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Shot Peening Effects on Material Properties: A Review

Hetram
M. Tech Student
Department of Mechanical Engineering
YMCA University of Science & Technology, Faridabad -121006

Lakhwinder Singh
Associate Professor
Department of Mechanical Engineering
YMCA University of Science & Technology, Faridabad -121006

Hari Om
Associate Professor
Department of Mechanical Engineering
YMCA University of Science & Technology, Faridabad -121006

Abstract

Shot peening is a method widely used to improve mechanical properties of materials. The improvement in mechanical properties such as surface hardness, fatigue strength, tensile strength, damping etc. are due to the induction of compressive residual stress in the metal parts. The residual compressive stress induced by shot peening is the function of material and mechanical conditions. Its beneficial effects are mainly due to the residual stress field caused by the plastic deformation of the surface layer of material resulting from multiple impacts of the shot, although strain hardening and grain distortion caused by the multiple impacts of the shot also play a role in the modified mechanical behaviour of the peened components. Due to several advantages shot peening has been in the focus of research persons for the purpose of increasing the properties of the materials. In the present paper, a review study has been done on the shot peening effects on different materials. This review will help the researchers and readers to better understand the several benefits and applications of shot peening. The present review of shot peening process is focused on the latest development and pushes the readers towards the on-going research in this classic process. The authors have not come across any such type of review which focuses mainly on shot peening process.
Keywords: Shot Peening, Compressive Residual Stress, Peening Intensity, Almen Strip

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I. INTRODUCTION

Shot-peening is a cold-working process used mainly to improve the fatigue life of metallic components [1-3]. It is used to set up residual compressive stresses in the materials and these residual stresses remains in the material whether a load acting on the body or not. The residual compressive stress induced by shot peening is the function of material and mechanical conditions. Shot peening process is impacting a surface with shot (round metallic cast steel, glass, ceramic particles) with force sufficient to create plastic deformation. It operates by the mechanism of plasticity, each particle functions as a ball-peen hammer. The magnitude of the compressive stress induced and the depth of the induced layer depend considerably on the peening intensity. Peening intensity can be defined as a measure of the kinetic energy within a stream of peening media (shot). Peening intensity attained can vary with shot size, shot hardness, shot speed, shot flow rate, impact angle, coverage, etc.
Shot peening application is in:
1) Increase the fatigue life of structural components [4].
2) Drive shafts, axles, and gears.
3) Aerospace industry.
4) Turbine blades
5) Heavy load applications
6) Components subjected to cyclic stress

Heat treatment process like case carburizing & nitriding are the most widely used processes for surface hardening of several components used in structures, automobiles, heavy duty machines, etc. In case carburizing and nitriding of steel components the composition of the surface changes by the diffusion of carbon and nitrogen respectively and results in a hard outer surface with good wear resistance properties. Similarly shot peening improves the surface characteristics by deforming the surface layer by the shots.

II. LITERATURE SURVEY

H.Y. Miao et al., [5] experimentally studied the quantitative relationships between the saturation, surface coverage and roughness with respect to peening time based on aluminum Al2024 test strips. He found that compressive residual stresses have beneficial effect for the improvement of the fatigue life of the peened component. However, surface roughness has detrimental effect on the fatigue life of the peened component.

Mehmood and Hammouda [6] carried out experimental study of the effect of shot peening parameters such as shot size, nozzle pressure, nozzle distance, impingement angle and exposure time on high strength aluminium alloy ASTM 2024 to determine Almen intensity. He examined the effect of peening parameters on the Almen strip. The Almen strip of "A" type having thickness 0.0031'' was used. Shot size, nozzle pressure, impingement angle, exposure time and nozzle distance from the specimen was varied to determine the relationship with almen height. It was found that nozzle angle has greatest effect on almen intensity. Low angle has less effects and high angle has good effects upto angle 55° for small shots and 65° for large diameter shots. After that almen intensity decreases. He also found that high intensities can be achieved with at low pressure with large size shots and flow rate has inverse relationship with the intensity. He also tested the fatigue life and on the fatigue test specimens. The fatigue test specimen was as per ASTM E606. Almen intensity was varied and fatigue life of specimen was studied. The fatigue life of specimen increased by 166%. Also It was found that upto certain intensity i.e. 12A fatigue life of specimen increases and after that it has adverse effects on fatigue property.

Jiang X.P., et al. [7] carried out the study of the effects of shot-peening and re-shot-peening on the profile of surface residual stress and the four-point bend fatigue behavior of Ti–6Al–4V (wt.%). The Ti–6Al–4V specimens for four-point bend fatigue tests were machined in the dimensions of 40mm×15mm×5 mm. All these samples were shot-peened to an intensity of 6–8A using MI-170-R cast steel shot with 125% coverage. After a certain percentage (50%) of the mean measured fatigue life was spent he again carried out a second shot-peening treatment on these samples. The conditions were exactly same as the initial shot-peening treatment. Then he conducted four-point bend fatigue tests in an Instron 8802 servo-hydraulic machine with a frequency of 20Hz and a load ratio (minimum load/maximum load) of 0.1 at room temperature and 150°C. The average roughness (*R*a) of the shot-peened surface measured was about 1.3 µm, and that of the untreated samples was 0.3µm. Some sites on the surface of the shot peened sample were as deep as 4µm from the mean line. The diameter of such a surface topography was typically ~200µm. The shot-peened specimens were fatigued for half of their expected fatigue lives at 75% σ_y at room temperature and 150°C under constant maximum stress until failure or the test was stopped at 5×10^6 cycles if the sample did not fail. He calculated he fatigue strength of the shot-peened and re-shot-peened specimens at room temperature and 150° and found that the fatigue limits of Ti–6Al–4V increased in bending fatigue from 65% σ_y to 71% σ_y at room temperature and 72% σ_y at 150°C which are almost identical. He also concludes that re-shot peening does not have any deterious effect on fatigue life.

Kirk and Hollyoak [8] carried out experiment to determine the shapes of the almen strips after the shot peening, the source of that shape and parameters affecting the curvature reading. They conducted the experiment with the clamped and unclamped Almen strips. One strip was held in spring loaded jaws at each end and hence free to deflect during peening while other strip was peened under standard conditions. Both strips were peened with S170 shots. The curvature of both the specimen was measured by computer controlled X-Y-Z co-ordinate measuring system that includes a Camco 600 co-ordinate measuring machine and QCT 3-D measuring software. They found that the curvature of both the strips was quadratic parabolas i.e. parabolic curvature. But the clamped strips had complex curvature than standard conditions.

Torres and Voorwald [9] carried out experiment to study gain in AISI 4340 steel under shot peening conditions. The mechanical properties of the material selected by him was 50-53 HRC, 1511 MPa yield strength, 1864 MPa Ultimate tensile strength, 800 MPa fatigue limit (54% of yield strength). The material was treated at four intensities of shot peening 0.0027A (8 psi), 0.0063A (13 psi), 0.0083A (18 psi), 0.0141A (45 psi) with an airflow of 3 kg/min, a speed of 250mm/min, a distance of 200 mm and a rotation of 30 rpm, shot S 230 (diameter 0.7 mm) with a coverage of 200% on an air blast machine as per MIL-S-13165. The shot peened specimen was tested by ASTM E 739 standard. The specimen were tested in rotating bending fatigue tests at frequency 50 Hz at room temperature and fracture planes of fatigue test specimens were examined by electron microscopy for crack initiation point. They examined the CRSF by X-Ray diffraction method. They conclude that the low cycle fatigue of AISI 4340 resulted in crack initiation at the surface while in high cycle fatigue components; the crack was initiated from beneath the surface. In their study it was difficult to determine best peening conditions and it was demonstrated that the shot peening that produces the best results depends upon several factors i.e. the induced compressive stress, surface conditions by shot peening and possibility of the CRSF to push the crack source beneath the surface.

Biggs, Adam Ashford [10] carried out the experiments to determine the factors affecting the arc height after shot peening. The effect of almen strip hardness, pre bow and impingement angle was studied on the material SAE 1070 cold rolled steel with a blue temper and a Rockwell hardness ranging from C45 to C48. The dimensions of the Almen strips were 76.2mm (± 0.381mm) by 18.9mm (±0.064) by 1.3mm (±0.025) and flat to within ±0.013mm prior to shot peening. They used Wheelabrator 12 wheel, centrifugal type machine; however only 6 of the 12 wheels were used in this investigation. Carbon steel conditioned cut wire shot, CW-28 as the shot material in all experiments. The experiment was design as a 2^3 factorial design of experiment (DOE). Six rows of Almen strips with fifty strips in each row were shot peened simultaneously. Rows A-C were oriented 45º to the shot stream while rows D-F were oriented at 90º to the shot stream. The tool used to hold the Almen strips was fixed in the Y and Z directions and fed in the X direction with respect to the shot stream. The standoff distance used was computer controlled to a distance of 60.96mm for each row. They tested about 1200 Almen strips and approximately 4000 data points were collected. After that statistically significant factors affecting the final arc height of the shot peened Almen strips were determined by an Analysis of Variance (ANOVA). The results of the ANOVA study were incorporated into a mathematical model to predict the Deviation From Target Magnitude values of the shot peened Almen strips based upon the intensity, orientation angle, saturation time, and the interaction between the angle and the intensity level and analysis of variance showed mathematically that these had significant effects on the final arc height of the Almen strips. Results also showed that almen strip hardness has no correlation with Deviation From Target Magnitude (DFTM).

Kirk and Abyaneh [11] carried out study to explain how the coverage in a shot peened specimen varies with the time and multiple impacts. He also concluded that the presence of small areas that have not been impacted near the dimples does not mean that there are 'weak points' in the surface i.e. it is not the dimples that generate the compressively stressed areas but rather the deformation zone under and around the dimples. In the figure below shown a single impact area, its adjacent deformation zone and a representation of the concentric 'envelope' of compressively- stressed material. The level of compressive stress falls the further it is from the centre of the impact area.

Hong et al, [12] carried out study to investigate the 3D finite element dynamic analysis of single shot impacting on a metallic component. A FE mesh was generated on a circular plate for investigation. The circular plate was restrained against all displacements and rotations on the bottom end and was given the following geometric properties: radius R = 8d_{shot}, height H = 3d_{shot} where d_{shot} is the shot diameter. Eight-node linear brick elements with reduced integration (C3D8R) were used with element size 0.05d_{shot} x 0.05d_{shot} x 0.05d_{shot} in the impact region. The shot selected by them was of spherical shape. They used the following properties for their single shot impact analysis: width W = 3.5 mm, height H = 2 mm, breadth B = 2.5 mm, mass density (ρ) = 7800 kg/m^3, elastic modulus E = 200 GPa, initial yield stress σ_0 = 600 MPa and a linear strain-hardening parameter H^1 = 800 MPa. The diameter and mass of shot was d_{shot} = 1 mm and m = 4.085 mg, respectively. Coulomb law with friction µ=0.25 was considered between the shot and component during contact. In the study they assumed the component to be an elastic–plastic with isotropic hardening material. The results were plotted in a normalised manner using the normalised depth z/d_{shot}, in which z is the deformed depth along the centre line of the component. They found that the shot diameter has a negligible effect on the magnitude of surface and maximum sub-surface residual stresses but the depth of the residual stress zone increases linearly with increasing shot diameter.

Hong et al. [13] carried out Tensile and low-cycle fatigue (LCF) test in air in a wide temperature range from 20°C to 750°C and strain rates of 1 x 10^{-4} – 1 x 10^{-2} to investigate the influence of strain rate on tensile and LCF properties of cold worked 316L (17% cold worked) stainless steel in the dynamic strain aging (DSA) regime. They found that cyclic stress response at all test conditions was characterized by an initial hardening during the few cycles, followed by gradual softening until failure. At the elevated temperature, a drastic reduction in fatigue resistance was observed and concluded that the regime of DSA accelerated a reduction in fatigue resistance by enhancing crack initiation and propagation. They prepared the material into dog-bone type specimens (polished using emery paper to ~13µm) having a gauge length of 36 mm and a gauge diameter of 8 mm in accordance with ASTM standard E606-92. A closed-loop servo-hydraulic test system with 5-ton capacity was used to accomplish the tensile and fatigue tests and A high temperature extensometer (MTS model no.: 632-13F-20, gauge length=25 mm) was used to control strain signal and measure strain. The fracture surfaces were studies using scanning electron microscopy. They found that an increase in material strength and decrease in ductility were induced by dynamic strain aging in the temperature range from 250° to 600°C. Also dynamic strain aging enhanced crack initiation, causing multiple crack initiation sites.

Mylonas, G. I et al. [14] carried out investigation on treated or shot peened material. a three dimensional numerical model is developed. He considered plate material AA7449-T7651 high strength Aluminium alloy for the shot peening. Multi shot study was conducted. After the validation of the numerical model, a parametric study was conducted in order to create a residual stress database, useful for the process parameters selection for different shot peening media. The database provided the basics for the development of a numerical model that could simulate the distortion of thin sheets. The parametric analysis was performed by applying the shot patterns previously presented, including 4 shot types (S110, S230, S330 and S550), different shot velocities in the range of 20 to 100 m/s and two impinging angles 75° and 90°. The maximum compressive stress computed for the 4 shot types and 2 impinging angles is plotted versus shot velocity. The results showed that the maximum residual stress was increasing with increasing shot velocities for all the cases. The results also showed that residual stress also increases with shot size and did not affect by the impingement angle.

Aggarwal M.L. et al, [15] conducted the study to see the effects of shot peening on Nitrogen austenitic stainless steel and concluded that Shot peening of nitrogen austenitic stainless steel increases its hardness. The hardness can be controlled by adjusting the intensity of the shot peening. Hardness increases with peening intensity. Also Endurance limit of RS561 steel improves with shot peening. However the fatigue life is unchanged for stress level higher than endurance limit. Double shot peening reduces the surface roughness without significant change in residual stress. Further, increase in the fatigue strength of the material is noted with primary and secondary shot peening.

K.A. Soady et al, [16] investigated the plastic deformation resulting from shot peening treatments applied to the ferritic heat resistant steel FV448. Two important effects were quantified: surface roughness and strain Hardening. Three different methods for evaluating the plastic strain profile were evaluated with a view to establishing the variation in yield strength near the surface of a shot peened component. Micro hardness, X-ray diffraction (XRD) line broadening and electron backscatter diffraction (EBSD) local misorientation techniques were applied to both uni-axially deformed calibration samples of known plastic strain and samples shot peened at intensities varying from 4A to 18A (here A stands for Almen Intensity) to establish the variation in plastic strain and hence the variation in yield strength. The results from the three methods were compared; XRD and EBSD profiles were found to be the most similar with micro hardness profiles extending much deeper into the sample. He also concluded that increasing the intensity above an industrially optimized process may not necessarily increase the depth of the plastic strain profile but may result in higher plastic strains being retained deeper in the profile. Reducing the intensity of the shot peening process tends to reduce the magnitude and depth of the plastic strain profile. The plastic strain profile is not just dependent on intensity, but also on the combination of shot size and velocity.

B. Hashemi et al, [17] investigated the shot peened nitrided stainless steel (316L stainless steel sheet, 3 mm in thickness) that was gas nitrided at 570 °C with pre-shot peening. The structural phases, micro-hardness, wear behavior and corrosion resistance of specimens were investigated by X-ray diffraction, Vickers micro-hardness, wear testing, scanning electron microscopy and cyclic polarization tests. The effects of shot peening on the nitride layer formation and corrosion resistance of specimens were studied (Corrosion and wear test specimens were prepared in sizes of 1 cm x 1 cm and 2 cm x 6 cm respectively). Shot peened–nitrided specimen had highest hardness and wear resistance due to the formation of nitride phases, induction of compressive residual stresses and grain refinement in the surface layers. He concluded that while corrosion resistance of the only-nitrided specimen in ringer's solution decreases tremendously in comparison with the untreated specimen, performing the shot peening surface treatment before nitriding, improves the corrosion resistance in comparison with the nitrided steel. This may be due to the formation of a thin-deposited layer at the surface of specimen. He concluded that shot peening enhanced the nitride layer formation and the shot peened–nitrided specimens had higher wear resistance and hardness than other specimens. He also concluded that, although nitriding deteriorated the corrosion resistance of the specimens, cyclic polarization tests conducted by him shows that shot peening before the nitriding treatment could alleviate this adverse effect.

Yu-Kui Gao et al., [18] carried out experimental study the compressive residual stress field (CRSF) introduced by shot peening on 40Cr steel. The specimens of ϕ30 mm x 50 mm were prepared. They were tempered at 200°C, 400°C, 550°C and 650°C for two hours. Shot peening was carried out on an air-blast machine with the cast steel shot with hardness of 50 to 60 HRC. They included about 60 kinds of heat-treating and shot-peening conditions. They used 2903-type strain diffractor meter using Cr *K*a radiation, the $\sin^2\psi$ method. They used diameter of shot is about 0.5 or 1.10 mm, air pressure of 0.2 to 0.6MPa and peening coverage rate of 100 to 600 pct. The experimental results show that the maximum of compressive residual stress field for a given material is almost the same even under different shot peening techniques and the surface residual stress values are dependent on both the mechanical properties of target materials and peening parameters.

Gao, Yukui, and Zheng Zhong [19] investigated the role of residual stress in the fatigue crack initiation and propagation behavior. They conducted the rotating bending fatigue tests (stress ratio R = -1) for some aeronautical metallic materials including high strength steels, aluminum alloys, and titanium alloys. A total of 20 specimens were tested as a group to determine the fatigue strengths/limits for each alloy at 1×10^7 cycles by staircase method. They determined the fatigue crack sources by scanning electron microscope (SEM) and the locations of fatigue crack sources were determined by the distance from surface. They analyzed the effect of residual stresses quantitatively by weight function methods and FASTRAN software. The study shows that the compressive residual stresses can be measured by X-ray diffraction or neutron scatting and simulated by finite element methods or boundary element methods. The study also shows that the fatigue crack sources always locate at the surface for unenhanced specimens, whereas for those surface-enhanced ones they are located beneath the surface-enhanced layer where residual stress is tensile.

Fouad, Yasser, and Mostafa El Metwally [20] carried out study to evaluate the effects of shot-peening on the high cycle fatigue performance of the age-hardening aircraft alloy Al 2024 glass shaped specimens with a gage diameter of 6 mm at different almen intensities (0.1, 0.2, and 0.3 mmA). Shot peening to full coverage (100 pct) was performed using spherically conditioned cut wire shot (SCCW-14) with an average shot size of 0.36 mm. Shot-peening was conducted using a gravity induction shot-peening machine type OSK-kiefer GmbH for 40 seconds. The distance between the nozzle and specimen was taken constant of 9 cm. They determined the residual stresses by means of the incremental hole-drilling method using a drill with 1.9 mm diameter and strain gage rosettes. The fatigue test was performed using rotating beam loading (R = -1) in air at frequency 50 Hz using ''SINCOTECH'' rotating beam fatigue machine The experimental results show that higher the almen intensity the higher the regions of plastic deformation, roughness and residual stress. The microhardness, surface roughness, and the residual stresses increased proportionally with the almen intensity.

The modeling and simulation of the shot-peening process has received some attention from the scientific community. This includes the contributions made by Shaw and De Salvo [21], Meguid et al. [22-23], Khabou et al. [24] and Li et al. [25] of the process using quasistatic analysis. The dynamic modeling of a single shot was initially conducted by Johnson [26] using a pseudo dynamic approach. In his approach, Johnson [27] took into account only the inertial properties of the shot. As a result, a relationship between the depth of the plastic zone and the shot parameters, such as radius, mass and velocity was obtained. This relationship was later validated by Clausen and Iida [28]. Edberg et al. [29] conducted dynamic three-dimensional finite element analysis of a single shot impinging viscoplastic and elastoplastic materials. Their results showed that the two material models give similar residual stress distributions.

III. CONCLUSION

The literature survey shows that shot peening is an important treatment of technical parts with continually growing areas of application. Also, to increase fatigue life, hardness etc., compressive subsurface residual stresses are possessed near the surface of the work-piece. In order to obtain optimal results the process has to be controlled properly.. There can be tremendous increase in the applications as peening process is versatile i.e. many properties are influenced by this process so a number of application in manufacturing industries. Also small components can also be machined by this process. A single process induces several properties in a component and hence it can be said as cumulative process where several properties influenced at once. This literature survey shows that the mathematical models and the optimisation of the Shot peening process are performed using Design of experiment, Full factorial design. Adequacy, significance and results from the models are analysed using the ANOVA and FASTRAN software. The examination of the fractured surfaces is done by X-Ray diffraction method, scanning electron microscopy, electron backscatter diffraction (EBSD techniques.

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