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Influence of residual stress relaxation induced by shot peening on the fatigue life of aluminium alloys: A review

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Abstract: The process of Shot peening involves improving the surface of the metallic components. In this process, the strength of the metals is increased by adding favorable compressive residual stress on the metal surfaces and improving the resistance to the stress corrosion cracks that could occur in the metal objects. However, the peening process can increase the fatigue life owing to the higher roughness of the surfaces and the residual tensile strength if this process is carried out improperly. The efficiency of the shot peening process does not depend on the applied compressive residual stress and the surface hardening but depends on the intensity and the coverage of the shot. The major advantage of using the shot peening process is that the fatigue life of several of the mechanical components can be considerably increased, especially those that have to undergo constant stress. This process is widely used in the industry, mainly in the manufacturing sector, where it is used for producing rockers, helical springs, aircraft parts, torsion bars, welded joints, transmission shafts, etc.

Key words: Shot peening residual stress relaxation; Surface treatment; Fatigue

1. Introduction

The shot peening process is widely used to treat surfaces of the metallic and engineering components by increasing their resistance to the fatigue failure(Troll et al., 1999). This process is more popular in the aeronautical industry and the components, which are fatigue-sensitive very frequently, undergo shot peening(Rios et al., 2002). From the last 5 decades or so, this process has become very popular and is being used for improving the fatigue life and similar properties of metals used in the aircraft. Some of the aircraft components that undergo regular shot peening include - bulkheads, wing ribs, fuselage skin, landing gear beam, and the lower wing skin of the crafts. In addition, the high-pressure turbine, helicopter rotor blades, other components of the drive elements, and the compressor discs undergo this process. Many of these aircraft parts are made from the Aluminium alloy, 2024-T351.

The process of shot peening refers to the mechanical surface treatment in which a compressive surface coating is layered along with a rough surface and an enhanced dislocation density (cold work) closer to the surface of the metal(Guagliano and Vegani, 2008). The process involving cold working refers to the process, which involves an impingement of smaller cylindrical or spherical pieces of steel, ceramic or glass on the surface of the component.

In the shot peening that are carried out in the industries, the process is carried out using Almen plates. Almen plates are thin standard plates, which are kept parallel to the surface of the components, and they then receive similar treatment as the metal part. In this treatment, a small amount of residual stress in induced in the plates, which then deform. This deformed shape, referred to as the Almen intensity, helps in adjusting the parameters of the shot peening process(Zhang et al., 1991; Schiffner, 1999). The kinetic energy of the applied shot is then transferred to the surface of the metal component. In addition, the shot stream is targeted to the metallic surface with very high velocities under specific conditions. Every shot that takes place on the metal surface adds a compressive residual stress to the surface.

As a result, the collision energy is focussed only on very small areas. Small amounts of the energy can go waste when the shot deforms and bounces, however, a large amount of energy is transferred to the point where the shot is directed, resulting in a radial plastic flow and could form a tiny visible crater at the metal surface. After the shot is directed to the surface, some amount of its kinetic energy gets absorbed and is used for cold work of the surface, thus placing the surface under compression.

Currently, the shot peening process intensity is determined by using small spring steel strips called as Almen strips. Three different the thicknesses of Almen strips of spring steel SAE1070 tempered to 44-50 HRC, as listed in Table. They have some special fixtures for evaluating the amount of energy

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that is absorbed into the metal surfaces. The energy, which is transmitted with the help of the shot peening process, is dependent on numerous factors like – mass, impact velocity and angle, the medium hardness, the total number of the shot balls, and the condition of the surface of the metallic component(Dassisti et al., 2012).

Shot peening specifications refer to this energy as intensity at saturation, which means the earliest point of the saturation curve that, if the exposure time is doubled, the arc height increased by 10% or less (Fig. 1).

In a study, the authors determined the effect of the numerous shot peening processes on the reverse bending fatigue performance of the aluminium alloy, Al-7075-T651. Considering the residual stress and the roughness of the surface, an analytical model was designed for the prediction of fatigue resistance. Finally, the authors concluded that a controlled process of shot peening, which uses ceramic beads, demonstrates a significant increase in the resistance of the high-cycle fatigue for the higher strength aluminium alloys, which range from 15-50%(Fontanari et al., 2009).

Literature review

In his study, Miao et al.(Demers et al., 2010) has shown the results of the shot peening process, which includes the coverage curve, saturation curve, roughness curve along with the residual stress profile. Additionally, he has presented the relation between the pre-bending moment and the resultant heights in the narrow and the square strips. They also carried out an experimental study for the intensity and the surface coverage using the Aluminium 2024. They further stated that the compressive residual stress has favourable effects for improving the fatigue life while the surface roughness can be unfavourable.

In their study, Mehmood and Hammouda (Mehmood and Hammouda, 2007)studied the influence of the shot peening process parameters, which included – nozzle pressure, the impingement angle shot size, nozzle distance, and the exposure time. These tests were carried out on the high-strength ASTM 2024 aluminium alloy for determination of the Almen intensity using the Almen strips. The influence of the parameters was determined on the Almen strips of Type "A" with a thickness of 0.0031". All the above-mentioned parameters were varied to study their relationship with the Almen height. From their results, the authors concluded that the nozzle angle greatly affected the Almen intensity. While lower angles did not have great effects, higher angles of 55° and 65° had greater effects on the small and the large diameter shots respectively. The Almen intensity decreased beyond this angle. The authors also determined that higher intensity could be achieved at lower pressures using larger size shots and the flow rate had an inverse proportion to the intensity. Additionally, the authors carried out the fatigue life test of the test samples using the standards as prescribed by ASTM E606. In these tests, the Almen intensity was altered and the fatigue life of the sample was determined. It was seen that the fatigue life increased by around 166% for their sample, under the specified conditions. The authors also noted that the fatigue life could increase up to a specific intensity equivalent to 12A; thereafter the fatigue life could be adversely affected. In another study, the authors, Kirk and Hollyoak (Kirk and Hollyoak, 1993),conducted experiments to study the shape of the Almen strips, the basis of the shape and the factors that influence the curvature readings after the shot peening process. These experiments were carried out using clamped and the unclamped type of the Almen strips.

One of the strips was held together by spring-loaded jaws at either end, and was capable of deflecting during the shot peening. The remaining strip was shot peened under the standardised conditions. Both of these strips were shot peened using S170 shots. To control the strip curvature, a computer-controlled, X-Y-Z coordinate measuring technique, equipped with the QCT 3-D software was used. The authors noted that the curvatures of the two strips resembled the quadratic parabolas i.e., they had a parabolic curvature. However, the curvature of the clamped strip was more complex as compared to the strip, which is peened under standard conditions.

Table 1: Almen strips dimensions(Kirk, 1999).

Strip	Thickness(mm)	Length (mm)	Width (mm)	Use for
N	76.00±0.4	76.00±0.40	18.90-19.00	Low Intensity
A	1.30 ±0.02	76.00±0.40	18.90-19.00	Average Intensity
C	2.38±0.02	76.00±0.40	18.90-19.00	High Intensity

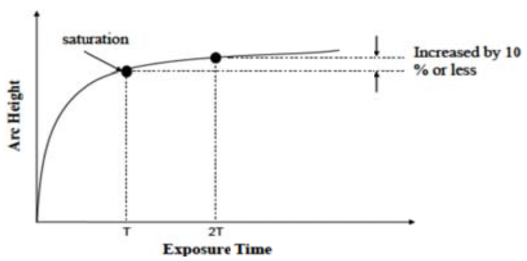

Fig. 1: Arc height vs. exposure time scheme(Baiker, 2006).

The effect of the sphere velocity was observed with 36, 72 and 108 m/s shown in Fig. 2 with the residual stress profile in XX. With increasing the speed of ball causes an increase in the compressive residual stress layer. From a certain velocity the Bielajev point also increases and moves into the sheet and the deformation increases proportionately(Silva, 2008).

Many reports(Lohe et al., 1986; Megahed et al., 2001; Guechichi and Castex, 2006; Pariente and Guagliano, 2008; Mirzazadeh and Plumtree, 2012) have stated that for the smooth steel peened samples, the work hardening greatly affected the sample as compared to the compressive residual stress that was generated. However, there are many other reports that contradict this statement and observe that the compressive residual stress greatly influenced the sample(Buque et al., 2006). After the process of shot peening, the original compressive surface residual stress is then relaxed and it is again distributed while the fatigue process is carried out (Zhuang and Halford, 2001; Torres and Voorwald, 2002). Many researchers have conducted studies on stress relaxation.

In this study, Soady et al. (Mellor et al., 2013) determined the deformation in plastic that could occur from the shot peening process when it was carried out on the heat resistant ferritic steel, FV448. They calculated two different effects – the strain hardening and the surface roughness. They applied three techniques for evaluation of the strain profile of plastic for determining the variation seen in the yield strength along the sample surface. The techniques of Microhardness, Electron Back Scatter Diffraction (EBSD) local misorientation, X-ray diffraction (XRD) line broadening were used on both the deformed uni-axially calibration specimens of pre-determined plastic strains. These samples were subjected to shot peening at different intensities from 4-18A (A refers to Almen Intensity) for determining the differences in the plastic strain and the variations in the yield strength. When the results of the applied methods were compared, it was noted that the techniques of XRD and EBSD generated similar profiles and the microhardness profile for these techniques extended very deep in the sample. The author also stated that an increase in the intensity value above that of the optimised industrial process could probably not bring an improvement in the depth of the profile for the plastic strain but could cause a greater plastic strain to be retained in its profile. On the other hand, a reduction in the intensity would result in a decreased magnitude and the depth of the plastic strain profile. It can be seen that a strain profile is mainly dependent on the shot size and the shot velocity along with the intensity.

Many researchers have begun taking an interest in the modelling and the simulation of the shot peening processes. Also, several authors like Shaw and De Salvo(Shaw and DeSalvo, 1970), Meguid et al. (Collins et al., 1977, Meguid and Klair, 1985), Khabou et al. (Castex et al., 1990), Li et al. (Mei et al. 1991)etc. have made significant contributions to the shot peening process with the help of the quasistatic analysis. By applying the pseudo-dynamic approach, Johnson(Clausen, 1981) carried out the dynamic modelling of the single shot. In this process, he considered the inertial shot properties only; thus obtaining a relationship within the depth of the zone and various parameters including mass, radius, and velocity. Furthermore, Clausen and Iida(Iida, 2000) and Edberg et al. (Edberg et al., 1995) confirmed this relation by carrying out a 3-D finite element analysis for the single shot, which is applied on the viscoplastic and the elastoplastic objects. According to their results, both of these objects produced the same type of residual stress distribution.

The simulated results shown in Fig. 3 indicate that the depth of the maximum compressive residual stress (t1) and the depth where the residual stress changes sign (t2) increase with increasing shot velocity and shot diameter. However, with increasing shot velocity, the surface residual stress decreases.

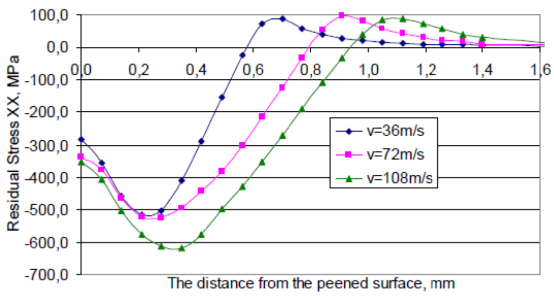

Fig. 2: Residual stress profile for three different shot velocity for a sphere radius R = 0.7 mm.

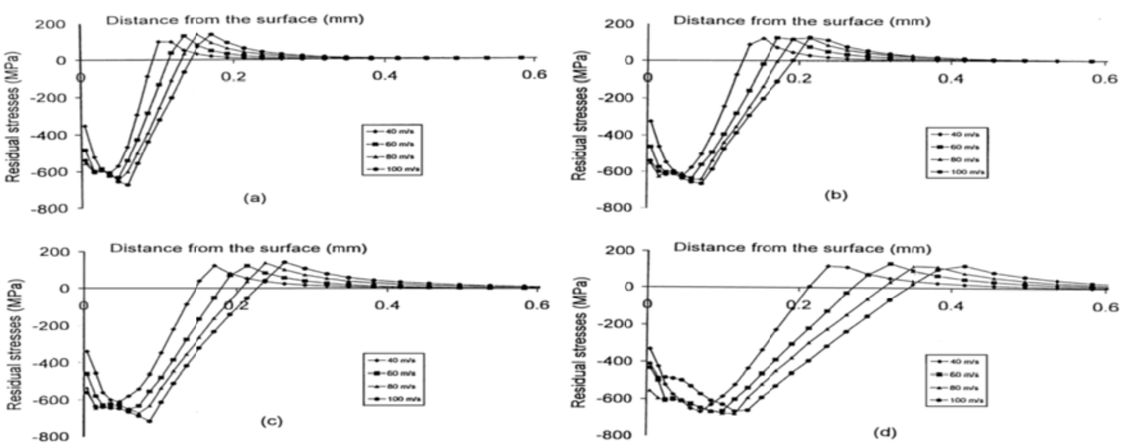

Fig. 3: Residual stress profiles due to shot peening in a thick component, with different shot diameters and at different shot velocities. (a) Shot diameter 0.3mm, (b) Shot diameter 0.5mm, (c) Shot diameter 0.7mm, (d) Shot diameter 1.0mm (Guagliano, 2001).

2. Conclusion

Increasing the intensity of the shot peening process yields higher compressive residual stress and higher width of the Compressive Residual Stress Field (CRSF). On the other hand, the peening conditions do not affect the residual stress on the surface. To ensure the validity and repeatability of the process of shot peening, one of the most important factors includes the Almen intensity. This study has detailed the effects on the Almen intensity due to various parameters involved in the shot peening like the size, peening angle, shot type (ceramic and steel) and velocity. The Almen test is very effective and acts like a control for the applications of the process. This test evaluates the total energy transferred to the sample by the process and also detects the variations that could occur. Any change seen in the Almen intensity is a reflection of the changes carried out in the process parameters. On the other hand, concurrent changes in several of the parameters (like the shot velocity and the shot diameter) could result in similar values for the Almen intensity, and could remain unobserved.

Moreover, when the association of the parameters like shot diameter and the shot velocity result in an exclusive residual stress profile, then the Almen intensity should not be the sole parameter for the fatigue life enhancement, but the shot diameter should also be taken into account. When the Almen intensity is kept constant, it should be noted that while substituting the peening parameters, a constant intensity would result in variations in the residual stress profiles and could also affect the component's fatigue life expectancy.

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