FATIGUE LIFE IMPROVEMENT BY SHOT PEENING

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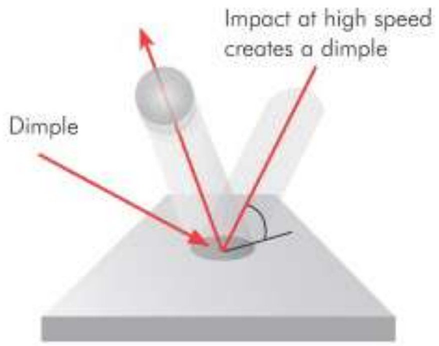
Abstract: The main advantage of using shot peening process is to increase the fatigue strength of components subjected to high alternating stresses. The fields of application for shot peening include all metallic components, which are subject to fluctuating and fatigue loads. Additional advantages of using shot peening include design of lighter weight and lower cost components, prevention of stress corrosion, formation of lubrication pockets and compensation of manufacturing related surface defects.

1 Shot Peening Process

Shot peening is a process used to produce a compressive residual stress layer and modify mechanical properties of metals. Residual stresses are stresses that remain after the original cause of the stresses (external forces, heat gradient) has been removed. They remain along a cross section of the component, even without the external cause. Machine parts when subjected to fatigue loading will experience maximum tensile stresses, normally over the surface. These tensile stresses initiate and propagate fatigue cracks. In order to counteract the effect of these tensile stresses, residual compressive stresses are induced over the surface of the metal parts by the controlled process known as shot peening [1].

Shot peening is a cold working process in which the surface of the finished part is bombarded with shots under controlled conditions. Each shot acts as a tiny peening hammer; making a small dent in the outer surface of the metal (Fig. 1). This impact causes a plastic flow of the surface fibers to a depth depending on the angle of impact, size of shots and physical properties of the material [2]. The resultant residual stressed surface layer, which is in compression, prevents formation of cracks, thus increasing the life of the component (Fig. 2). The maximum residual compressive stress produced on the surface is at least half the ultimate tensile stress of material.



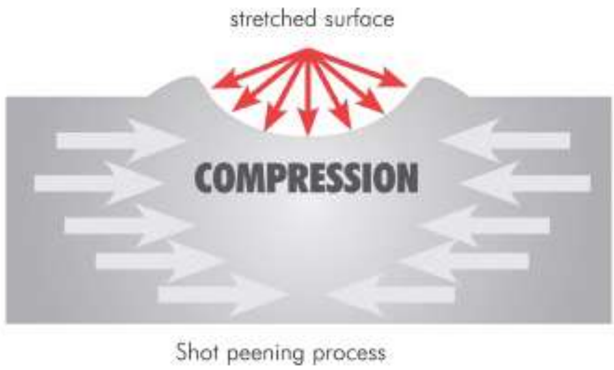


Fig. 1 Shot Peening Process **Fig. 2: Shot Peened Surface**

Shot Peening serves to increase the fatigue strength of parts subjected to high alternating bending or torsional stresses. The process has very effectively replaced other time consuming and expensive processes of improving fatigue strength. It permits the design of less expensive and light weight components.

Conventionally, when a part is not able to withstand the stresses that it is required to, a lot of trial and error effort is put into design of the part. Its material may be changed, the part may be subjected to heat treatment process, attempt may be made to change its machining techniques, or the designer may even go to the extent of changing the design of the part. If analyzed properly, it may be found out that all the above exercises are totally uncalled for. What may have offered a better solution at a nominal cost could have been the shot peening of the part [3].

Shot peening process increases the fatigue life of the part. It toughens the outer surface of the part, effectively increases the tensile strength and eliminates cracks and other imperfections. This is made possible due to the evenly spread compressive stress patterns that are developed during shot peening. The process effectively eliminates microscopic defects in the thin surface shell of the part. It is intended to reduce residual surface tensile stresses in metal parts which are subjected to repeated application of complex load patterns. Typical components that are shot peened for the purpose of improving resistance to fatigue and stress corrosion cracking are axles, springs, gears, shafting, aircraft components and structural parts. Shot peening is also used for other applications such as to close porosity in castings and to straighten or form the parts.

The process of shot peening can be conceived as a further development and perfected rendition of shot blasting process. It is a cold forming process, with which internal residual compressive stress is induced into the zone close to the surface of the work pieces. Shot-peening replaces complex, cost-intensive processes and reduces material costs. It allows the design of lighter weight components, thus increasing the strength/weight characteristics and the benefit/cost of the workpiece.

2 Historical Background

Weibel, in 1935, was the first person to appreciate the value of shot blasting in connection with fatigue resistance. Moore stated that shot peening, when properly carried out, strengthens parts that are subjected to bending or torsion. However, metal1urgiss and testing engineers are not all agreed on the exact mechanism by which it strengthens metal parts [4].

Shot peening has been carried out under three methods and periods. Firstly, the smith created the peening effect with his hammer in the old days, Secondly, the initial semi-mechanical process of shot peening used from 1930 when the work was carried out solely by the means of compressed air shot blasting. Finally, the mechanical method of peening that is used today for mass production and greater control.

Although the earliest publication and the earliest patent application were found in the German literature, it seems that the process was first applied in production and developed in the United States, without benefit of the German work. Bush, Almen, Danse and Heiss [1962] recall that during 1928, the service life of valve springs was a subject of concern. Various methods of cleaning the springs were tried.

Danse at Cadillac and Heiss at Buick observed that springs cleaned by shot blasting were clearly superior [5].

The process was used in production, but the reasons for its success were not clearly understood. Zimmerli in 1940, reported on these early developments from the spring makers viewpoint. In a summary of this paper he starts by saying, "Shot blasting has done more to increase fatigue life of our small springs than any of the alloy steels ever used."

J. 0. Almen, inventor of engines, transmissions and many other devices, devoted himself to the investigation of shot peening when he was working for Buick Motor Division of General Motors Corporation. He noticed that shot blasting, as it was then called, made the exposed side of the sheet metal to begin to bend and stretch. He claimed that residual stresses (self stresses) were the cause of the effect. These stresses could not be calculated from loads and geometry alone and that fatigue cracks would not propagate unless tensile stresses were present [Almen 1951]. He later created the Almen strip to measure the compressive stresses in the strip induced by the ball peening operation.

During the Second World War, 1941 to 1945, shot peening applications spread from the automobile industry to the aircraft industry and others, largely through the missionary work of Almen whose efforts were supported by a government grant. He started the *Society of Automotive Engineers (SAE,.)* committee on shot peening in 1943 and was its guiding spirit. In 1944, John Strub, one of Almen assistants, transferred himself from General Motors to Wheelabrator Corporation to work on using their machines for shot peening applications. Almen's views were unorthodox at the time, and strongly resisted by some academics. But they prevailed and were eventually legitimized through the development of fracture mechanics. By 1950, twenty years after the beginning, shot peening was well accepted and discussed in engineering handbooks. [Almen 1950, Horger 1964].

Early applications of shot peening in the 1930s and 1940s relied upon proprietary specifications, primarily from General Motors. Efforts to improve fatigue life of critical aircraft components resulted in creation of specifications by the US Army, Navy and Air Force and also SA.E [6]. Intensity of peening was initially described as the point on the Almen strip saturation curve where it flattens out. This was often accompanied with a notation that this can be difficult to determine and some judgment may be required. The concept of assigning a numerical value to saturation using the 10 % rule was introduced in 1984. SAE Surface Enhancement Division of Fatigue Design and Evaluation Committee eventually created an entirely separate document for peening coverage to emphasize that coverage is not related to Almen strip performance.

3 Fatigue Failure

Fatigue cracks initiate at the surface of the material, where the stresses are maximum. Any design or manufacturing defect at the surface concentrates these stresses and encourages the formation of a fatigue crack. Similarly, temperature influences the fatigue resistance. As the temperature of the material increases, the strength decreases and consequently both fatigue life and endurance limit decrease. Surfaces of structural materials, regardless of smoothness, are much weaker in fatigue than are sub-surface materials [7].

Service failure of engineering products and structures can occur by cyclic application of stresses (or strains), the magnitude of which would be insufficient to cause failure when applied singly. As a failure mechanism, fatigue involves initiation and gradual growth of cracks until the remaining section of material can no longer support the applied service load. There are a range of mechanisms found in practice that include high-cycle, low-cycle, thermal, surface, impact, corrosion and fretting fatigue. Fatigue as a failure mechanism has been attributed to playing a significant role in the demise of many engineering products and is considered one of the most common causes of structural failure found in-service, even though laboratory fatigue behavior of most metals and alloys is well understood. There are a plethora of variables that influence the mechanism of fatigue, many of which are taken into account when attempting to designing for safe life of a component. However fatigue failures still occur regularly, demonstrating the complex nature of this problem [8].

A part fails by overloading if the statically applied stress exceeds the tensile strength of the material. However, failure can still occur at a stress level less than the yield strength, if the applied stress is fluctuating with time. Failure caused by cyclic loading is termed *fatigue* and the number of total loading cycles applied until fracture is called the *fatigue-life.* The majority of engineering components experience some sort of load fluctuations and it has been estimated that fatigue is responsible for more than 70 % of all engineering material failures.

American Society for Testing and Materials ('ASTM,) defines fatigue life as the number of stress cycles of a specified character that. a specimen sustains before failure of a specified nature occurs. Fatigue life is influenced by a variety of factors, such as temperature, surface finish, microstructure, presence of oxidizing or inert chemicals, residual stresses etc.

3.1 Fatigue Failure Stages

The complete fatigue failure process of materials can be subdivided into five phases:

1. Cyclic hardening and / or softening.
2. Fatigue crack initiation.
3. Micro crack propagation.
4. Propagation of large cracks.
5. Final fracture.

The number of cycles to failure, *N1,* is the sum of *N0,* the number of cycles until the first crack appears (crack initiation), and the number of cycles *N* (crack propagation) up to final fracture. In the investigated model alloy A286 the first fatigue cracks were initiated at all stresses after less than 10 % of the total number of cycles to failure *Nf* [9]. More than ninety percent of the fatigue life is determined by the propagation of small micro cracks in the surface. The fatigue cracks are formed at high, sharp slip steps in the surface. Therefore, the shot peening treatment should be very promising for such a material because the initiation and propagation of small cracks can be strongly retarded by surface hardening and surface compressive residual stresses respectively.

For machine components containing no pre-existing cracks, the majority of fatigue life is spent in initiating or starting fatigue cracks and the fatigue process is described as initiation-controlled. Examples of these include crank shafts, gear teeth, and rotating shafts or axles. On the other hand, large structures or welded parts almost always contain pre-existing cracks such as in bridges, ships, aircraft body, and pressure vessels. In such structures, the majority of fatigue life is spent in growing a pre-.existing crack to a critical size and then to final fracture. The fatigue process in this case is described as propagation-controlled.

A number of factors influence the fatigue life of a component in service:

1. Complex stress cycles.
2. Engineering design.
3. Manufacturing and inspection.
4. Service conditions and environment.
5. Material of construction.

Analysis shows that premature fatigue crack initiation in the components can be attributed to defects of various types introduced mostly inadvertently in various stages of component design, manufacture, maintenance, inspection, operation etc [10].

Engineering structures and components often contain features such as notches and reducing diameters that act as stress concentrators. Fatigue cracks almost always start at regions of high stress concentrations. Fracture surfaces of components failed by fatigue are usually flat and perpendicular to the applied stress and often show some marks on the surface. These marks are positive indication for fatigue failure and they represent the crack fronts during loading. Furthermore, fatigue failure is brittle in nature and does not involve gross plastic deformation even in metals that behave in a ductile manner under static loading. Hence, fatigue failure occurs suddenly and can cause catastrophic consequences.

3.2 Design for Fatigue Loading

Three major factors must be considered in designing **a** machine component to withstand fatigue loads [11]:

1. Service Loads.
2. Critical Stresses.
3. Material behavior.

1. Service Loads

The factors involved in analyzing service loads require careful evaluation by the design engineer. These factors can best be represented by a cycle-load histogram of the machine, which should represent all conditions, environments, and malfunctions expected during service life. A typical histogram of expected loads on a structural part is shown in Fig. 3.

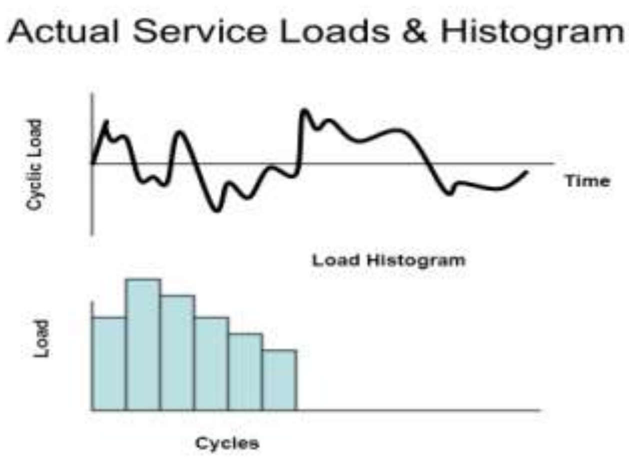


Fig. 3: Load — Cycle Histogram

Various loads and the corresponding vibration cycles for each critical component of the machine or structure during the expected life of the component should be determined as completely and realistically as possible. This should include loads induced by improper operation and by malfunction, since service life may be limited by the number and magnitude of loads occurring during infrequent overloads or improper operation. For example, the life histogram of rotating machines (reciprocating engines, steam turbines, turbojets, etc.) should include resonant loads or stresses that may occur while the machine is brought up to the operating speed.

2. Critical Stresses

After a histogram has been constructed, a preliminary design can be made. From this design, critical fatigue stresses may be computed. The following factors should be taken into account when computing critical stresses:

1. All stress concentrations that may exist at the point in question. Stress concentrations introduced by improper handling or by service environments (such as stone ingestion in turbojet engines) should be recognized, as well as those resulting from the design itself.
2. The state of stress, whether stress is alternating or pulsating, or whether it is an alternating stress superimposed on a steady stress. Also, the principal stresses and their phases must be calculated.
3. The effect of stresses introduced inadvertently in the assembly. For example, transportation of parts by rail or truck involves considerable jolting, which causes fatigue stressing.
4. The effect of manufacturing tolerances on stresses. A stress histogram based on these points should be compared with the fatigue strength of the material to be used for the part.

3. Material Behavior

To determine if a material will fail under calculated stresses, it is necessary to have knowledge of the behavior of the material under all environmental conditions that might affect fatigue-inducing stresses. This should include the effects of manufacturing processes. Fatigue data, including *S-N* curves, published on a material are not sufficient, since such information is usually based on laboratory tests of small, carefully polished specimens.

The fatigue strengths observed in the laboratory is seldom, if ever, realized in fullscale components subjected to service environments. Numerous factors can reduce the *par* fatigue strength obtained from laboratory specimens, but there are relatively few methods of preventing or compensating for environmental effects. Also, a detailed knowledge of manufacturing processes and service environment is necessary before the structural adequacy of the component can be judged.

4 S-N curve

In high-cycle fatigue situations, a material's performance is commonly characterised by *S-N curve,* also known as a *Wohler curve.* This is a graph of the magnitude of cyclical stress, *5,* against the logarithmic scale of cycles to failure, *N.* During fatigue testing, the test specimen is subjected to alternating loads until failure occurs. The loads applied to the specimens are defined by a constant stress range, *UR,* or constant stress amplitude, a4, which are defined as [12]:

$\sigma_R = \sigma_{max} - \sigma_{min}$,

$\sigma_A = \sigma_R / 2 = (\sigma_{max} - \sigma_{min})/2$,

where σ_{max} and σ_{min} are the maximum and minimum cyclic stresses respectively. The magnitude of the stress range or amplitude is the independnt variable and the number of cycles to failure is the dependent variable. Most of the time, *S-N* fatigue testing is conducted using fully reversed loading, which indicates that loading is alternating about a zero mean stress. The mean stress and stress ratio are defined as:

$\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$,

$R = \sigma_{min} / \sigma_{max}$.

The following equation represents a typical *S-N* curve:

$\sigma_A = \sigma'_f (2 N_f)^b$

where *b* is fatigue strength exponent, and σ'_f is fatigue strength coefficient. This expression, known as the *Basquin relation* developed from log-log *S-N* graph, is the most widely used equation in a stress-based approach to fatigue analysis and design. For example, the fatigue life of extruded Magnesium alloy is shown on the *S – N* curve in Fig. 4. Similarly Fig. 5 shows the *S – N* curve for an Aluminium alloy.

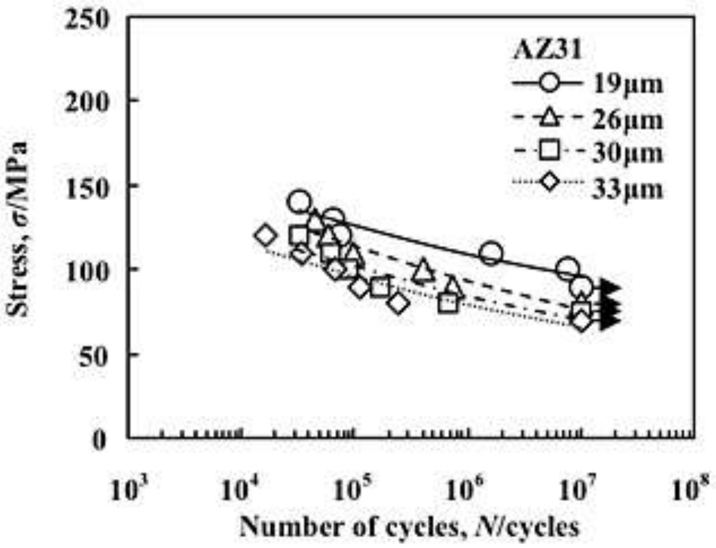


Fig. 4: S-N Curve for AZ31 Alloy

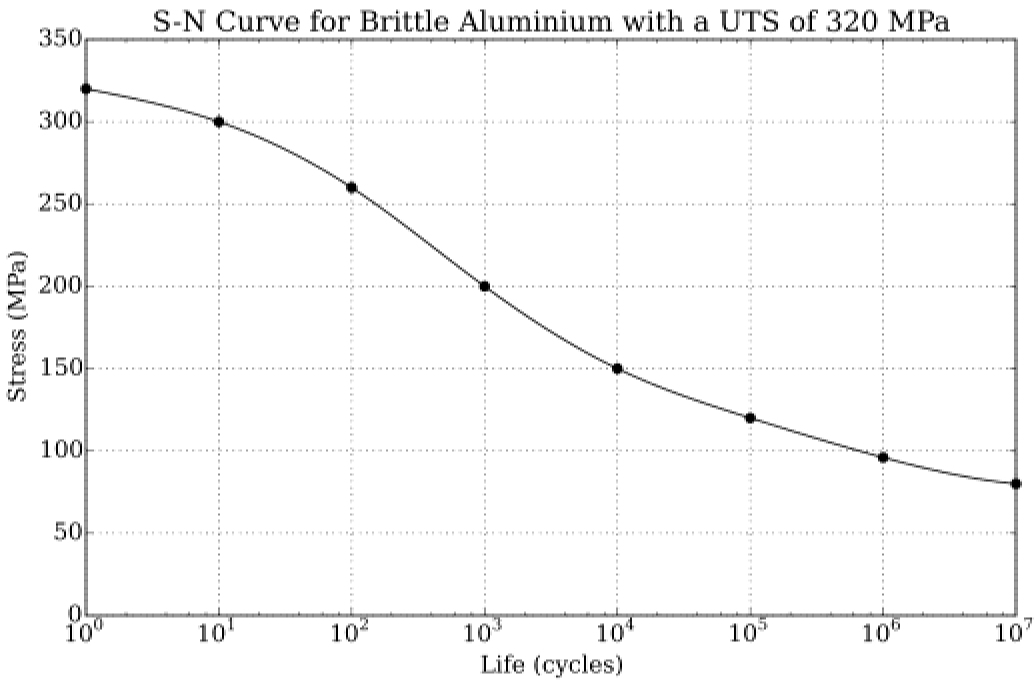


Fig. 5 : S-N Curve for Brittle Aluminium with UTS of 320 MPa

5 Fatigue Strength of Different Materials

The ratio of surface fatigue strength to sub-surface fatigue strength is probably not the same for all structural materials. It is also probable that in any material this ratio varies with such properties as hardness and ductility. The surface of a specimen of very hard steel, in which the hardness is uniform throughout the cross section, does not have the surface protection of residual compressive stresses that occur in case hardened surfaces. Through hardened steel specimens will therefore be more susceptible to surface fatigue failure, because the low ductility of the hard metal reduces the ability of the surface to relieve local tensile stresses by plastic adjustment. Such specimens are said to be notch sensitive or brittle.

5.1 Effect of Surface Stress Raisers in Statically Loaded Ductile Metals

In ductile metals under static loading, the effect of surface stress raisers is negligible. Any local increase of stress in a stress raiser, for example a scratch, is dissipated by plastic flow of the metal affected by the stress raiser. Such localized plastic adjustments may he said to occur on a micro scale. The result is that the surface stress becomes quite uniform in spite of surface imperfections. Also, in statically loaded ductile specimens, the effect of the inherent weakness of surfaces is also reduced by general plastic yielding of the surface at nominal stresses less than the yield strength of the core.

Results obtained from experiments show that the endurance limit increases linearly with hardness until a specific hardness value is reached. At higher hardness levels, the reduced ductility does not permit adequate plastic relief of the tensile stress in local stress raisers. The rate of fatigue strength increase is therefore sharply reduced, although the strength of the subsurface steel presumably continues to increase at high hardness levels, Materials of low ductility fail at low stress by brittle fractures under static and impact loads, because they are not capable of yielding to relieve local high stresses whether from surface imperfections, residual micro stresses or just plain undefined surface weakness.

5.2 Effect of Surface Stress Raisers in Brittle Metals

Pre-stressing by mechanical means can only be accomplished in materials having some ductility. Peening with low intensity can develop a residual compressive stress that extends to a specific depth. Mechanical pre-stressing can, therefore, be expected to increase the static, impact, and fatigue strength of many hard metals. Brittle materials suffer from surface imperfections whether the applied load is static, impact, or repeated fatigue loads. The imperfections may or may not be in the form of recognizable stress raisers but, regardless of smoothness, the surfaces are weaker than sub-surface material. Since completely brittle materials fail only by tensile stresses, their strength, under various kinds of loading, is increased by inducing residual compressive stresses in the fracture sensitive surface layer.

6 Fatigue Life Improvement

Critical stresses at stress concentrations should not exceed design stress —- often called *allowable* or *working stress* — for the proposed structural material. Selection of design stresses for static loading is not difficult when the ultimate tensile and yield strength are known. However, for fatigue loading, the problem is more complicated. Many factors affect fatigue strength: metallurgical treatment, mechanical treatment, environment, number of cycles (perhaps at different stress levels), probable scatter in strength values among parts made to the same design, etc. The effect of these factors can be controlled in part by the designer when he specifies a material. For example, he may call for specific methods of surface finishing coating, for carburizing Or nitriding, etc. Although in some cases such things have little effect on static strength, they may change fatigue strength appreciably [13].

Shot peening removes residual tensile stress in the unpeened sub-surface metal and replaces it with residual compressive stress in a thin surface layer. The residual tensile stress in the core increases as the depth of the peened layer is increased. Also for constant depth of peening, the tensile stress in the core increases as the thickness of the specimen is decreased. The internal tensile stress must vary with the uepth of peening and with the specimen thickness since, to satisfy equilibrium conditions, the compressive force in a surface layer that results from peening must be balanced by an equal tensile force in the core metal.

The increase in fatigue strength that follows shot peening is explained by two theories.

1. Surfaces are weaker under repeated loading than sub-surface material; and
2. Fatigue fractures can develop only from tensile stresses.

Shot peening removes the residual tensile stress and replaces it with compressive stress. Since fatigue failure never starts in an area under compression, the applied tensile load must first overcome the residual compressive stress before fatigue is initiated. Thus the objective of shot peening process is to produce a residual compressive stress high enough to counteract the effects of the applied load. Shot Peening allows metal parts to accept higher loads or to endure a longer fatigue life in service without failure. In usual applications shot peening can be done without changing the part design or its material. Distribution of compressive stress and tensile stress in the upper layers of high strength steel component with respect to the depth from surface is shown in Fig. 6 and Fig. 7 [14].

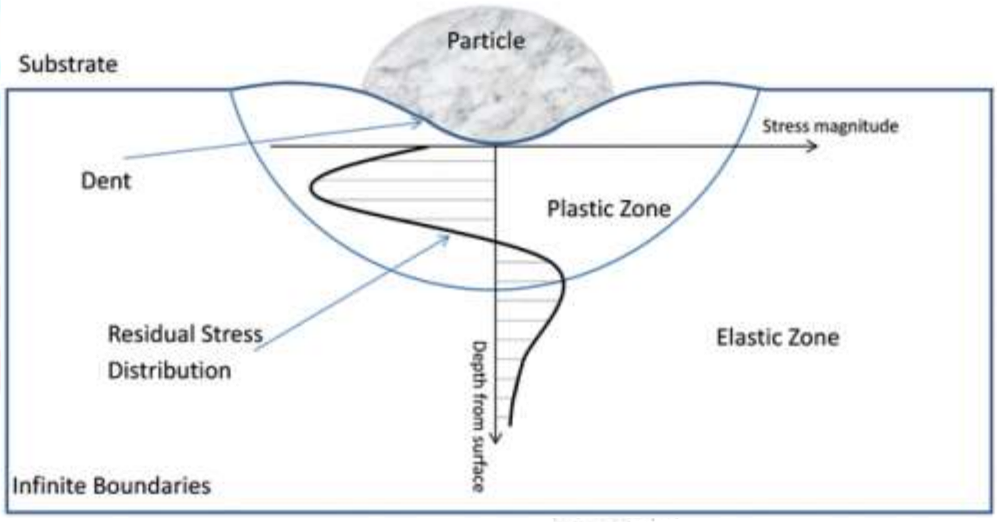


Fig. 6 : Residual Stress Distribution Near the Surface of a Specimen

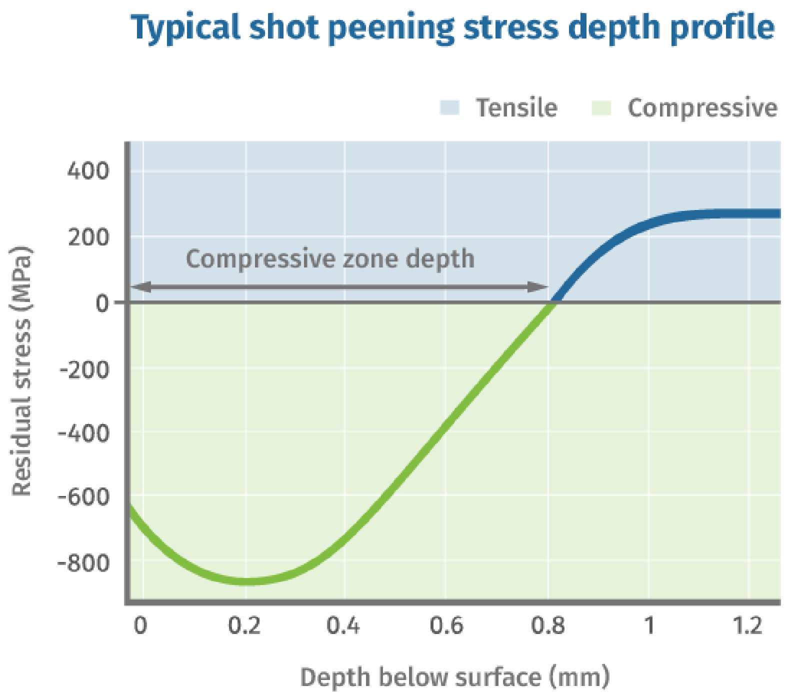


Fig. 7 : Stress Distribution with Respect to Distance from Surface

The surfaces of repeatedly stressed parts, no matter how perfectly they are finished, are much more vulnerable to fatigue than the deeper layers. It has long been established that the vulnerability to fatigue increases as the surface roughness is increased, especially if the roughness consists of sharp notches and more particularly if the notches are oriented at right angles to the principal stress. The practice of carefully finishing the parts is, of course, recognition of this vulnerability in so far as visible mark or scratches are concerned.

These precautions are known to be effective in increasing the fatigue strength of parts. The parts approaching perfection in finish give the highest possible fatigue endurance for any particular material, and that they accurately measure the ultimate fatigue properties of that material. It seems that the part surface is highly vulnerable simply because it is a surface that there is an extra hazard in the surface layer not shared by the deeper layers. This extra surface hazard may be due to sub-microscopic notch effects, or to the fact that the outer crystals are unsupported on their outer faces.

6.1 Compression Lessens Surface Vulnerability

The fatigue strength of the most carefully prepared specimen will be increased if a thin surface layer is pre-stressed in compression by a peening operation. This increase in fatigue strength, resulting from the surface layer being stressed in compression can be shown by the *S-N* curve. The surface, stressed in compression, is effective either on highly finished specimens or those with comparatively rough surfaces [15]

Local stresses from the overloads exceed the elastic limit of the material and, therefore, the tension stress at the working load is decreased. This treatment has been practiced on many production items. It is the equivalent of rolling since, in the unloaded state, the member is stressed in compression in the areas where tension yield occurs during the overloading. The tensile stress in the surface layer is reduced by the amount of the compression pre-stress, and since fatigue failure starts only from tension stress, the fatigue durability of the surface layer is increased. However, the tensile stress in the material below the pre-stressed layer is not reduced but may be actually increased, not withstanding which the fatigue strength of the part is increased. It follows, therefore, that the lower layer is inherently stronger than the surface layer. The German investigator Foppl has shown that the fatigue fracture in cold rolled parts does not originate at the surface but in the material below the pre-stressed layer, as would he expected if the surface is sufficiently pre-stressed in compression. Similar sub-surface fatigue failures, usually called *fissures* and attributed to faulty material, have long been known to occur in railroad rails in which the surface is stressed in compression from the cold work of heavily loaded car wheels.

6.2 Increase in Ultimate Tensile Stress

The stresses induced during different manufacturing processes reduc the UTS value for a component. For instance, if the designer considers X Nm as UTS value, then after the manufacturing processes the available value could he *0.5 X* Nm, thereby reducing the factor of safety limit. This decrease in UTS value can be counteracted by performing shot peening over the part. The component is subjected to shot peening which induces compressive residual stresses thereby increasing the yield point or counters the induced residual tensile stresses.

6.3 Plastic Deformation

Shot peening is the bombardment of a metal surface by high velocity particles. As each particle strikes the work piece, it deforms the surface plastically, stretches the surface radially, and induces tensile stress. When the particle bounces off, tensile stress is relieved, and because of the plastic deformation, an overall compressive stress is left in the surface. This residual stress offsets the detrimental effects of the applied tensile loads [16].

Upon impact, the kinetic energy of the shot is transformed into plastic deformation of the component surface and the shot itself, as well as into a slight temperature increase of the shot and the component (lost energy), During the very short impact time, very high forces act locally. After impact, the shot is reflected from the component surface with the remaining kinetic energy.

All mechanical surface treatments that should improve the fatigue strength of components are based on the principle of preventing dislocation movement in the surface layer either by a local increase of the yield strength in the outer surface (mechanical hardening), the introduction of favourable compressive residual stresses or by reducing the surface roughness.

When individual particles in a high velocity stream contact a metal surface, they produce slight rounded depressions in the surface, stretching it and causing plastic flow of surface metal at the instant of contact. The effect usually extends to about 0.1 *20.25* mm below the surface. The metal beneath this layer is not plastically deformed. In the stress distribution that results, the surface metal has induced residual compressive stress parallel to the surface, while metal beneath has reaction induced tensile stress. The surface compressive stress may be several times greater than the subsurface tensile stress [17]. The depth of plastically deformed layer is influenced by:

1. Nature of material shot peened.
2. Projection velocity.
3. Shot size.
4. Hardness of material.

The depth of deformed layer decreases with increasing hardness of the material treated. Also the depth increases with increasing projection velocity (i.e., Almen intensity) (Fig. 8). The increasing diameter of the shot increases the work hardened depth and the effect saturates at a limiting diameter (Fig. 9). Furthermore, the work hardened depth increases more rapidly with a progressive reduction in the hardness of the material shot peened.

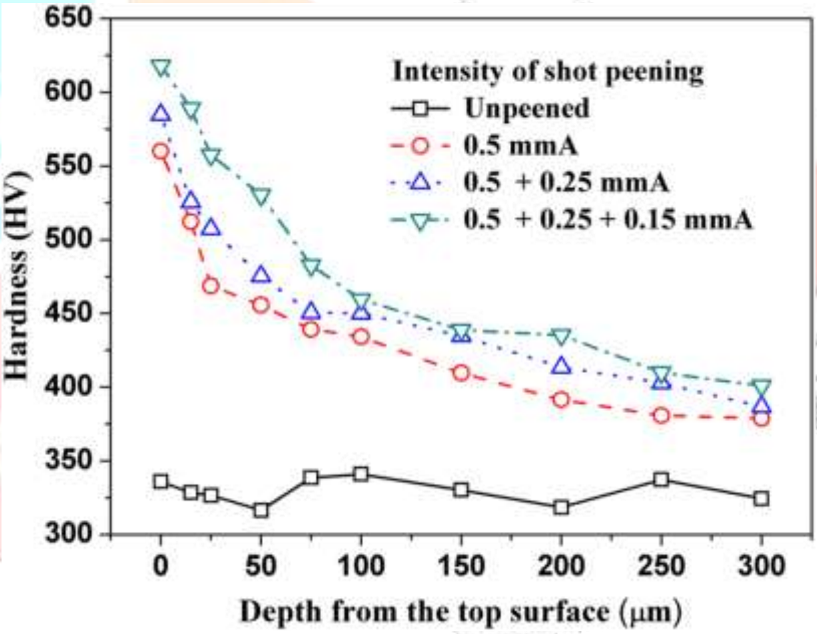


Fig. 8 : Variation in Work Hardened Depth Because of Almen Intensity

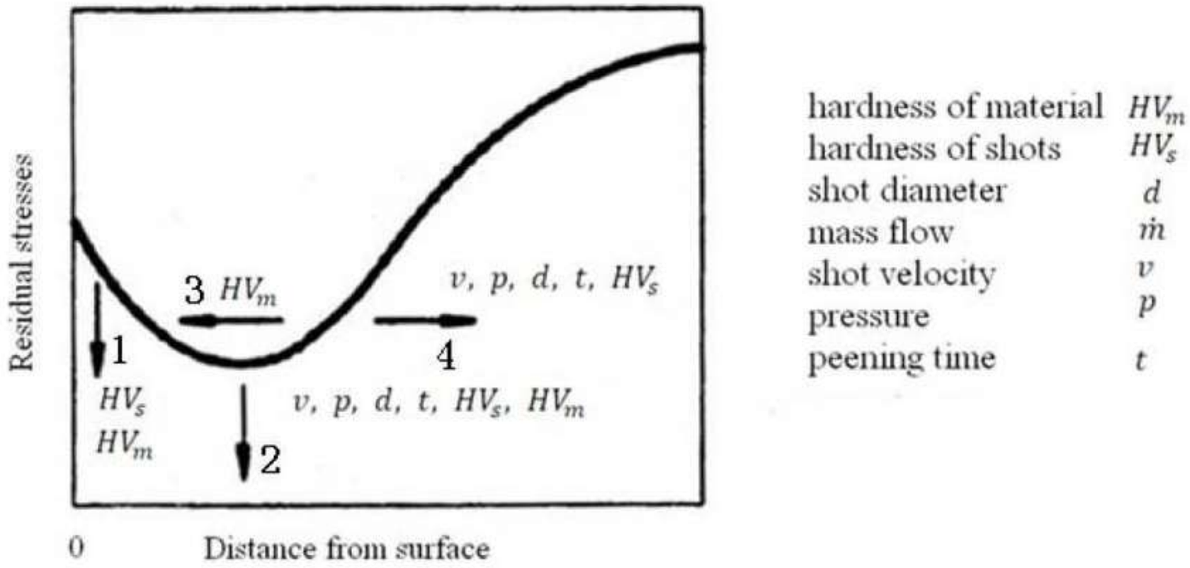


Fig. 9 : Variation in Work Hardened Depth Because of Shot Diameter

6.4 Surface Finish

Shot peening may also be used to enhance the surface finish of a component. It is known that the surface finish has considerable effect on fatigue strength and corrosion cracking resistance of alloys. To improve the surface finish a double shot peening operation may be required in which a heavy shot peening operation is followed by a micro-ball shot peening operation. Sometimes the surface is also subjected to chemical or electroehemical polishing after shot peening to improve the surface finish. The surface roughness increases with increase in Almen intensity caused by increasing velocity. Also a greater increase in surface roughness is noticed in the material with lower hardness level. The effect of shot size on surface roughness, however, is not very clear. For any given material hardness, there is an optimum ball diameter (shot size) that represents the best surface finish obtainable.

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