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# MECHANICAL SURFACE ENHANCEMENT (MSE) TECHNIQUES FOR FATIGUE LIFE IMPROVEMENT – A REVIEW

*Prabhu P R[1], Kulkarni S M[2] and Sharma S S[3]

[1, 3]Department of Mechanical & Manufacturing Engineering, MIT, Manipal, Karnataka - 576104, India
[2]Department of Mechanical Engineering, National Institute of Technology, Surathkal, Karnataka - 575025, India

## ABSTRACT

This paper presents a review of the most commonly used mechanical surface enhancement techniques and their applications in various industries mainly in automobile and aerospace industries. A brief description of each technique, as well as the advantages and limitations over other techniques are given. The effects of those techniques on the surface characteristics and service properties of components are summarized. It provides a know-how information and also comparison of various techniques. It guides researchers and engineers towards proper and appropriate use of each technique for relevant case or application. The list of techniques can be extended to a wider range of surface enhancement methods. This paper introduces the most commonly used modern Mechanical Surface Enhancement (MSE) techniques and their effects on the service properties of various components.

**Key words:** *Surface Enhancement, Service Properties, Fatigue, Residual Compressive Stress and Fatigue Life*

## 1. Introduction

Most of the components used in aerospace and automobile industry are working under heavy and critical conditions. They require good service properties (i.e. high fatigue life, good surface finish, etc.) in order to provide efficient and long performance under service [1].

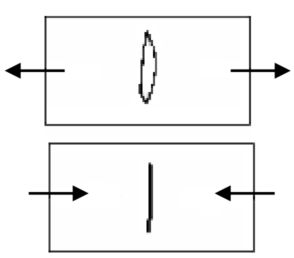


**Fig. 1 Effect of Tensile & Compressive Residual Stress on the Crack Propagation**

Fatigue is one of the major reasons for failures of the engineering machine components. It is of great concern for components subject to cyclical stresses, particularly where safety is paramount. It can also contribute to the failure of components such as moulds/dies, gears, bearings and shafts, and therefore have a detrimental effect on life cycle/operating costs [2]. It has long been recognized that fatigue cracks generally initiate from free surfaces and that performance is therefore reliant on the surface topography/integrity produced by machining [2]. The main property affected by machining is high cycle fatigue (HCF) strength, the actual endurance limit being dependent on the particular process used and the severity of operation. Whilst it is known that fatigue life is heavily influenced by residual stresses, the metallurgical condition of the material (microstructure and hardness) and the presence of notch-like surface irregularities induced by machining play a key role [2, 3]. Figure 1 illustrates that the surface tensile residual stress opens crack and increases crack propagation whereas compressive residual stress developed will closes crack and slows crack propagation.

The manufacturing processes such as turning, milling, drilling, grinding and welding are sometime detrimental to surface characteristics and fatigue properties of parts. They induce tensional residual stresses on the part surface, thereby lowering fatigue characteristics of parts [1, 4].

Surface enhancement is the introduction of a surface layer of compressive residual stress to minimize sensitivity to fatigue or stress corrosion failure mechanisms, resulting in improved performance and increased life of components. The presence of a stable compressive layer with a depth and magnitude of

**Corresponding Author - E- mail: raghuprabhu123@yahoo.com*

 

compression and cold work designed for the service stresses and environment can dramatically improve the effective material properties. The improvements in life and performance can far exceed those achieved by alloy substitution. If the compressive layer is of sufficient depth, damage mechanisms such as corrosion pits, foreign object damage, and fretting can be completely mitigated. The effective strength improvement achieved by surface enhancement can allow substitution of less expensive materials, reduction in cross sections and weights, and mitigation of failure mechanisms. Component life and performance can be increased, avoiding the expense of changing either material or design.

## 2. History of MSE Methods

Technological practice today particularly in the spring manufacturing, automotive and aerospace industries is hardly imaginable without mechanical surface treatments. The first modern day application was found in military technology in railroad technology [5] reports that in 1789, the outer surfaces of artillery gun barrels were hammered in order to improve their strength, and by 1848, train axles and bearing bolts were evened out by rolling. It was only in the 1920s and 30s that surface treatment evolved into technical processing methods. Foppl's seminal treatises of 1929 [6] established the correlation between mechanical surface treatment and increased fatigue strength, indicating significantly higher fatigue strength in surface rolled samples than in polished samples. Consequently, Foppl's group extended their examinations to include notched components and found that the fatigue strength increased by 20-56% in the case of deep rolled thread rods. These findings were confirmed by Thum [6] in his systematic examination. He also found that resistance to corrosion fatigue and fretting fatigue are increased.

An alternative to rolling emerged in the form of shot peening, its precursor was developed in 1927 by Herbert [7], a process he termed "cloudburst", in which large quantities of steel balls are rained onto component surfaces from a height of 2-4 meters. He observed increase in hardness, but did not give any indications regarding contingent increases of fatigue strength. In his aforementioned paper of 1929, Foppl showed that the samples treated with a ball shaped hammer also exhibit significantly higher fatigue life under cyclic stress than polished samples. In 1935, Weibel [8] proved that sand blasting increases the fatigue strength of wires. In 1939, v. Manteuffel [9] found higher degrees of fatigue strength in sandblasted springs than in untreated springs. An alternative to shot peening process, laser shock peening is developed by L.H. Burck, C.P. Sullivan, and C.H. Wells in 1970 as a process to enhance the fatigue of a Nickel-Base Super alloy [10]. Paul S. Prevey has developed a burnishing method and apparatus for providing a layer of compressive residual stress in the surface of a work piece in 1998. Mark Richards initiated a deep rolling project in 2001 to both develop a meaningful test and began studying the effects of the various material/rolling parameters. Figure 2 lists the major approaches in the history of MSE.

## 3. Fatigue Damage Mechanisms

Static or quasistatic loading is rarely observed in modern engineering practice, making it essential for the designer to address the implications of repeated loads, fluctuating loads, and rapidly applied loads. By far, the majority of engineering design projects involves machine parts subjected to fluctuating or cyclic loads. Such loading induces fluctuating or cyclic stresses that often results in failure by fatigue. Fatigue process embraces two domains of cyclic stressing or starting that are significantly different in character, and in each of which failure is produced by physical mechanisms.

### 3.1 Low cycle fatigue (LCF)

Here the cyclic loads are relatively high, significant amounts of plastic strains are induced during each cycle, and short lives or low numbers of cycles to failure are exhibited if these relatively high loads are repeatedly applied. This type of behavior is commonly called low cycle fatigue or, more recently, cyclic strain controlled fatigue. High-speed rotating equipment is susceptible to many kinds of problems. Problems range from bearing wear and vibration to component failure from internal flaws. One of the problems that have plagued the jet engine manufactures for decades is failure due to Low Cycle Fatigue. Low Cycle Fatigue, commonly referred to as LCF, is the fatigue of rotating components brought on by the continuous imposing and relaxing of centrifugal force caused by fluctuation in speed. Typically, rotating components, much like automotive engines, have an idle or low speed and an operational or high speed. Cycling from the low speed (low centrifugal stress) to the operational speed (high centrifugal stress), continuously stresses the rotor material.

### 3.2 High cycle fatigue (HCF)

High-Cycle Fatigue has been identified as a leading cause of turbine engine failures, excessive maintenance costs, and source of responsibility for numerous stand downs affecting operational readiness over the past decade. High-Cycle Fatigue (HCF) is fatigue that occurs at relatively large numbers of cycles and is caused by high frequency vibrations in both static and rotating hardware. The distinction between high-cycle fatigue and low-cycle fatigue is made by determining whether the dominant component of the strain imposed during cyclic loading is elastic (high cycle) or plastic (low cycle), which in turn depends on the properties of the material and on the magnitude of the stress. Table 1 shows the comparison between high cycle fatigue and low cycle fatigue.

**Table 1: Comparison between HCF & LCF**

| **High Cycle Fatigue** | **Low Cycle Fatigue** |
|---|---|
| Stress Controlled | Strain Controlled |
| Associated with cycle lives from one up to $10^4$ or $10^5$ cycles | Associated with cycle lives greater than about $10^4$ or $10^5$ cycles |
| Crack has not started | When will crack start? |
| Facilitates design | Not easy to use in design |
| Associated with elastic behavior | Involves cyclic plasticity |
| Associated with high loads and short lives | Associated with lower loads and long lives |

## 4. Fatigue Damage Prevention

Engineers who want to improve the life of a component will eventually have to take into consideration the surface of the component. The “integrity” of surface in resisting failure depends upon several characteristics including surface finish, residual stress, and cold working. Surface finish has long been known to have an impact on the life of a component that undergoes cyclic loading in service [11, 12]. This is why so much time and effort is spent on finish machining; finish grinding, honing, lapping etc. The purpose of these processes is to produce a surface that is free of defects, such as gouges and scratches. A surface free of such defects has fewer flaws from which cracks can originate. A component that is free from surface defects will generally survive longer in cyclic loading conditions [11]. However, surface finish actually has only a minimum influence on fatigue strength. To substantially improve the life of a component, it is important to produce compressive stresses in a component’s surface to reduce tension during cyclic loading [11].

Component surfaces are usually in some state of residual stress. They can be in compression, tension, or stress free. Residual stress has a direct impact on service life [11]. In fact, residual stress has a greater impact on service life than surface finish. A surface in high tension will crack and fail quicker than if there were no stress at all. This is because the surface, which is already in tension, will be put in even higher tension during a loading cycle [11]. This tension pulls at the surface of the material and weakens it. The oscillating tension eventually causes damage at some small point on the surface, usually at a flaw or stress concentration such as a sharp corner or fillet. This point is called the initiation or nucleation point. A crack develops at this location and begins to grow through the component until failure occurs. A surface that is in compression will experience less tension during the loading cycle (11). Because of this, it is more difficult to start a crack or for a crack to grow. Therefore, the component lasts longer under cyclic loading conditions.

Fatigue failure is a general term given to the sudden and catastrophic separation of a machine part into two or more pieces as a result of the application of fluctuating loads or deformations over a period of time. Failure takes place by the initiation and propagation of a crack until it becomes unstable and propagates suddenly to failure [1, 11, 13]. The propagation of a crack depends upon the stress conditions near its tip. Crack arrest by residual compressive stress is based upon the following factors:

1) A crack does not propagate unless a tensile stress forces it open near the tip; and
2) The crack tip does not open as long as a compressive force acts upon it.

One way to increase the life of a component is by introducing residual compressive stress on the surface layer through mechanical surface enhancement technique. The next section of this paper covers most of the major MSE techniques used.

## 5. Mechanical Surface Enhancement (MSE) Techniques

It is well established that near-surface compressive stresses as well as work-hardening states induced by mechanical surface treatments play a dominant role in extending the fatigue life of metallic materials. MSE techniques, such as shot peening, laser shock peening, ball/roller burnishing, low plasticity burnishing and deep cold rolling, induce plastic deformation in near-surface area of the components resulting in formation of compressive residual stresses, work hardening and changes in surface topography [13, 14]. These near-surface alterations serve to inhibit or retard fatigue crack initiation as well as crack growth. They induce residual stresses in the near surface area of components, which results in the improvement of fatigue life of components [1, 13, 15, and 16].

### 5.1 Shot peening (SP)

Peening is a process in which peening media with a specific shape and a sufficiently high degree of hardness are accelerated in peening devices of various kinds and interact with the surface of the treated work piece. Main aim of this process is the generation of compressive residual stresses and work hardening close to the surface [14, 17-20].

In this process, the metal surface is collided repeatedly with a lot of steel, making overlapping indentations on the surface. The metal undergoes large plastic deformation near the surface due to the collision of a lot of shots. Large plastic deformation is generated only in the metal surface. The surface layer is work-hardened and residual compressive stresses are generated. These characteristics are called the "peening effect". It is very useful for the improvement of the surface properties. Especially, residual compressive stresses induced by shot peening improves fatigue life of the parts [18, 21, and 22].

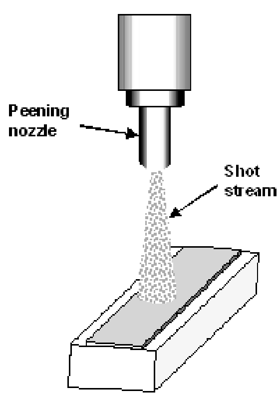


**Fig. 3 Shot Peening Process**

Figure 3 shows the shot peening process. The shot size is to fit the dimensions and geometry of the components to be treated. On the one hand, the shot size must be sufficiently small to reach areas which are hard to access, such as small notches. This also serves to avoid notch effects due to impact-induced roughness. On the other hand, the dimensions and shape of thin walled components are not to be changed inadmissibly.

Steel work pieces are usually treated with steel shot. Glass beads are primarily suited for low intensity shot peening treatments and for components which would otherwise be contaminated and, for example become more prone to corrosion. Therefore they are used primarily on small diameter components and on titanium and aluminium alloys sensitive to contamination by iron. [23] Ceramic beads combine high hardness with medium densities and are used for the shot peening of titanium alloys [23]. Recent research deals with shot peening using zirconium oxide and hard metal shot for the strengthening of the ceramic samples made of silicon nitride and aluminium oxide [24 - 26]. Figure 4 shows some of the important process parameters studied by some of the researchers on shot peening process.

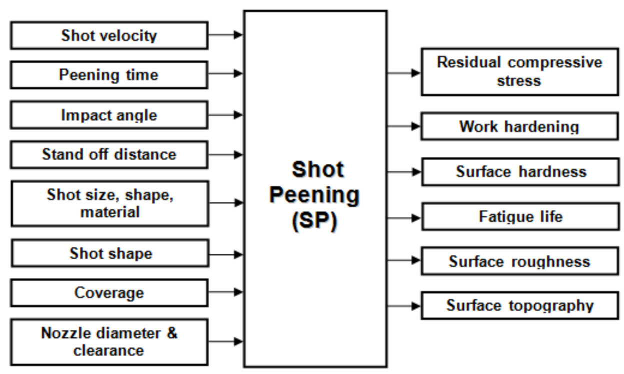


**Fig. 4 Typical Process Parameters Reported for Shot Peening Process**

### 5.2 Laser shock peening (LSP)

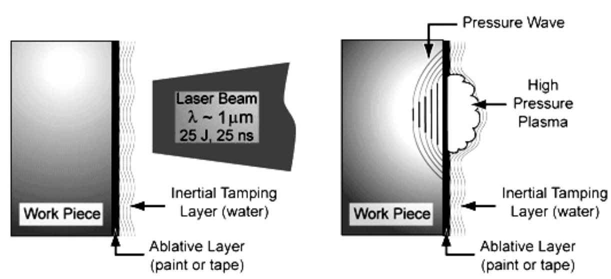


**Fig. 5 Laser Shock Peening Process [61]**

Laser shock processing (also known as laser peening), can induce greater depths of residual stress into metal surfaces using high-power, Q-switched laser pulses. The ability of a pulsed laser beam to generate shock waves was first recognized and explored in the early 1960s [27, 28]. Figure 5 shows the schematic view of the LSP process. This process drives a high-amplitude shock wave into material surface using a high energy pulsed laser. Figure 9 shows the principle of LSP process. Before processing, an opaque overlay (typically black paint or tape) and a transparent overlay (typically flowing water) are applied to the surface to be processed. The laser pulse passes through the transparent overlay and strikes the opaque overlay causing it to begin to vaporize. The vapour absorbs the remaining laser light and produces a rapidly expanding plasma plume. Since the expanding plasma is confined between the part surface and the transparent overlay, a rapidly rising high-pressure shock wave propagates into the material. When the peak stress created by the shockwave is above the dynamic yield stress of the metal, the metal yields; and the metal is "cold worked" or plastically deformed at the surface.

The plastic deformation caused by the shock wave results in compressive residual stresses in the surface of the part [29]. The depth and magnitude of the residual stresses depend upon the material and laser peening process conditions, which are tailored for a specific application. Compressive residual stresses typically extend as deep as 0.040-0.060 inches (1 to 1.5 mm) below the surface and can approach the yield strength of the material [30, 31, 32]. Figure 6 illustrates some of the important process parameters studied by various researchers on laser shock peening process.

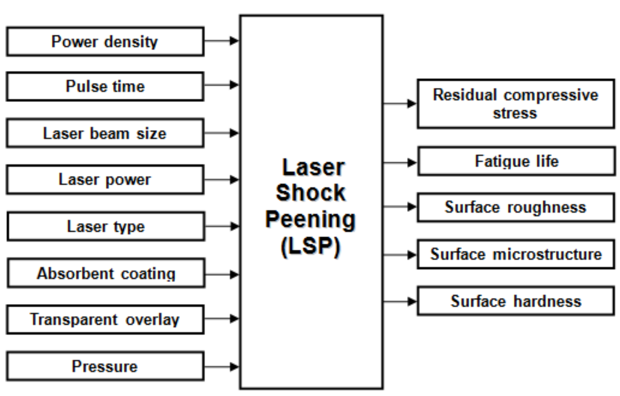


**Fig. 6 Typical Process Parameters Reported for Laser Shock Peening Process**

### 5.3 Low plasticity burnishing (LPB)

It is a patented method of controlled burnishing. It has been developed by Lambda Research Inc. It produces a layer of compressive residual stress of high magnitude and depth with minimal cold work [33-38]. It is usually performed using a single pass of a smooth free rolling ball under a normal force sufficient to plastically deform the surface of the material. Hertzian loading creates a layer of compressive residual stress to a depth exceeding 1 mm [33, 38, 39, and 40]. These stresses act parallel to the plane of the surface and reach a maximum beneath the surface. With sufficient pressure applied normal to the surface, the subsurface stress exceeds the yield strength of the work piece material, thereby producing deep subsurface compression. The normal force required and the depth at which yielding first occurs depend upon the ball diameter [34, 37].

The ball is supported in a fluid bearing with sufficient pressure to lift the ball off the surface of the retaining spherical socket as shown in Figure 7. LPB is performed in a machine shop environment using conventional or CNC machine tools at speeds comparable to machining operations [33, 39, 40, and 41]. The machine tool's coolant is used to pressurize the bearing and "float the ball." The ball does not contact the bearing seat, even under load. The ball is loaded normal to the surface of a component with a hydraulic cylinder that is in the body of the tool. The ball rolls across the surface of a component in a linear stepping pattern. Since there is no shear being applied to the ball, it is free to roll in any direction. As the ball rolls over the component, the pressure from the ball causes plastic deformation to occur in the surface of the material just under the ball. Since the rest of the material is constraining the deformed area, it springs back into a compressive state after the ball passes. No material is removed during the process. It is only displaced inward by a few ten-thousandths of an inch (0.0001- 0.0006 inches). It also smoothes out the surface and improves surface finish.

The major benefit of LPB is the improved high cycle fatigue life [38]. An LPB treated surface is resistant to foreign object damage and stress corrosion cracking [34, 42, 43, and 44]. Shallow cracks, less than 0.010" deep, have had their growth arrested after being treated by LPB. The LPB process can control the plastic deformation that the material undergoes during the process. Both the depth of compression and amount of cold work being put into the surface of the component can be controlled. LPB can be applied to all types of carbon and alloy steel, stainless steel, cast iron, aluminum, titanium, and nickel-based super alloys [45-48].

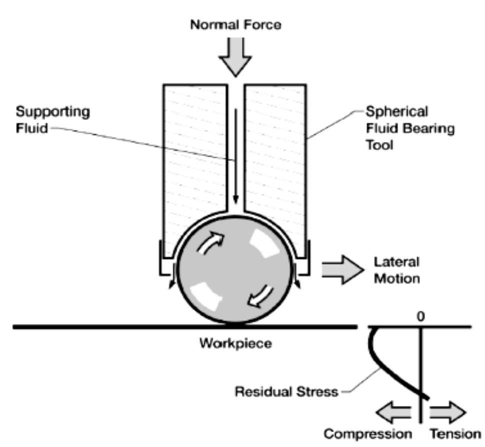


**Fig. 7 Low plasticity burnishing process [62]**

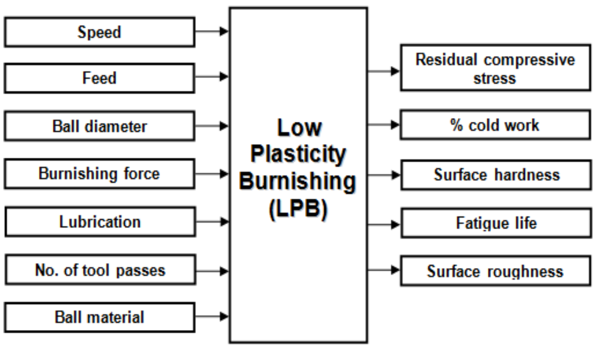


**Fig. 8 Typical Process Parameters Reported for Low Plasticity Burnishing Process**

LPB introduces similar or even more applicable, compressive residual stress than LSP. The LPB manufacturing process is highly controllable and operates at cycle times that greatly lower cost of production and provide processed parts in minutes, thus preventing production bottleneck constraints typical of LSP processing. However, development and application of LSP has proven to be very costly. LSP processing is difficult to control and cycle time per part is longer than acceptable. LPB has significant process cycle time advantages relative to LSP. This cycle time advantage and lower capital cost translate to substantially lower cost for LPB relative to LSP. Figure 8 illustrates some of the important process parameters studied by various researchers on LPB process.

### 5.4 Deep Cold Rolling (DCR)

Deep cold rolling is a non-cutting production method which, next to finish rolling and size rolling, is counted among the fine surface rolling methods according to VDI guideline 3177 [6]. The objective of deep cold rolling is to introduce work hardening and compressive residual stresses into near surface regions in order to increase the fatigue strength [12, 49 - 52]. It is a process in which a ball or roller is pressed against the surface of a work piece by applying a static pressure. The ball is then rolled along the surface to be treated. Figure 9 explains the principle of operation of DCR process. During the process, surface pressure created between the work piece and the tool in the contact zone. It causes triaxial stress states, which change with distance to surface. They are dependent on contact geometry. They cause smoothening and friction effects at the immediate surface. When the yield strength is exceeded by the resulting equivalent stress, local plastic deformations occur, creating residual stresses and the associated micro structural work-hardening or work softening effects. Figure 10 illustrates some of the important process parameters studied by various researchers on DCR process.

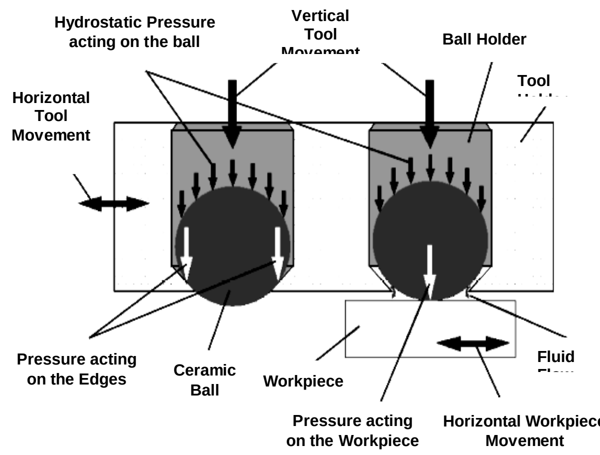


**Fig. 9 Deep Cold Rolling Process [55]**

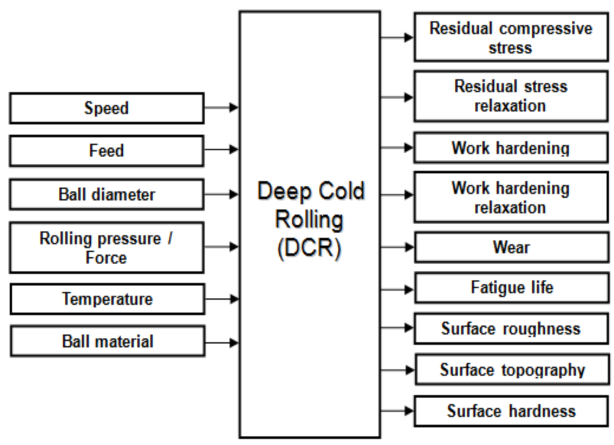


**Fig. 10 Typical Process Parameters Reported for Deep Cold Rolling Process**

Deep cold rolling is the most efficient mechanical process to improve the fatigue strength of dynamically loaded components. It eliminates or at least reduces fatigue especially on notches like fillets and shoulders which can lead to fatigue cracks. The deep cold rolling process works similarly to roller burnishing but the task is different. To guaranty equal component quality, all process parameters, but especially the burnishing force must be controlled during the process. The compressive stress, generated in the surface layer during the rolling process remains to a high extend after the rolling process is finished. The compressive stresses in axial direction are most important for the improved fatigue strength.

 

## 6. Comparison between Different MSE Techniques

Table 2 and Table 3 show the comparison between different MSE techniques. From Table 3 it is clearly understood that laser shock peening is a costliest process among the 4 MSE techniques that we have discussed but the same can be compensated by providing a deeper layer residual compressive stress. LPB process develops a very low cold work of about 2 to 5% where as deep cold rolling process develops a cold work of about 10 to 50 % on the surface. Out of all the techniques studied, shot peening is one of the cheapest method of introducing residual compressive stress on the surface layer where as the limitation is difficult to achieve the full coverage of the surface to be treated, especially for complex geometries.

## 7. Discussion and Conclusions

This paper presents a review of currently available literature to support each of the mechanical type surface enhancement techniques. A thorough understanding of the each of the process helps the user to select an appropriate technique for relevant case of application. There are number of automobile and aerospace components subjected to high dynamic loads and heavy service conditions. Failure of critical components due to insufficient service properties threatens the industry and greatly increases the cost of maintenance. Redesign and/or replacement of such components are generally not allowed or requiring considerable cost and time. Surface enhancement is a practical and affordable solution for preventing failure mechanisms and also for improving the service properties of many critical components in aerospace and automobile industry. The most commonly used MSE techniques for improving the service properties of various components to eliminate their failure during service are reviewed in this paper.

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