et al.(92) observed that the fatigue stress resulted in a reduction of the residual stress and the micro strain for the spring steel samples. The decrease was a function of the stress applied along with the height of the plastically deformed layer. Nevertheless, the residual stress was still compressive after the final fracture.

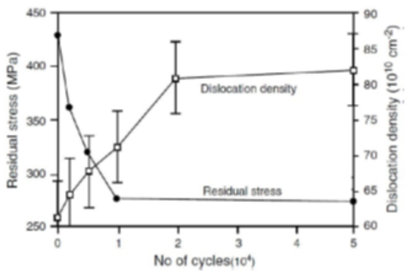

Figure 6. Effect of cyclic loading at 250MPa on surface residual stress and dislocation density on rolled mild steel EN3b(85).

3 Methodology and modelling of residual stress relaxation

The modelling of the compressive residual stress field (CRSF) that is caused after shot peening can be carried out in two ways. The first method involves the numerical methods like the finite element, which due to a rapid advancement of computational skills, have been effectively used for the analysis of the process(93-95). The second technique involves the empiric models which are dependent on the experimental results(96, 97).These types of methodologies would help in the calibration and validation of the model predictions. Researchers are focusing more on the development of better prediction models for fatigue life which incorporated the residual strain effects (15, 98-100).

Al-Hassani (101) carried out the numerical simulations of the single and the multi-shot impacts which confirmed that the non-linear work hardening and the dependency of the material strain rate impacted the residual stress profiles and the degree of the surface hardening. For the quantification of the cyclic residual stress relaxations, Morrow and Sinclair(87), carried out the strain-controlled fatigue analysis and then suggested a relation between the mean stress and the load cycle, which is described as:

$$\frac{\sigma_{mN}}{\sigma_{m1}} = \frac{\sigma_y - \sigma_a}{\sigma_{m1}} - \frac{\sigma_a}{\sigma_y} \log N \quad (1)$$

where σ_{mN} refers to the mean stress present at the Nth cycle, and σ_{m1} refers to the mean stress present at the first cycle, σ_a refers to the alternating stress amplitude, σ_y= material yield strength, b is the constant which is dependent on the softening of the material and the applied strain range,$\Delta\epsilon$. The Eq.(1)cannot be applied to the load ratio,R$\neq$-1 as the surface residual strain is similar to the mean stress only if the material has been subjected to complete reversed loadings. Eq. 1 supported the experimental data for the values of N$> 10^6$ and$\sigma_{mN} < 20$ MPa . In his study, Han et al.(86) suggested a linear reduction of residual strain as a function of the cycle number, N, which is described as:

$$(\sigma_{res})_{relax}/(\sigma_{res})_{1cycle} = N^k \quad (2)$$

where;$(\sigma_{res})_{relax}$ refers to the residual stress relaxation, $(\sigma_{res})_{1cycle}$ refers to the residual stress for the first cycle and the factor, k depends on the material softening and the applied stress.

However, Zaroog et al(102) stated that based on the observed data, the rate of relaxation would increase with an increase in the loads and is influenced by the shot-peening intensity. A model fit for the relaxed residual strain versus the cycle number indicated that the residual stress relaxation was a function of the exponents of the cycle number, and the general equation is described below:

$$\sigma_N^{re} = R\sigma_0^{re}(N)^c \tag{3}$$

where σ_N^{re} referred to the residual stress relaxation for the cycle,N ,$\sigma_0^{re}$was the initial residual strain, R= constant, C= relaxation exponent on the load applied and the shot peening intensity. The relationships between the mean strain and the load cycle for the quantification of the cyclic relaxation of residual stress was proposed by Jhansale and Topper(88), and is described as follows:

$$\sigma_{mN} = \sigma_{M1}(N)^B \tag{4}$$

where B = relaxation exponent based on the softening of the material and the applied stress range.

The residual stress reduction on the shot peened surface was measured by the X-ray diffraction techniques suggested by Kodama(22) and he proposed the logarithmic linear relation between them as follows:

$$\sigma_N^{re} = A + m \log N \tag{5}$$

whereσ_N^{re} = surface residual strain after the N cycles, A and m= material constants that depend on the stress amplitudes, σ_a.

Zhuang and Halford(103) proposed an analytical model for estimation of the relaxed residual stress using the finite element technique. This model was successful in the prediction of the stress relaxation for R=0 and R=-1 and the values were very near to those calculated by the finite element technique. This model incorporated the effect of the primary cold work in the equation used for predicting the residual stress relaxation and is described as follows:

$$\frac{\sigma_N^{re}}{\sigma_0^{re}} = A(\frac{\sigma_{max}\sigma_a}{(C_w\sigma_y)^2})^m(N-1)^B - 1 \tag{6}$$

where C_w refers to the parameter that accounted for the degree of the cold working. Moreover, the material constant, m, is dependent on the cyclic stress and the strain response, whereas the constant, A, also depends on the cyclic strain and the stress response. B, controlled the relaxation rate as compared to the loading cycle, while,σ_0^{re} referred to the initial residual strain. The finite element technique is a great method for simulation of the shot peening technique and for the estimation of the residual stress relaxation. The appropriate finite element method takes into consideration the dynamic impact of single or the multiple high-velocity shots and the double non-linearity problem that occurs when the two bodies come into contact and the elastic-plastic local behaviour of the components. Hardy et al.,(104) initially, studied the problem of the contact of the sphere shot which created an indent in the elastic local plastic half space using the finite element technique.

Edberg et al. (105)first suggested the finite element analysis for the shot peening technique with the help of the commercial FE software, DYNA3D. Meanwhile, the analysis for the residual strain distribution for the shot peening technique was carried out using the dynamic elasticplastic finite element analysis method that was developed by Al-Obaid(106). Meguid et al.(95) proposed a 3-D finite element model for the dynamic single and double impact shots using the metallic targets and rigid spherical shots. The authors evaluated the impact of the shot size, velocity, shape and the target features for the residual strain distribution in the materials. They observed that the impact of the shot factors was greater as compared to the materials strain-hardening rate. Several reports have used specified numerical values for the model factors so it becomes difficult to understand the impact of every factor on the stress distribution developed after simulation.

4 Result and conclusion

Shot peening technique helps in improving the material fatigue life as seen in the case of the aluminium alloy components under optimised conditions, or appropriate results cannot be obtained and it could even result in unfavourable results. Moreover, the beneficial effects of the shot peening technique are better for longer fatigue lives as compared to the shorter fatigue lives. The bigger shots produced more residual surface stress in the specimens than the smaller shots, whereas the smaller shots were more effectual than the large shots. Moreover, the distance of the nozzle from the surface did not affect the intensity greatly, while the media flow rates were inversely proportional to shot intensity. The Almen intensity also increased with an increase in the media size. The optimal shot peening intensity for the aluminium alloys ranged between 8- 13A.

As the shot peening technique depends on several parameters, it is difficult for determining the best conditions for increasing the fatigue strength. The shot peening intensity which produced best results for fatigue life depended on many parameters like the surface conditions which were created after shot peening; relaxation of the induced compressive stress produced in the fatigue procedure; and the probability of the compressive residual stress field causing the development of cracks below the material surface. The compressive residual stress is determined using techniques like X-ray diffraction or the neutron scattering and is simulated using the finite element method or the boundary element method, which enables the quantitative analysis of the fatigue and fracture. The residual stress reduces by the amount which depends on the value of the load amplitude. The quasistatic relaxation effects caused the decrease of the residual stress which took place in the initial loading cycle. In the successive cycles, the gradual stress relaxation was collected from every cycle and the relation between the relaxation of the residual strain and cycle number was a logarithmic relationship. The residual stress relaxation and the varying degrees of the surface cold working that was induced due to shot peening technique as compared to the simulation techniques indicated that the analytical model was quite robust especially for the cyclic loading stages for the low cycle fatigues. This is an important feature as the majority of the stress relaxation took place in the earlier stages, as could be seen from the previous reports. Though the analytical model, which has been proposed in this study, could predict the trend for the residual stress relaxation, an experimental report is needed, for the loading cycle-based residual stress relaxation, which would then act as a benchmark for the other numerical and analytical models.

Acknowledgment The authors would like to thank Ministry of Higher Education of Malaysia under Fundamental research grant number FRGS/1/2015/TK03/UNITEN/02/3 for supporting the research work.

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