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Optimization of the fatigue strength of materials due to shot peening : A Survey

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Abstract

Imparting residual compressive stresses in the surface layers of metallic components is one of the ways to improve their fatigue strength characteristics. Shot peening is employed for imparting residual stresses by means of cold work. Shot peening is a complex random process with many input variables. The material responses include residual stresses, cold work, surface roughness, micro-cracks and micro-structure changes. To obtain the maximum fatigue strength, the designer needs to consider both favorable and detrimental aspects of these responses together. The prediction of the responses from the input parameters involves many methods spanning across multiple-disciplines such as plasticity, fracture, optimization etc. The paper presents an overview of the studies that predict the various material responses and suggests a method based on continuum mechanics in order to optimize the fatigue strength of any material.

Key words: shot peening, optimization, fatigue strength, cold work, residual compressive stress, fracture

1. Introduction

Fatigue cracks originate mostly from the surface, as the stresses due to loads (such as bending and torsion) are generally high at the surface compared to the inside material. The fatigue resistance of sub-surface material is also higher (approximately by 1.4 times) than that of the surface (Peige *et al.*, 1996). Besides, the surfaces are subjected to machining and handling defects which act as stress raisers. These machining operations induce detrimental (tensile) residual stresses that can adversely affect the fatigue response and even the dimensional stability as well as further machining.

It is always a challenge to the designer to maximize the fatigue strength without any additional weight or cost increase. The fatigue strength can be enhanced by the use of controlled cold working methods. Shot peening (SP) is one such process which induces residual compressive stresses (RCS). The process is schematically explained in Figure 1. Typical residual stress distribution developed by the SP process is given in Figure 2. The RCS reduces the tensile mean stresses due to the applied loads and manufacturing thereby it increases the fatigue strength.

The shot peening process is controlled by many input parameters. Besides, the microstructure is different for different metals and alloys. The RCS distribution, which plays crucial role in enhancing the fatigue strength of the material, depends on the various input parameters and the material microstructure. Besides, the development of RCS is always accompanied by cold work, microcracks, surface roughness and the microstructure changes.

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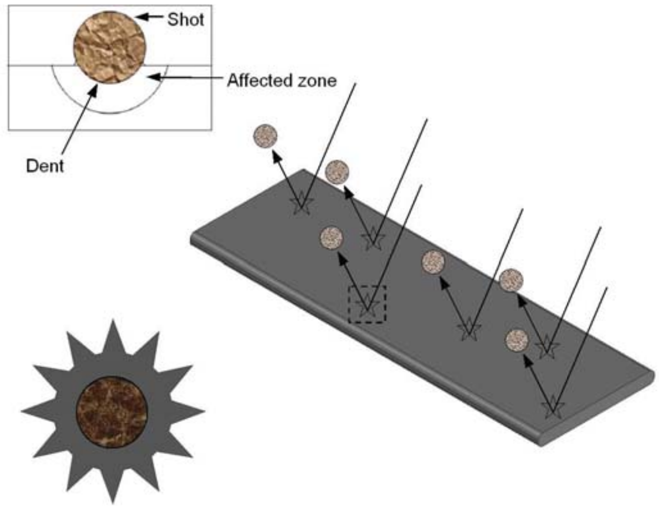

Figure 1: Schematic diagram showing shot peening. Shot peening involves multiple and progressively repeated impacts, resulting in plastic deformation of the surface layer. Once the shot leaves the work piece, the adjoining layer of material resists any further deformation thus causing RCS.

While underpeening is likely result in poor RCS development, overpeening causes serious deterioration of surface integrity causing reduction in fatigue strength. As the peened components are subjected to mechanical and/or thermal loadings of static or fatigue nature, the residual stresses relax. However, adverse effects such as surface roughness are retained. Extensive experimental and theoretical studies have been performed in evaluating the effects of peening and the material responses such as RCS development, crack growth, relaxation, cold work etc. The above mentioned effects need to be looked at together in order to optimize the fatigue strength.

This survey paper focuses on the different modeling strategies employed in the theoretical prediction and optimization of the material responses due to the shot peening process. The peening process is explained first, covering the different input parameters and the measures of peening. In the next section, the effects of shot peening on the materials are discussed with special focus on the residual stress prediction methods. The methods of evaluating the stress relaxation due to mechanical and thermal loads are discussed next. This is followed by the the studies on optimization related to shot peening. Thus, the paper attempts to provide a unified method to obtain the optimium response and the possible future directions in the next section.

2. Shot peening -an overview

The compressive stresses developed due to shot peening have two components a) stresses developed due to the cold work as a result of shot impact and b) the Hertzian contact pressure. The near-yield stress compressive stresses at the surface are balanced by sub-surface tensile stresses.In parts with lower thickness such as thin sheets, the tensile stresses can be higher than components with larger thickness. The typical stress distribution due to shot peening can be seen in the work by Champaigne (2001) for different treatments and failure mechanisms.

Many specifications, both commercial and military, have evolved to ensure process quality. The SAE specification AMS 2430 (SAE, 2009) includes the requirements for the set-up, operation and verification of the process; AMS 2431 (SAE, 2006a) discusses about the peening media and the general requirements; AMS 2432 (SAE, 2006b) covers the continuous computer controlled peening for critical parts. The military specification MIL-S-13165C discusses procedure requirements for peening (MIL-S-13165C, 1989). The J specifications, SAE J442/443, discuss about for general applications and ground vehicles (SAE J442, 1961; SAE J443, 1961).

2.1. Input parameters

Shots play the key role in the peening process. They are spherical in shape and manufactured in different sizes from different materials such as cast steel, carbon steel, ceramics, glass etc. The selection of the shot is

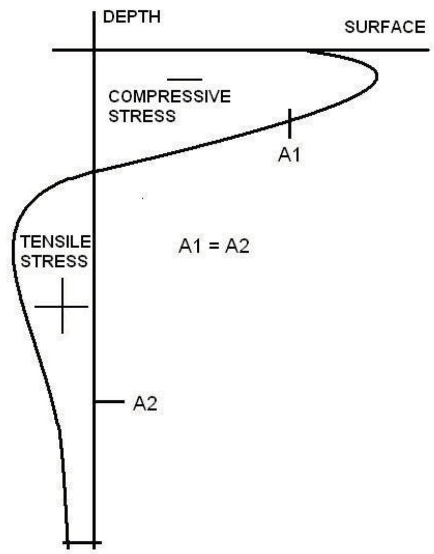

Figure 2: Residual stress distribution. The large compressive stresses acting on a small thickness (A1) are balanced by small tensile stresses acting on a large thickness (A2).

based on the peened material, its hardness, intensity, allowable contamination and permissible surface roughness (Kiefer, 1987). The shot size depends on the smallest feature size that needs to be peened. The shots must be at least as hard as the peened material according to Gillespie (1993).

The key peening parameters that affect the work hardening and hence the compressive stresses are a) shot size, b) shot velocity, c) shot material and the hardness, d) angle of impact, e) part material and hardness, and f) friction. The SP process develops different RCS magnitudes depending on the values of input parameters. Researchers, for example, Kirk (2005) and Simpson and Garibay (1987) have grouped the shot peening parameters in different ways. A detailed flowchart by Simpson *et al.* (1987) covers the comprehensive list of the input parameters.

2.2. Peening measures

In order to determine the quality of the peening process, three different peening measures have been evolved at. They are a) coverage b) intensity and c) saturation.

Coverage. It is measured as the ratio of the peened surface over the total area. To measure the peened area, the projected area of the dents is considered. Sometimes, the surfaces are peened beyond 100% coverage. A coverage of 200% is said to have been achieved, when the peening duration is doubled in comparison to 100% peening. In the industry, 100% coverage is considered essential for uniform development of RCS.

There are two expressions that are mainly used to calculate the coverage theoretically. The first one is the Avrami equation (Kirk and Abyaneh, 1993), given by:

$$C(t) = 100\Big(1 - e^{(-3R^2\dot{m}t)/(4AR^3\rho)}\Big) \quad (1)$$

where C defines the coverage, R the shot radius, t and $t + \delta t$ are the time steps, $\dot{m}$ is the mass flow rate of shots, ρ is the shot density. The other expression, the Holdgate model seems to predict the coverage better than Avrami model, according to Karuppanan *et al.* (2002). According to Lombardo and Bailey (1996), the average number of impacts on any point for near 100% coverage is 3.9, due to the randomness.

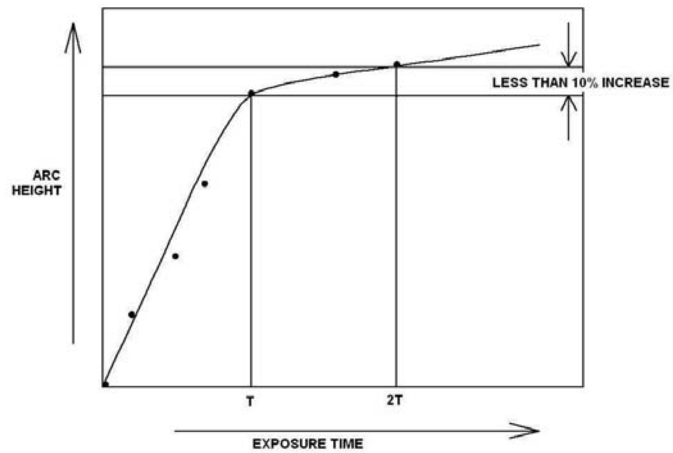

Figure 3: Saturation curve obtained through Almen intensity

Intensity. In the industry, Almen intensity is used as a measure of the residual stresses. The Almen strips are made of spring steel, SAE 1070. The material and dimensions of Almen strips are standardized by Aerospace Material Specifications. The details of calibration of Almen gages are given by Champaigne (2002). In practice, Almen strip is kept along with the part and is subjected to the same peening conditions. During this state, the strip is kept flat using screws on its holder. After the peening is completed, the magnitude of residual deflection is measured as the *Almen intensity* between a central span of 31.75 mm (1.25 in) using Almen gage, upon removing the screws.

Three types of Almen strips, N, A and C are used in the industry. The length and width of all these strips are the same, but their thicknesses are different. Generally, N type strip is used for low intensity applications, while A and C type strips are used for medium and high intensity applications.

After peening, the parts undergo fatigue or field testing (Leghorn, 1957). If the parts meet the fatigue loading requirements, all the future peening operations are done with the same set of peening parameters that led to the same Almen intensity. The process, however, needs to be repeated if the part fails to meet the fatigue requirements, causing huge cost and time overruns. However, the Almen strip is still widely used as it remains as the simplest, the most flexible and the least expensive measurement method to repeat the peening process, once the peening process is standardized (Nachman, 1999). Matsumoto *et al.* (1990) have regressed the relationship between peening parameters such as shot velocity, intensity, residual stress etc. In spite of such developments in understanding the Almen system, it does not provide a very accurate prediction of the strain hardening and the RCS due to various peening factors, requiring a detailed study of the peening process.

Saturation. As the Almen strip is peened for more duration, the permanent deflection of the Almen strip continues to increase. However, the increase in the deflection continues to reduce and finally stops even if the peening is continued. The strip is assumed to be saturated with peening for the given parameters, if the intensity increase is below 10%, when the duration of peening is doubled, as defined in the Figure.3.

2.3. Effect of shot peening parameters

Herzog *et al.* (1996) have conducted a set of experiments on X35CrMo17 steel and Al7020 aluminium alloy exploring the influence of different peening parameters. Typically, the shot velocity (function of air pressure or wheel speed), diameter, hardness and the peening time (coverage) increase the magnitude of the maximum RCS value as well as push its location further inside away from the surface. In addition, shot hardness increases

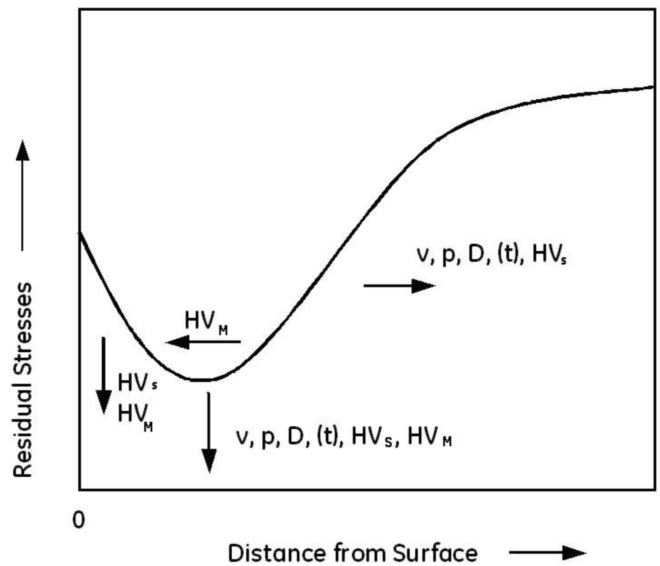

Figure 4: Effects of input parameters on RCS. HV represents the hardness, V the shot velocity, D the diameter, p the air pressure from nozzle and t the time. The subscripts s and m denote the shot and the target material respectively.

the surface RCS value as well. The target material hardness and the dent depth increase with shot velocity. Robertson (1987) has mentioned that the maximum stress occurs farther away from the surface and the total affected depth increases, as the shot size is increased. The harder target materials increase the magnitudes of the surface and maximum RCS values. However they reduce the depth of the maximum RCS. The depth of RCS field is more for 90° impact (normal to the surface) than say 45° impact and hence normal impact helps to reduce the fatigue crack growth (FCG) (Ebenau *et al.*, 1990b). While normal impacts increase the fatigue strength, shallow impacts increases surface roughness. Figure 4 captures the effect on the response parameters.

3. Residual stress prediction from the material responses

SP is found to improve the mechanical properties such as fatigue, corrosion, stress corrosion, wear etc. Several literature point towards the residual compressive stress as the primary reason for fatigue life improvement. The fatigue performance not only depends on the RCS at the surface, but also on the gradient inside the material. Researchers, such as Hornbogen *et al.* (1981), point out that SP has improved the fatigue life due to surface cold-working than the unpeened or bulk-formed (steel) specimen. The cold work in turn increases the material hardness in most materials. Thus, it is clear that cold work and the RCS are inter-dependent in enhancing the fatigue life.

3.1. Effects of peening on materials and the residual compressive stress prediction

The peening parameters modify the following aspects of the peened material (Niku-Lari, 1981):

- Metallurgical: structure, hardness
- Mechanical : residual stresses, residual stress gradient, depth of plastic deformation
- Geometrical : roughness

A more detailed list of the different effects due to shot peening on the materials is shown in Figure 5, developed by Schulze (2002). The effect of shot peening varies depending on the microstructure of the material. It results in work-hardening, work-nonhardening or work-softening on the target material (Iida and Tosha, 1987). Work

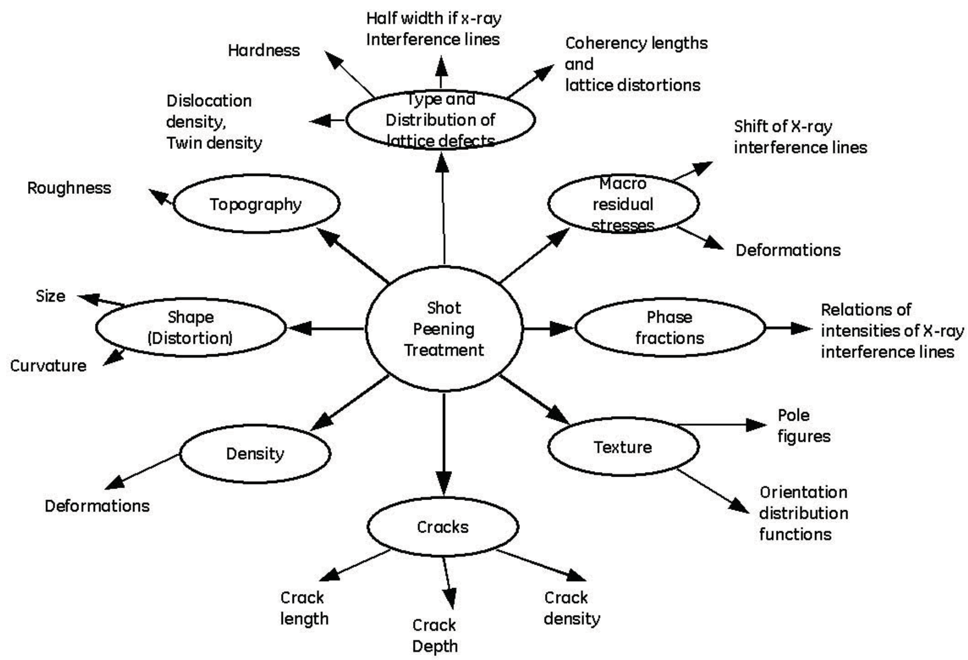

Figure 5: Changes in the material due to peening. (Schulze, 2002)

hardening occurs in the low-hardness target materials while work-softening happens in high hardness materials (Burgahn *et al.*, 1990). The material responses due to shot peening depend on the target material microstructure. But, the microstructure is also modified during the shot peening. The microstructure changes of target material include recrystallization, nano-grain formation (Xinling *et al.*, 2003), phase-transformation (Schulze and Niku-Lari, 2002) and hardness changes. For example, austenite to martensite phase-transformation occurs in steels (Ebenau *et al.*, 1990a; Kirk and Payne, 1999; Hashimoto *et al.*, 1990). Wagner and Lutjering (1984) have reported that dislocation density, residual stress and plasticity depth increased while micro-hardness decreased during peening of Ti-6Al-4V. For any material, the recrystallization to a fine structure at the surface helps fatigue properties while the coarser grain at the bulk region improves creep performance. Titanium alloys with creep-resistant coarse grain structure are peened and annealed at high temperatures to form fatigue-resistant fine grain structure at the surface (Gray *et al.*, 1987a). Inco718 alloy shows improvement in fatigue possibly due to the elimination of small machining defects(Guedou and Evry, 1987). The Rene-95 powder superalloy undergoes reduction in microporosities due to SP and the fatigue strength improves due to RCS, smaller grain-size resulting in increased density(Ru *et al.*, 1996). Even in the case of ceramics, SP is able to induce RCS to a magnitude of 1GPa apart from fracture toughness improvement(Pfeiffer and Frey, 2005). Zhang and Lindemann (2005) have studied the high cycle fatigue behavior of AZ80 magnesium alloy due to peening. Increasing beyond certain peening intensity reduced the fatigue strength possibly due to increased crack size in the surface layer. This could be due to the hexagonal structure with limited deformability by slip (Dorr *et al.*, 1999). The metallic surfaces are also significantly modified by shot peening. The surface topographies due to cold work of aluminium alloy, copper alloy and austenitic steel materials are provided by Kohler and Hornauer (1987). The surface roughness due to SP is analyzed as a local increase in the far-field stress (Rodopoulos *et al.*, 2002).

Most theoretical studies have been performed to determine the improvements at continuum level. The approaches used to predict RCS due to shot peening can be broadly classified into empirical, analytical and numerical methods. In early studies, the efforts were focused on relating the residual stresses found from experiments in empirical or in semi-empirical forms. For example, DeLitizia (1984) measured the residual stresses in spring steel plates by X-ray diffraction (XRD) method and came up with a cubical expression of depth for the residual stresses. Wang *et al.* (1998) have conducted a series of experiments on different steels and aluminium alloys. They have empirically determined the relationships between material properties such as yield strength, σ_y, the ultimate tensile strength, σ_u, and the peening intensity to the response parameters such as the surface and maximum values of RCS, total depth of RCS and depth of maximum RCS using regression methods. Li *et al.* (1990a) have come up with similar empirical relations as functions of yield and ultimate strengths of the target material, coverage, shot diameter and the dent diameter. These empirical relationships have limited applicability depending on the range of parameters tested in the experiments.

Analytical methods usually provide a computational advantage, but with a trade-off on modeling accuracy. General approach solving for RCS due shot peening in such methods involves, analysis of a single shot and based on the results of the single shot, RCS due to multiple shots are estimated. To estimate the stresses developed in a single shot, the analytical solution proposed by Hertz is considered. The expression for the maximum elastic compressive stress, σ_c for two spheres in contact (Timoshenko and Goodier, 1970):

$$\sigma_c = -0.62\left[\left[\frac{P}{\Delta^2}\left[\frac{1}{R}+\frac{1}{R_s}\right]^2\right]\right]^{1/3} \tag{2}$$

where P is the contact force, E is the elastic modulus, ν is the Poisson's ratio, R is the shot radius and $(1/E_0) = \frac{1}{E_s}(1-\nu_s)^2 + \frac{1}{E}(1-\nu)^2$ represented by Δ. The subscript s denotes the shot and the variables without any subscript point to the target material. Satraki *et al.* (2005) have found that the analytical solution proposed by Hertz represents the maximum compressive stress for two spheres in contact. Based on the Hertz contact analysis approach, Al-Hassani (1981) proposed an estimate of the plasticized depth as a function of peening parameters using a damage number represented by $\rho V^2/p$ from the following equation of motion:

$$\frac{4\pi}{3}\rho R^3\frac{dV}{dt} = -\pi a^2 p \tag{3}$$

where p is the average pressure resisting the motion and is evaluated as,

$$\frac{p}{\sigma_y} = 0.6 + \frac{2}{3}\frac{Ea}{\sigma_y R} \tag{4}$$

The plasticized depth due to single impact is calculated as:

$$\frac{h_p}{R} = 2.57(\frac{2}{3})^{(1/4)}(\frac{\rho V^2}{p})^{(1/4)} \tag{5}$$

where h_p is the thickness of plastic layer. This value of h_p is used in further calculations of the residual stresses in thin plates. The approach for calculating the RCS is by using the concept of 'source' stress introduced by Flavenot and Nikulari (1977). The residual stresses are evaluated by superimposing the bending and axial stresses onto the 'source' stress which is a function of the plastic layer thickness. Al-Obaid (1995) has introduced a different scaling factor of 3 in stead of 2.57 in the previous expression. Watanabe and Hasegawa (1996) has modified the expression for thickness of plastic layer with more terms that contain the cubic expressions.

Al-Hassani (1982) further elaborated on the role played by shakedown, reverse yielding, Bauschinger effects and strain-rate in the accurate prediction of RCS. Li *et al.* (1990b) have introduced the concept of internal fatigue strength as their theory relates the fatigue failures to subsurface residual tensile stresses in stead of the residual compressive stresses at the surface layers. On the contrary, in their experimental studies on Ti-3Al-2V alloy, Hanyuda *et al.* (1993) conclude that the fatigue strength improvement depends mainly on the magnitude of surface RCS and not on the tensile stresses developed inside the material.

Based on experimental observations, Johnson (1987) proposed a different approach in which the spherical indentation in an elastoplastic half-space is considered. It is equivalent to a spherical cavity expanding in an infinite medium with the same elastoplastic property, which is commonly cited as the expanding cavity model (ECM). In a spherical coordinate system, for $p > 2\sigma_y/3$, the stress field in the plastic zone ($a < r < c$) is given

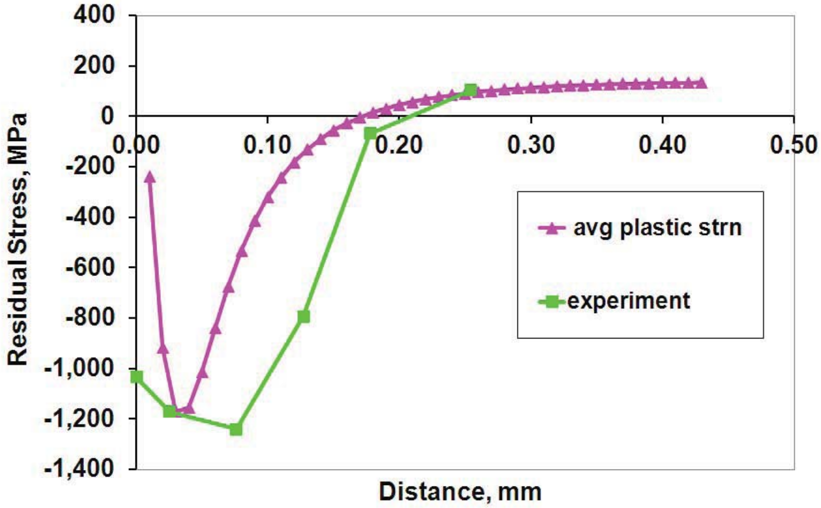

Figure 6: Comparison of residual stresses obtained by analytical method with experimental results reproted by Cammett *et al.* (2005)

by:

$$\sigma_{rr}(r) = -2\sigma_y ln\frac{c}{r} - \frac{2\sigma_y}{3} \tag{6}$$

$$\sigma_{\theta\theta}(r) = \sigma_{zz}(r) = -2\sigma_y ln\frac{c}{r} + \frac{\sigma_y}{3} \tag{7}$$

where a is the indentation radius and c is the plastic zone radius. In the elastic zone ($r > c$), the stresses are given by,

$$\sigma_{rr}(r) = -\frac{2\sigma_y c^3}{3r^3} \tag{8}$$

$$\sigma_{\theta\theta}(r) = \sigma_{zz}(r) = +\frac{\sigma_y c^3}{3r^3} \tag{9}$$

The expression for $\sigma_{\theta\theta}(r)$ due to spherical indentation, again can be merged together for obtaining the stresses in a thin plate, similar to the method explained before. The current expression provides more accurate prediction as the maximum stress occurs exactly at a depth of h_p below the surface.

Li *et al.* (1991) utilized the Hertz theory of elastic contact and a simplified elastoplastic theory to develop simplified formulae to predict the maximum value and the peak depth of the RCS field. Shen and Atluri (2006) have extended the analytical method proposed by Li *et al.* (1991), that considers shot velocity, to predict the residual stresses. This method uses a linear hardening material model and reverse yielding for rate-independent plastic deformations. It approximates the calculation of plastic strain through the ratio of indentation diameters in elastic and elastic-plastic cases. When multiple impacts occur, residual stresses prevent further plastic flow and after a few cycles the entire deformation will be elastic, thus causing shakedown (Al-Obaid, 1993). Shen and Atluri (2006) have applied a relaxation factor on the single shot residual stress results in order to assess the effect of multiple impacts. In all the works described above, the contact is assumed to be quasi-static. As peening is a dynamic event with high strain rates, it is important to consider strain-rate effects for better estimates of peening. Bhuvaraghan *et al.* (2010a) have included the strain-rate effects in the method proposed by Shen and Atluri (2006). They have considered the average plastic strains along the indentation to evaluate the residual stresses due to multiple impacts. Figure 6 shows the comparison between the residual stresses evaluated by analytical method and the experiemntal values reported by Cammett *et al.* (2005).

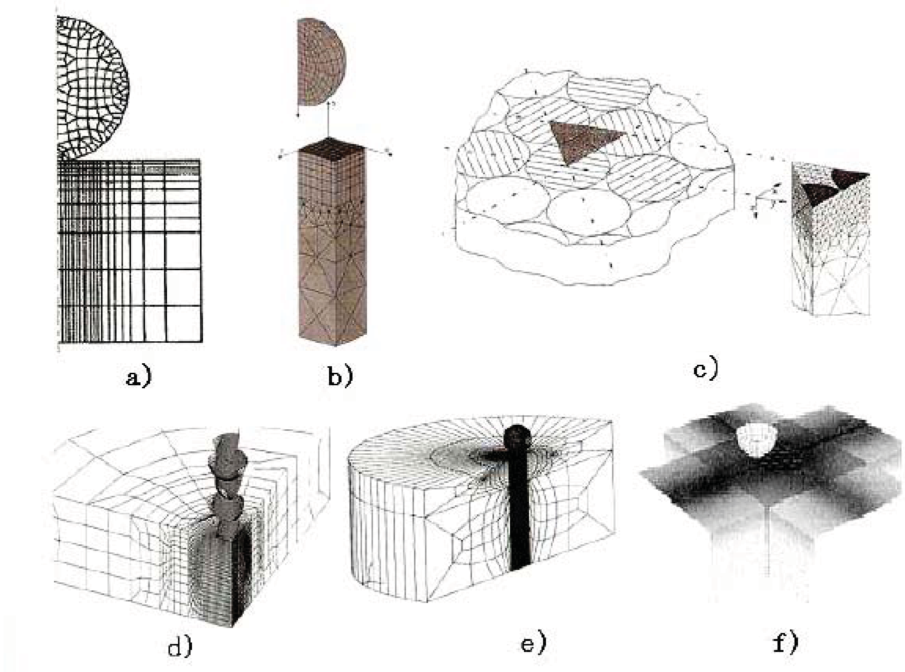

Figure 7: FEM based simulation techniques used by a) Mori *et al.* (1994) [2D], b) Meguid *et al.* (2002), c) Schiffner and Helling (1999), d) Guagliano (2001), e) Baragetti (2001) and f) Schwarzer *et al.* (2002) [(b) to (f) different unit cells with different predetermined location concepts]

The need for handling complex geometries and material models coupled with enhanced computing power have made numerical simulations a preferred choice for the designers. The numerical studies that have been done use mostly the finite element method (FEM). While most approaches use a unit cell, each of the modeling approaches are quite different from the other. The Figures 7 and 8 show a few different FE modeling approaches employed in shot peening simulations (Mori *et al.*, 1994; Meguid *et al.*, 2002; Schiffner and Helling, 1999; Guagliano, 2001; Baragetti, 2001; Schwarzer *et al.*, 2002). The simulations range from 2D to 3D, from single impact to multiple impacts and predetermined locations to random locations with different material laws.

A few such simulations are covered in the following paragraphs. Using ADINA software, a two-dimensional axi-symmetric analysis has been performed by Schiffner and Helling (1999). This analysis, which has included dynamic effects as well, is one of the first attempts on shot peening simulation. In another two-dimensional simulation, Meo and Vignjevic (2003) have analyzed the residual stress development in the welded structures due to shot peening using transient dynamic method by a single shot impact simulation. The tensile stresses from the weld are modified by the compressive stresses due to shot peening by superposition. Baragetti (2001) has used axi-symmetric analysis to determine the residual stress field. The main limitation of these analyses is that it is capable of simulating either single impact or co-indentations only.

In a unique study by Levers and Prior (1998), pre-stress effects have been created using temperature loads to avoid the complexity of modeling of multiple impacts. This has been extended by Gardiner and Platts (1999) to simulate shot peen forming (SPF). Wang *et al.* (2006) also have used an equivalent temperature load, that produces the same strain pattern as that of multiple shots alternately to predict SPF.

Realizing the limitations of 2D analysis, researchers have resorted to 3D simulations. Meguid *et al.* (1999) have simulated single and double shot impacts through an elastic-plastic three-dimensional impact analysis for different shot velocities, sizes and hardening characteristics. A unique simulation involving ellipsoidal shots is also performed to see the shape effect of shots. Kyriacou (1996), Baragetti (2001) and Guagliano *et al.* (1999) also have performed a 3-D FEM simulations to simulate shot peening. Using LS/DYNA software, Meguid *et al.* (2002) have analyzed the effect of peening on AISI 4340 steel through a 3D analysis. Another study involving

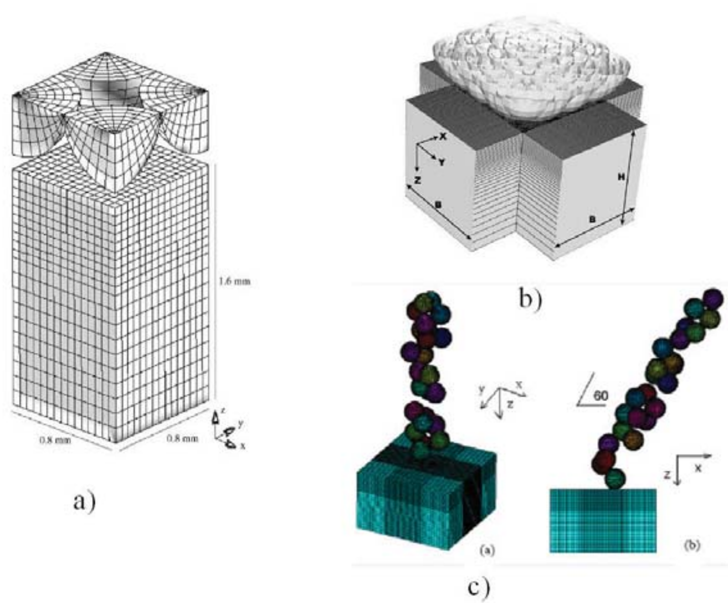

Figure 8: FEM models by unit cell methods a)Majzoobi *et al.* (2005) (rate dependent model), b)Klemenz *et al.* (2005)(combined hardening model) and c)Miao *et al.* (2009) (model with random locations)

LS/DYNA software is performed by Majzoobi *et al.* (2005). They have simulated multiple shot impacts using LS/DYNA software for different velocities. They have found good correlation with tests conducted by Torres *et al.* (2002). Guagliano and Vergani (2004) have combined FEM and a set of non-dimensional parameters to relate the peening parameters and the stresses. Li *et al.* (2007) have performed two types of simulations, viz., single and multiple impact simulations, with strain hardening. Meguid *et al.* (2007) have employed an enhanced unit cell method which has increased the number of impacts at the cost of simulation time. All these processes involve shots located in a predetermined manner to get the required coverage. Miao *et al.* (2009) have extended the approach by Guagliano and Vergani (2004) by applying random impacts on a unit cell of aluminium.

While using unit cell approach, static stabilization runs are required to annul the effect of stress wave propagations. Infinite element boundaries reduce the simulation time by eliminating the static runs that eliminates inertial effects. A 3D analysis is performed for simulating multiple shots using ABAQUS-explicit tool that uses infinite boundaries by Schwarzer *et al.* (2002). The infinite elements are added only on the sides and also the shots are arranged in a predetermined way. Klemenz *et al.* (2009) have performed 3D explicit analysis using ABAQUS program with infinite elements with very similar unit cell. The authors have performed a unit-cell based FE simulation with rate-dependent properties and random impact locations 9.

Double-sided peening has been simulated with two-step process of explicit and implicit analyses to correlate with experiments (Kopp and Schulz, 2002). In a unique study, relatively large number of impacts are simulated using FEM approach by Wang and Platts (2002). Based on plastic strain levels the coverage is estimated and an explicit-implicit analysis is done to simulate the impact of nearly 1000 balls.

Though Almen strips are widely used in the industry, very few attempts are seen to predict their intensities and the related RCS distributions. However, Guagliano (2001) has applied an FEM based approach to calculate the RCS distribution at the impact point in SAE1070 and 30NiCrMo3 steels due to multiple shots with regular locations. The RCS distribution, thus obtained, is used to evaluate the Almen intensity using theory of elasticity approach, as mentioned by Al-Obaid (1995). The final RCS is assumed to be the sum of the RCS from FEM analysis and stresses due to equilibrating axial force and moment appearing when Almen strip is removed from its holder. Bhuvaraghan *et al.* (2010c) have performed simulations to capture the actual peening process on the Almen strips with random impacts. Figure 10 shows the FE model while Figure 11 shows the defelction obtained

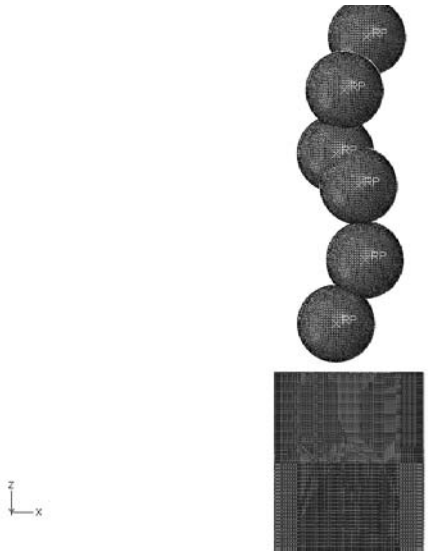

Figure 9: Unit cell simulation with random shot locations. The number of shots are derived based on the indentation diameter from a single shot impacting at the same velocity and angle.

from the analysis. The authors have expressed the residual stresses in the actual material in terms of the stresses in the Almen strip through the ratio of the dynamic yield strengths of the respective materials.

Some of the key findings from various numerical studies are summarized here:

Kyriacou (1996) has concluded that higher the hardening modulus, the lower is the maximum sub-surface compressive stress. This result is also confirmed by experiments conducted by Torres *et al.* (2002). When the material hardness is high, less energy is absorbed to deform the surface layer plastically, but more energy is used to deform the deeper layers due to Hertzian loads (Wohlfahrt, 1984). Guagliano *et al.* (1999) have come up with a peening index, $N = V\sqrt{(\rho/\sigma_u)}$ where ρ is the shot density, σ_u is the target material strength. This parameter is used to define other material response parameters such as RCS in non-dimensional forms. They also have concluded that the first impact has maximum effect on the RCS value at any impact location.

Webster and Ezeilo (2001) have indicated that apart from temperature effect, high cyclic plastic strains can also wipe out the fatigue strength improvement in the part due to peening. Meguid *et al.* (2002) have concluded that strain-rate is a key parameter that affects plastic strain and residual stresses along with shot velocity and hardness. The residual stresses depend on the coverage and their distribution is uniform when subjected to multiple impacts. The friction effect on both plastic strain and compressive stresses is very minimal. The multiple impacts are located in a predetermined manner to assess the influence of the distance between the impacts.

Single-shot simulation indicates that the dent formed is influenced by the yield strengths of shot and material and the hardening effects (Hirai *et al.*, 2005). Stress stabilization after a small number of impacts at the same location based on FE analysis has been reported by Nakonieczny and Monka (2005). The results from the simulation by Meguid *et al.* (1999) reveal that the depth of the compressed layer and the surface and sub-surface residual stresses are influenced by shot velocity, shot shape and to a lesser extent by the strain-hardening rate of the target. However, with strain rate-dependent models, the effect of strain-hardening is likely to be more significant. Majzoobi *et al.* (2005) have concluded that beyond certain limit, the RCS will decrease as velocity increase. It is shown that the stress field created by impacts of first set of shots being is made inhomogeneous by subsequent impacts (Helling and Schiffner, 2001).

The SP process results in the modification of material properties and roughness. Conventional meshing techniques are difficult to be applied where the surface deformations are extremely high. Adaptive meshing

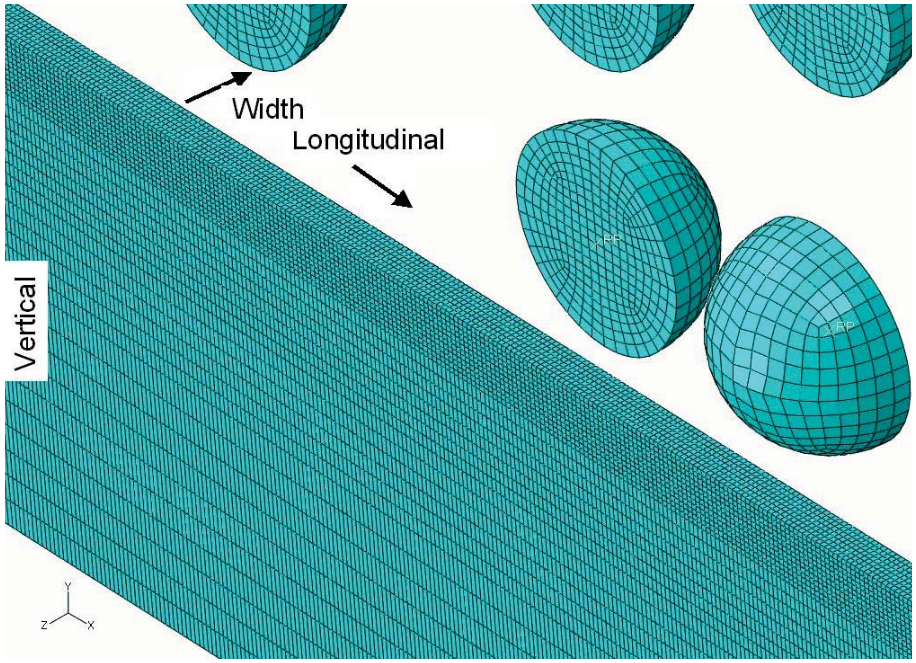

Figure 10: Almen Strip simulation. The shots are located randomly along the length.

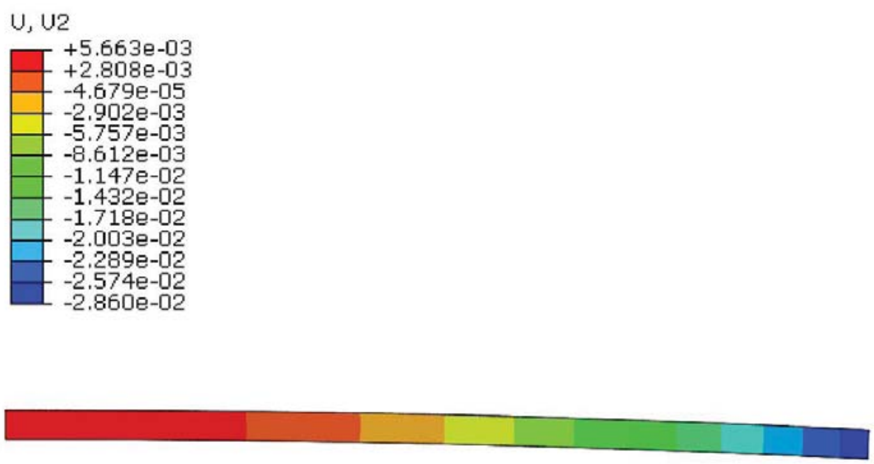

Figure 11: Longitudinal deflection of Almen strip in inches.

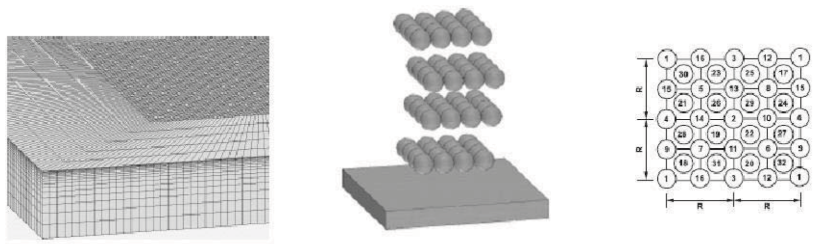

Figure 12: Multi shot simulation by discrete element method by (Han and Peric, 2000)

techniques and meshless methods can be employed to simulate the surface effects and reduce the computing costs.

The simulation process, to be more realistic, must have the ability to handle large number of shots impacting at random locations and rate-dependent properties. An elastic-plastic FEM analysis with many shots demands a lot of computing resources. The discrete element method (DEM), used for particle dynamics, is coupled with FEM to simulate peening by a few researchers to address this issue. An overview of combined DEM/FEM method is given in Ref.(Munjiza, 2004) where the interactions between entities are governed by DEM while each entity is meshed by FEM.

The shots are generated by particle factories. The target surface is modeled with triangular tessellations. There can be shot-shot and shot-target contacts which are assumed to be elastic. The major steps involved in the DEM are the contact detection, the force calculation at the contact locations and updating the frame. The contact detection is efficiently handled by considering bounding box techniques and employing octree data structures. Different contact laws are available for force estimation. The contact forces are evaluated based on the model chosen by the designer using the contact overlap. Based on the force magnitude and directions, the positions of shots are updated. The shots that cross the domain are removed from the calculations. New shots are continuously added till the simulation time is complete.

Han *et al.* (2000) have performed a two-dimensional analysis treating the sphere as a rigid circle. They have used different interaction laws (linear, Hertz, Winkler and power laws) and also included damping. In the 2D DEM-FEM analysis the surface stresses have been evaluated as tensile in nature, necessitating three-dimensional analysis for more accurate stress prediction. The work has been extended with three-dimensional models by the same authors (Han and Peric, 2000). They have also simulated multi-impact (Figure 12) and found that the single-impact results have been significantly different from multi-impact results. The above studies using discrete element methods may preclude the effects of shots made from different materials and hardness. Hong *et al.* (2005) also have performed DEM based shot peening simulations. Though the plasticity effect is brought in through coefficient of restitution (CoR) in the DEM simulations, the work focuses mainly on the kinetic energy loss as a measure of residual stresses. It does not attempt to calculate the residual stresses and strains in the target material. The effect of strain hardening on CoR is not included. Bhuvaraghan *et al.* (2010d) have developed a new method to connect DEM to FEM. This is accomplished by transferring the contact forces from DEM to equivalent pressures in FEM. The strain-rate effects are included in the material model in FEM and the CoR is appropriately modified to include the strain hardening due to random impacts. Figure 13 shows the shot peening simulation using DEM. In shot peening, DEM can be used to handle peening of non-regular target surfaces such as fillets and non-spherical shapes of shots. The method can be expanded to include appropriate material models to calculate the contact forces and stresses. Figure 14 provides the approach to simulate SP using FEM-DEM approach.

Material models. The effect of shot peening can be captured effectively only if the material models accurately depict the material behavior. Most of the material models used today are not capable of linking the shot peening to the microstructural changes. However, they can predict the hardening/softening effects.

Many of the material models used in the studies are rate-independent and linear hardening. For example, a

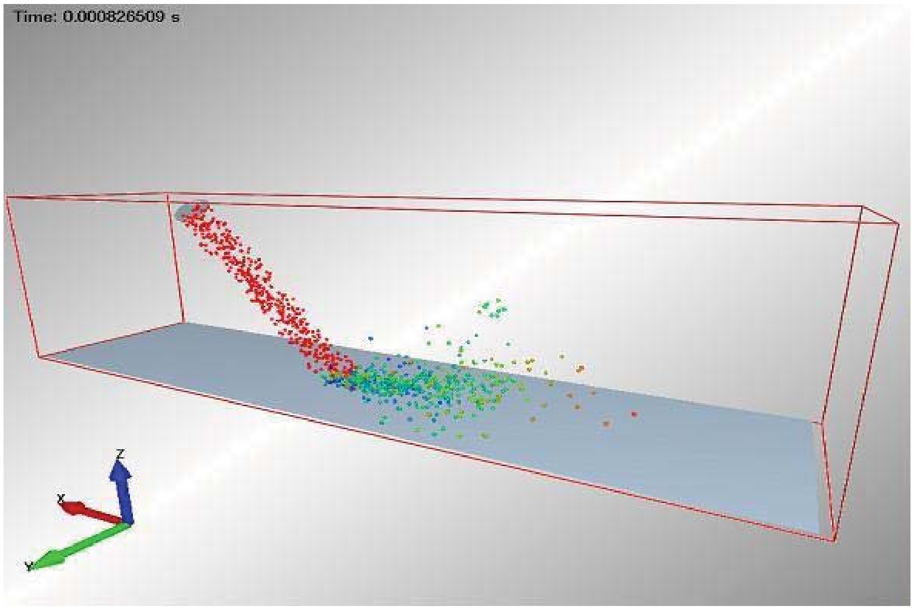

Figure 13: Shot peening simulation using DEM

3-D elastic-plastic analysis with strain-hardening is performed by Kyriacou (1996) with linear hardening models. Another example is the work by Guagliano *et al.* (1999) who have performed a 3-D FEM simulation with kinematic hardening material model. Similarly, the simulations performed by Miao *et al.* (2009) have used rate-independent properties.

A few unique examples are discussed here. Meguid *et al.* (2007) have included the strain-rate properties of Ti-6Al-4V alloy, by extrapolating from the static stress-strain curve. The approach by Al-Hassani *et al.* (1999) has used Cowper-Symonds equation for predicting the stresses and strains for different strain rates due to co-indentations. The material model does not segregate the strain, strain rate effects. Slim *et al.* (1995) use the elastic-plastic method proposed by Zarka and Inglebert to calculate RCS. This model consists of cyclic constitutive relations that are developed by a family of internal parameters. The effect of temperature rise due to SP is coupled with mechanical effects through a thermo-elastic plastic model (Rouquette *et al.*, 2005). Fathallah *et al.* (1998, 1996) have used the material model by Guechichi and Khabou, while Barrallier *et al.* (2001) use Chabache model for engine disk components. The Chabache model is capable of handling both isotropic and kinematic hardening through two internal variables and back stress. It is to be verified if the model is applicable for large cold work occurring in the surface layers due to shot peening. Klemenz *et al.* (2009) also have performed using combined hardening visco-plastic (Chabache) model. Frija *et al.* (2006) have used a combined damage model of Chabache and Lemaitre for Waspalloy. This model considers the surface defects due to shot peening in the form of a damage parameter. Elastic-plastic material model with strain rates, damping and deformable shot are considered to predict the stress field due to SP (Eltobgy *et al.*, 2004).

A comprehensive study on the effect of hardening models is conducted by Rouhaud *et al.* (2005). They have found that isotropic hardening model gives better shape compared to kinematic and combined hardening models. They have also found that the RCS continuously increases due to successive impacts when isotropic hardening is used. These models, however, do not consider strain-rates.

The material models used include both rate-independent and rate-dependent models. As SP induces stress waves, rate-dependent models are more appropriate. Besides, the material is likely become anisotropic due to cold work which also needs to be considered in modeling. The hardening of many materials is not purely isotropic or kinematic. Studies must include such combined hardening effects in future. To simulate relaxation, material models that include cyclic stress-strain relations that are temperature and strain-rate dependent are required.

A consolidated database with predictive capability is a major source of help for the designer, as it provides

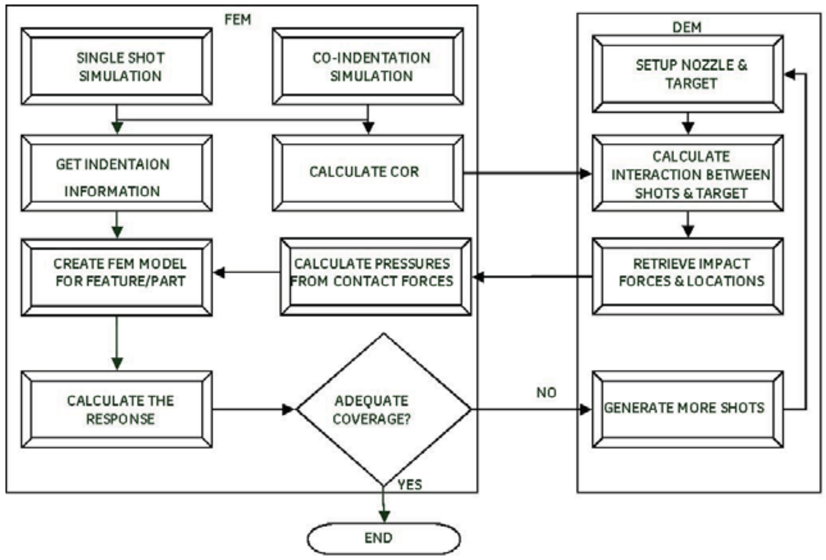

Figure 14: Schematic combined DEM-FEM method. The contact forces and duration from DEM method are applied to FEM on random indentation areas as equivalent pressures. The pressure variation are applied from single-shot analysis.

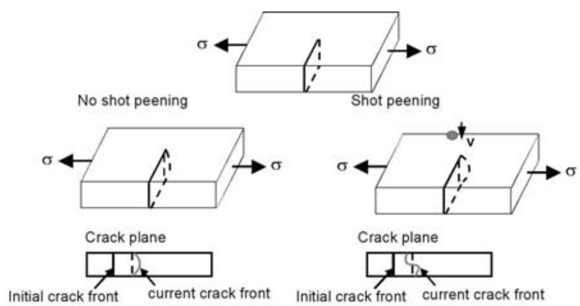

Figure 15: Crack Growth with and without SP

the necessary information with negligible effort and in little time. *Peenstress* is a software developed by Metal Improvement Company that helps to choose the correct process variables and it predicts the velocity and RCS (Wandell, 1997; Guernic and Eckersley, 1996) for the given shot, material and intensity. The software has a library of materials and geometries to choose from. As further enhancements, FEM and knowledge integration can form the first step in this multi-disciplinary work, similar to what is mentioned by Crump *et al.* (2005). Information based approach can be used to analyze the complex processes, as discussed by Azizi and Disfani (2005). This can result in consolidating all the knowledge that has been acquired into a common database. Neural networks can be used to predict material response for any combination of shot and target materials and other input parameters.

4. Crack growth prediction

SP induces residual stresses, cold work and surface roughness and each response parameter is critical in fracture mechanics studies. To have low fatigue crack growth, the surface residual stress should be as high as possible (Tange and Takamura, 1990). Figure 15 gives the crack growth phenomenon with and without SP, peened on one side. It can be visualized that RCS prevents the crack growth. Surface roughness accelerates the crack initiation while cold work retards it. Gray *et al.* (1987b) point out that the crack nucleation is primarily

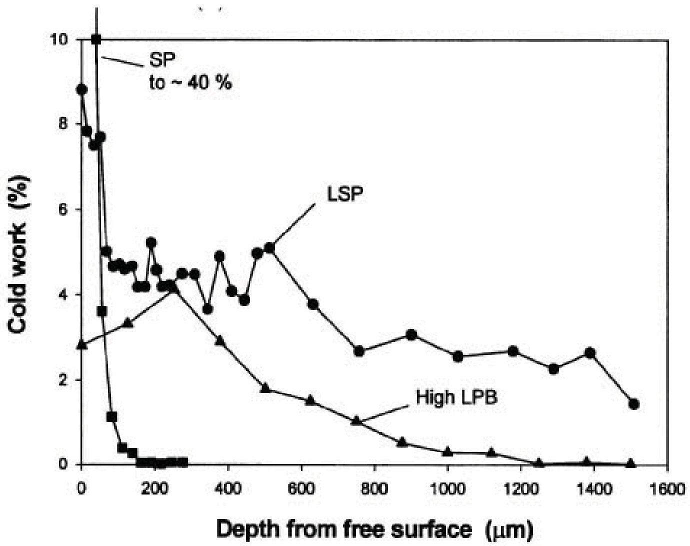

Figure 16: Relaxation due to loads(Zhuang and Halford 2001)

due to surface roughness. The propagation is controlled favorably by RCS and unfavorably by high dislocation density. Altenberger (2002) also point out that crack propagation is accelerated by cold work but is retarded by RCS. Fine crystalline structure at the surface helps in controlling crack initiation while the coarser bulk material retards crack growth (Schulze, 2002). This occurs as RCS reduces the tensile stresses at the crack tip (Naito *et al.*, 1990).

Due to the residual compressive stresses, SP shifts the fatigue crack zone to the subsurface area (Gao *et al.*, 2003). This is beneficial as the fatigue strength is higher here. The RCS and the hardened layer make crack formation not occur in the surface, but still micro-cracks develop at sub-surface.

Crack initiation life has been predicted using equivalent strain energy density with Neuber's rule and Morrow's equation (Ferreira, 1996). Jaensson (1981) has indicated that the crack initiation mechanisms, such as shear mode or tensile mode, are dependent on the preload type.

FE models with residual stresses, contact between crack faces and applied load have been used to predict SIF (Guagliano, 2001). Another FE analysis calculating the stress intensity factor (SIF) has concluded that SP induced RCS has locally retarded the crack growth, but has not affected in an overall sense (Honda *et al.*, 2006). Analytically, it is shown that the crack growth is delayed in RCS environment using fracture mechanics and S-N curves. The conditions for crack arrest are presented in the form of fatigue damage map (Rios *et al.*, 2000). Romero *et al.* (1999) propose a suitable adaptation of Navarro-Rios model using microstructural fracture mechanics.

5. Stress relaxation

When mechanical and/or thermal loads (static and cyclic) are applied, the RCS relaxes to lower levels (Konig, 2002). The stages of residual stress creation and relaxation are explained by Bonnafe *et al.* (1987):

- cyclic cold working with RCS evolution
- plasticization of surface and stabilization of stresses
- appearance of micro-cracks without any change in stresses
- coalescence of cracks with stress relaxation

Figure 16 provides a perspective of relaxation due to mechanical loads (Zhuang and Halford, 2001). This relaxation phenomenon is observed in many metallic materials. Hasegawa *et al.* (1993) have observed relaxation in carbon steel when high-temperature fatigue testing is performed. Torres and Voorwald (2002) and Hanagarth *et al.* (1990) have observed relaxation in AISI 4340 and 42CrMo4 steels. Aluminium alloys also exhibit stress relaxation similar to steels (Bonnafe *et al.*, 1987) and (Roth and Wortman, 2002). Stress relaxation is reported in titanium alloys such as Ti-6Al-4V, by Boyce *et al.* (2003) and Lee *et al.* (2005). Superalloys, such as Inco100, Inco718 are also found to exhibit stress relaxation behavior due to mechanical and thermal loads (Buchanan *et al.*, 2004), (Ofsthun, 2003).

McClung (2007) points out that the RCS does not relax to zero due to these loadings. The fatigue strength drops below the unpeened value at elevated temperatures because the surface roughness remains, but the stress relaxation occurs (Kato *et al.*, 1996). Buchanan *et al.* (2004) have concluded that the benefit of residual stresses can still be considered in the design despite the relaxation effects. Capello *et al.* (2004) report that stress relaxation starts from first cycle of mechanical loading. According to Zhuang and Halford (2001), the relaxation depends on the surface cold work, stress amplitude and the cycles. The heat generated during SP may reduce the residual stresses (Vohringer, 1987).

A few researchers have utilised analytical expressions to predict the stress relaxation. The relationship for stress relaxation due to cyclic loads is given by the following Morrow's equation (Lieurade and Bignonnet, 1987):

$$\frac{\sigma_m(N)}{\sigma_m(0)} = \frac{\sigma_{ys} - \sigma_a}{\sigma_m(0)} - \Big[\frac{\sigma_a}{\sigma_{ys}}\Big]^b \tag{10}$$

and due to temperature(T) and time (t) by the relationship:

$$\sigma_R(t) = \sigma_{R0} - \frac{RT}{\beta} log\big(\frac{t}{t_0} + 1\big) \tag{11}$$

where β and t_0 are material dependent constants. An empirical Zener-Wert-Avrami equation is used to represent stress relaxation given by

$$\frac{\sigma^{RS}(T,t)}{\sigma_0^{RS}} = e^{(-At)^m} \tag{12}$$

where m and A are constants. A depends on material defined by $A = Ce^{(-Q/kT)}$ where C is a constant. The Avrami equation has been able to predict the relaxation in Timetal (Berger and Gregory, 1999) and 42CrMo4 steel (Schulze *et al.*, 1993). Analytical models using strip method (Wang and Liu, 2002) show good correlation of relaxation rate with experimental results.

Stress relaxation is evaluated numerically, as mentioned in the following studies. In order to simulate the relaxation due to quasi-static loading at high temperatures, FE model with different material properties at different layers are used (Iida, 1993). Including the cyclic properties of the surface layer after peening helps in better prediction of the relaxation (Lu and Flavenot, 1987). Using ABAQUS code, Dattoma *et al.* (2004) have simulated stress relaxation with welding as a prestress condition . Johnson-Cook model is used to evaluate stresses at different temperatures. Meguid *et al.* (2005) have developed a unit cell involving strain-rate, multiple impacts phenomena to calculate the shot peening and subsequent relaxation effects. Different hardening models (isotropic, kinematic and chaboche) have been performed. Thus, appropriate material models that can capture both development and relaxation of RCS are the best to be used to cover the reduction of yield strength due to temperature along with relaxation due to loads.

6. Optimization of the responses

Inadequate peening causes poor development of RCS. Boyce *et al.* (2003) have observed significant tensile stresses at the indentation edge. In the case of multiple overlapping shots, the tensile zone is offset as a result of successive impacts, which indicates that incomplete peening coverage will leave uncompressed rims leading to degradation of fatigue life. Kyriacou (1996) also has come to the same conclusions about incomplete coverage. Similarly, Li *et al.* (2007) have determined the influence of coverage ratio on the residual stress and mechanical properties which are validated by experiments. In many peening applications, 100% coverage is specified. For

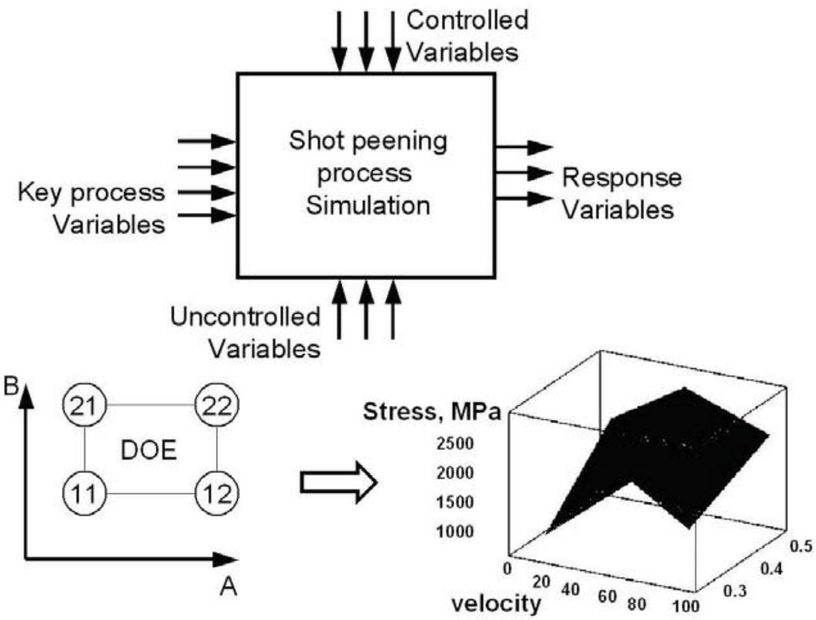

Figure 17: Design of experiments- a schematic representation

some critical components, even beyond 100% coverage is required. However, researchers such as Cammett *et al.* (2005) have mentioned that 100% coverage is not required as the plastic zone size is always larger that the dent size.

On the other hand, overpeening can cause cracks even on the surface. At highly localized areas, it can cause even erosion of metals (Sharma and Mubeen, 1984). For example, when coverage upto 600% is reached in CrMo gear steels, white layer of adiabatic shear bands are formed which can cause tooth-chipping (Adachi, 1990). More cold work arising out of such overpeening can cause even inversion of stress thus reducing the compressive stress (Happ, 1987). Therefore the designer needs to optimize the shot peening parameters.

Design of experiments (DoE) studies are generally employed for optimizing responses of any process. The design space defines the range of values for the input parameters. The values of the output parameters are obtained from either experiments or simulations. The regression generally uses polynomial functional fits, parabolic or cubic. Subsequently, the optimization is performed by gradient method which is an incremental approach. Figure 17 shows the DoE methodology in a schematic way.

Some of the optimization studies (experimental and theroretical) based on DoE method are presented here. Baragetti (1997) has proposed design of experiments (DoE) based optimization of peening parameters. Five response parameters, such as maximum RCS, have been measured with respect to six control parameters to optimize through an DoE study by Petit-Renaud (2002). This study is likely to cause less accurate response surfaces, as it uses quadratic expression for developing the surface fits. Taguchi technique is used to optimize the shot peening parameters by George *et al.* (2004). The Taguchi method is more efficient than DoE approach as it uses orthogonal arrays to reduce the number of sampling points and Analysis of Variance (ANOVA) technique to identify process parameters that are statistically significant. A DoE study has been conducted on SAE 8620 material to determine the optimum peening parameters (Lassithiotakis *et al.*, 2005).It is found that the surface RCS is influenced by mass flow rate and impact angle of shots. The maximum RCS is influenced by the peening time and air pressure (velocity). The air pressure also influences the depth of the maximum RCS. In another study involving ABAQUS explicit code, an elastic-plastic analysis has been performed to study the peening parameters for steel and aluminium (Eibella *et al.*, 2006). A two-dimensional FEM based parametric study has been performed by Zion and Johnson (2006) with single shot impact. The study concludes that the shot with hardness higher than the target provided better RCS than the softer shot.

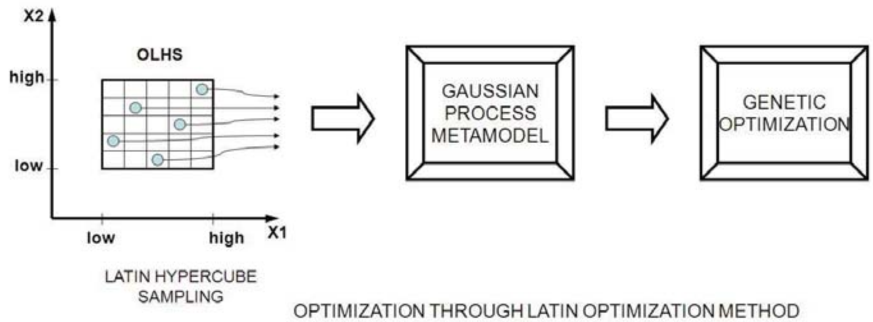

Figure 18: Optimization by DACE(Design and analysis of computer experiments). In this method, better meta-models are built using radial basis functions and genetic algorithms are employed for optimization. The random variation of input parameters are considered in obtaining the robust optimization.

In such optimization studies, different researchers have chosen different input parameters. For example, Seno *et al.* (1990), in a DoE study, have found that the shot hardness and exposure time to have influence over the RCS while stand-off distance and shot diameter have less influence. Tufft (1999a) has conducted a DoE study of peening parameters and concluded that velocity is the key parameter influencing the intensity and it influences the slip band development and transient temperature rise (Tufft, 1999b).

Different response parameters of the target material are also identified for optimization. The area under the RCS distribution curve between the surface and maximum values is used as a measure of fatigue property (Xu *et al.*, 1981). Wohlfahrt (1987) point out that in an optimum condition, the surface roughness should be as low as possible with the magnitude and depth of RCS should be as high as possible. The optimum results depend on the ratio of compressive stress layer to the tensile stress layer. Simpson and Probst (1987) have concluded that the optimum intensity range is determined by the peening induced surface damage rather than by RCS. Baragetti *et al.* (2000) and Baragetti and Terranova (2000) have performed numerical simulations using DoE and have identified a non-dimensional ratio of RCS magnitude to yield point to express the shot peening conditions that can be applied to different materials with different treatments.

Randomness is associated with shot peening in many ways. Typically, the impact locations, the process parameter variations and the response such as surface roughness vary in random manner. A few studies in these areas focusing on stochastics are presented here. The impact locations are specified by random numbers to specify the coverage (Tange and Okada, 2002). The peened area is specified as a rectangular grid of points and the random locations of shots blank out the points in the grid. The ratio of the blanked out points to the total number of points defines the coverage. FEM in conjunction with statistical analysis of peening parameters is used to optimize the forming of sheet metals (Kopp and Wustefeld, 1990). A robust design method is proposed by treating some variables as controllable by Nevarez *et al.* (1996). The surface topography is simulated using Monte-Carlo method and is found to match well with experiments (Knotek and Elsing, 1987).

In summary, optimization studies have used similar, not same input and response parameters (for example, (Baragetti *et al.*, 2000). A common set of output parameters that will include both favorable and detrimental effects to fatigue is needed. The area under compression in the RCS curve, cold work, coverage and surface roughness may be considered for a given set of input parameters. These parameters will help even to model stress relaxation, when RCS reduces but surface roughness remains. Nonlinear optimization techniques using the Latin Hypercube method and genetic algorithms can provide better optimized values (Ramnath and Wiggs, 2006). Figure 18 shows such a method schematically. A probabilistic approach must find its way in the theoretical models to decide the optimum input parameter values. This approach will eliminate optimum values that can become infeasible due to inherent variation of input paramers. Covering the above aspects, a multi-objective optimization has been performed on Inco718 material that maximizes the area under compression while the

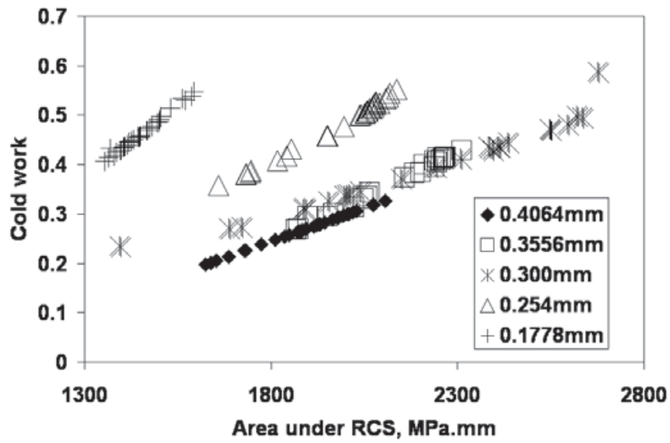

Figure 19: Pareto fronts for different shot sizes. The results are compared between area under compressive stresses and cold work. Similar comparisons can be made with surface roughness.

cold work and surface roughness are minimized (Bhuvaraghan *et al.*, 2010b). Two input variables, velocity and impact angle, are considered continuous while shot size is treated as discrete. Figure 19 shows the set of solutions (Pareto fronts) between the area and cold work for different shot sizes.

7. Discussions and future work

This section describes two different approaches to evaluate the effects of shot peening. One approach employs continuum mechanics approach to determine the final fatigue life. The other approach proposes a dislocation dynamics based approach.

7.1. Continuum based integrated model approach

The studies on SP process, so far, have focused on the development of RCS and cold work, fatigue strength optimization, fracture or relaxation. These measures are closely linked to each other. For example, cold work development in the surface layers is the basis for RCS development. Similarly, stress relaxation is also linked to cold work.

Typically, the stresses due to loads or manufacturing are superimposed and the RCS reduces the effect of the tensile mean stress. However, the surface roughness results in stress concentration factor, K_t, thus reducing the effectiveness of the RCS. As the component is put into service, the RCS relaxes further due to static and fatigue mechanical and thermal loads. To be conservative, the reduced value of RCS needs to be considered for superposition with the applied stresses to calculate the crack initiation cycles. To this number of life cycles, the crack propagation life can be added using fracture mechanics approach. The evaluation of RCS is accomplished mostly by FEM with suitable material models. The plastic strain and the surface roughness can be also obtained from the same analysis. Using expressions such as Avrami's equation, the remaining RCS after relaxation can be obtained. Using Neuber's relation, the K_t can be evaluated. The applied mean tensile stresses can be scaled appropriately using the K_t calculated before. The net RCS can be used in the evaluation of the crack initiation life for the applied multi-axial stresses. While numerical or analytical fracture mechanics can be used to get additional life due to crack propagation, it must be noted the RCS relaxes due to crack propagation. These steps are shown in the Figure 20.

The effect of microstructure in continuum mechanics based approach is handled by appropriate material models. These material models are employed to obtain mostly the residual stresses. This can be extended to cover the relaxation through FEM, as performed by Meguid *et al.* (2005). Rate-dependent models that consider

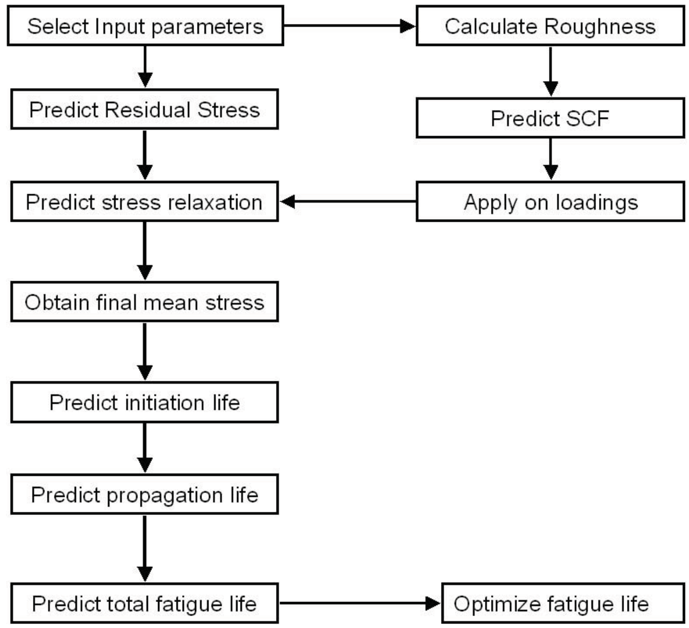

Figure 20: Unified approach in predicting the fatigue life

combined hardening and anisotropy due to work hardening are more appropriate. These models must consider the cyclic stress-strain relations that are temperature and strain-rate dependent to simulate relaxation. The simulations can be extended further to include the numerical fracture mechanics.

Another area where limited efforts are found is the thermal effects. The cold work due to the SP process is likely to cause an increase in the temperature. As the crystal structure is likely to change at higher temperatures, more studies will be necessary to include such thermal effects. Such an integrated approach with thermo-mechanical material models considering all the aspects together is yet to be realized.

Neural networks can be used to predict material response for any combination of shot and target materials and other input parameters. Similarly, parallelizing the DEM/FEM simulation will also help to handle complex systems, as proposed by Owen and Feng (2001). Adaptive meshing techniques and meshless methods can be employed to simulate the surface effects and reduce the computing costs.

7.2. Multiscale methods

Peric and Han (2002) have advocated strongly the case for multiscale modeling in SP due to the very small shot size when compared to the size of the component (leading to spatial scaling). Researchers such as Koch *et al.* (2005) report that a strong and hard nano-crystalline structure develops due to peening. These nano-crystals form at the surface of the shot-peened component (Lu and Lu, 2005) due to dislocation formation, movement and annihilation.

In metals, dislocations cause the slip which results in plastic deformation (Hull and Bacon, 2005). Typically metals show very low dislocation density after annealing (Figure 21). Shot peening process develops high dislocation densities due to the development of plastic strains (Wagner, 1999). Work-hardening occurs due to peening when dislocations find increased glide resistance as they move, interact and change their density and distribution. The piled-up dislocations at the boundaries of plastically deformed grains make dislocations in the adjoining grains to operate. The type of fracture is again decided by the amount of dislocation generation and the way of their propagation. The higher the amount of dislocation density, higher is the stress relaxation (Altenberger, 2002). This fact is also confirmed by Hoffmann *et al.* (1987) as high dislocation density in the hardened surface creates higher relaxation than the bulk material in plain carbon steel. Hence, better understanding of the dislocation dynamics with respect to specific materials through simulations can help linking the

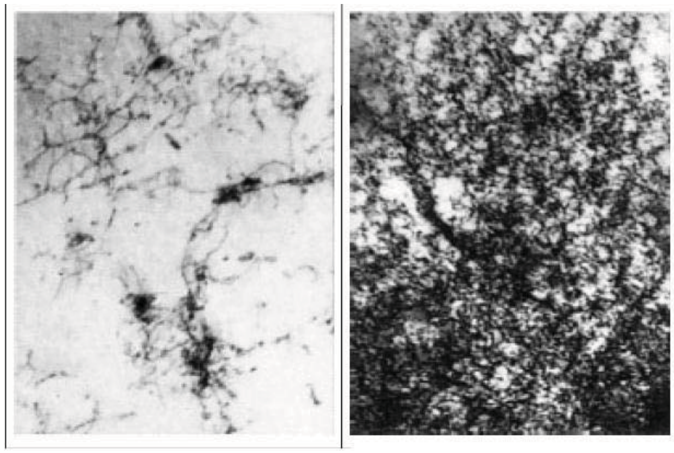

Figure 21: Dislocation before and after SP (Schulze, 2002)

different phenomena such as cold work, RCS and fracture that occur during SP process and the stress relaxation. Dislocation dynamics forms the basis of analysis at meso-scale (Figure.22). Xinling *et al.* (2003) has developed a method of using dislocation dynamics to evaluate plastic strains due to shot peening. It also needs to be pointed out full-fledged simulation of dislocation dynamics demand huge computing resources.

8. Conclusions

With the improvements in different fields and computing power, the methodology to maximize the fatigue strength using shot peening can be looked at. A more integrated approach is required either through continuum based modeling or multi-scale modeling that involves dislocations.

In the short term, continuum based approach can be enhanced. Focusing on enhancing the material models and developing a unified approach to calculate the fatigue life are the immediate steps. Using probabilistic optimization techniques, the fatigue life can be optimized. In the long run, employing multi-scale models linking dislocations and microstructure of the material to continuum will help in reducing experimental studies.

Acknowledgment

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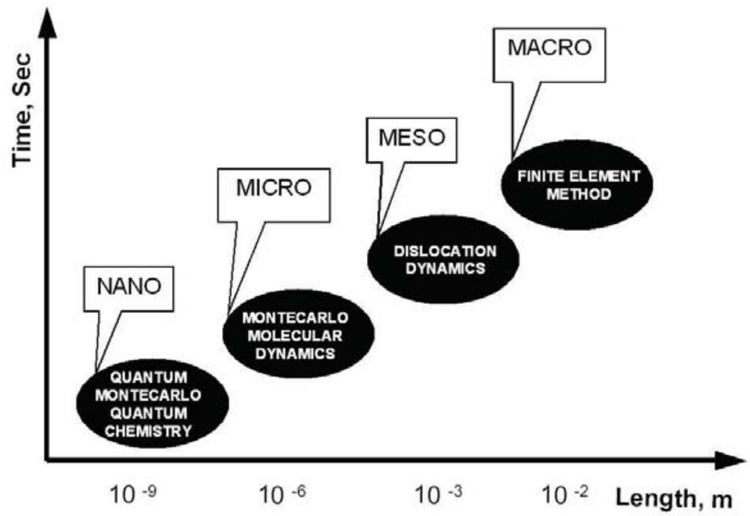

Figure 22: Multiscale methods

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