Laser Peening vs. Shot Peening: engineering of residual stresses, surface roughness and cold working

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Abstract

In Laser Peening (LP), compared to Shot Peening (SP), the magnitude of residual compressive stress at the surface is the same: about 60% of elastic limit; but the depth is much higher. In Low Cycle Fatigue (LCF) depth of residual compressive stress is beneficial because it does not only delay crack initiation, but also crack propagation. Depth of residual stress is also critical in Foreign Object Damage (FOD) and Crack Grow Rate (CGR) applications.

Changes in surface roughness, as soon as cold work, are much more significant in shot SP compared to LP. Those changes can have a positive, or a negative influence depending on application and condition: HCF or LCF, deteriorating or non-deteriorating environment such as corrosion or FOD, fretting, surface contact fatigue.

Thus, LP is complementary to SP in some specific applications such as LCF, FOD, CGR. The other advantage is the extremely high process control that allow more easily to take into account the credit of LP in the design..

Keywords: shot peening, laser peening, fatigue life, crack nucleation, crack propagation

Introduction

Laser Peening (LP) is a process in which an iintense beam of laser light (irradiance 2 to 10GW/cm2) is directed on to a sacrificial ablating material placed on the surface of the component to be treated. The light rapidly vaporizes a thin portion of the ablative layer, producing a plasma that is confined by the inertia of a thin laminar layer of water (~1mm thick) flowing over the surface. In response to the rapidly expanding plasma, a shock wave (peak pressure ~100 kbars) is generated in the part, and run into the material, creating a plastic strain that result in residual stress field (Fig.1).

The spot size for an individual laser peening impact is a square in the range of 3 mm to as much 10 mm on a side scaled so that the shock wave intensity is one to two times the dynamic yield strength of the material being peened. This pressure wave generated by this large footprint laser beam can propagate into the metal to a depth roughly equivalent to its width with nearly constant yielding intensity thereby plastically compressing deeply into the material. The resulting transverse expansion of the compressed material reacts within the component to generate a compressive stress field and/or strain (shape change) depending on the component's geometry and material properties. The plastic strain depth results in residual compressive stress induced to depths up to 8 mm.

Shot peening (SP) [1] is process in which the surface of a part is bombarded with small spherical media called shot (material can be steel, glass or ceramic, from 50µm to 3mm in diameter). Each piece of shot striking the metal acts as a tiny peening harmer imparting a small indentation or dimple on the surface. In order for the dimple to be created, the surface layer of the part must be yeld in tension. Below the surface the compressed grains try to restore the surface to its original shape producing a hemisphere of cold-work material highly stressed in compression. Overlapping dimples develop a uniform layer of residual compressive stress (Fig.2).

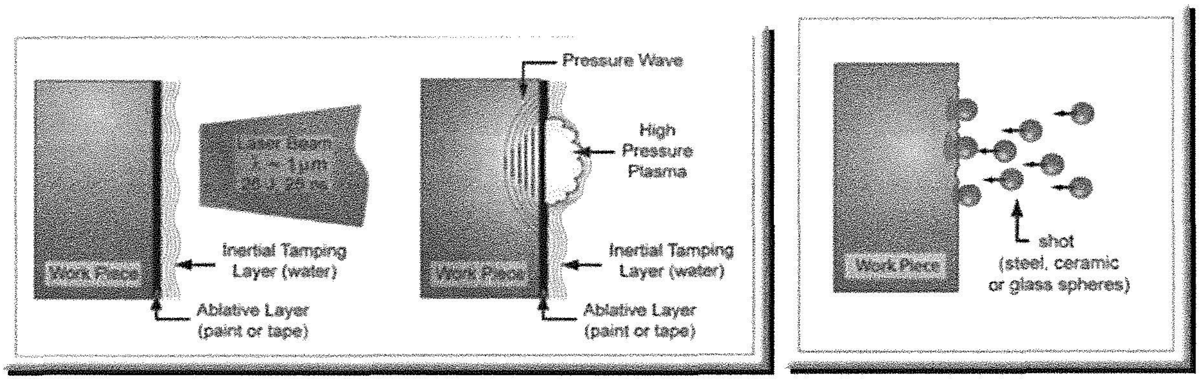

Fig.1 & 2: laser peening (left) and shot peening (right) basic concepts

1- Effects of Laser Peening and Shot Peening on material

The effects of laser peening and shot peening on the processed material can be grouped in three categories:

- Redistribution of residual stresses
- Surface topography modification
- Cold work

1-1 Residual stress

Residual stress profile resulting from shot peening and laser peening can typically be described by two values:

- The magnitude of compressive stress at the surface (or just below the surface): nearly the same in LP or SP, about 60% of the elastic limit.
- The depth of compressive stress, which is the depth where residual compressive curve cross the residual stress in the bulk material: it is up to 10 times deeper in LP compared to SP.

An example on carburized 9310 is shown on figure 3.

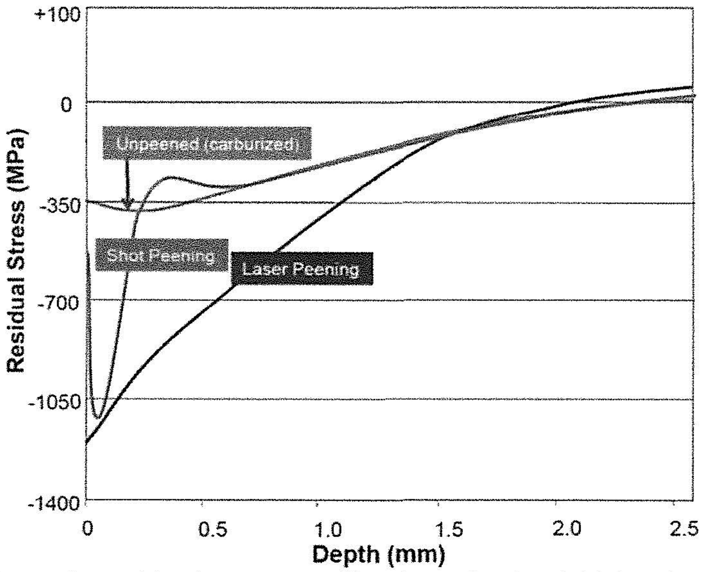

Figure 3: residual stress profiles in carburized 9310 after heat treating, SP and LP

1-2 Surface topography

In LP there is almost no surface topography modification because spots are very big (3 to 10mm) and depth of indent is very small (a couple of tenth of microns).

In SP on contrary, each dimple is much more deep (figure 4), depending of course on SP parameters.

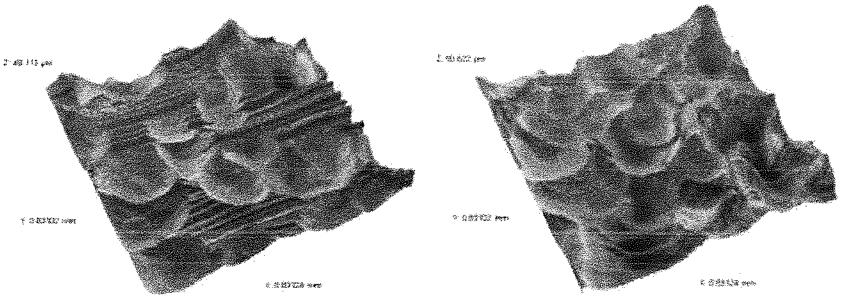

Figure 4: surface topography on aluminum blocks 8.5 x 8.5mmafter shot peening, partial coverage on left and full coverage on right

1-3 Cold work

SP induce a lot of cold work, while LP almost not. Reasons are:

- Each dimple from SP creates more plastic deformation than LP shock wave and indent.
- SP is stochastic process: each zone needs in average to be stroked 13 times to achieve 100% coverage while one or two shots are enough in laser peening (assuming square shots).

Most of metallic materials will harden during cold working, figure 5.

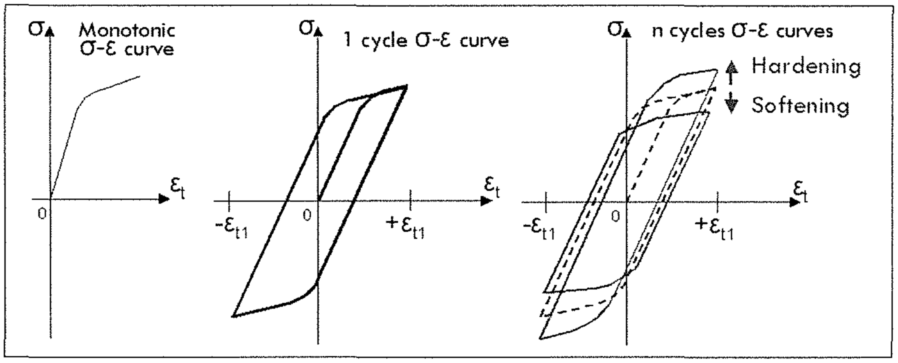

Figure 5: Cyclic elasto-plastic deformations can result in hardening, or softening the material

2- Different phases of the fatigue life

Understanding of the fatigue mechanism is essential for engineering of residual stress, surface roughness, and cold work.

Crack nuclei start as invisible microcracks in slip bands. Nucleation of microcracks generally occurs very early in the fatigue life, almost immediately if a cyclic stress above the fatigue limit is applied. Microcracks remain invisible for a considerable part of the fatigue life.

After a microcrack has been nucleated, crack growth can still be a slow and erratic process due to effect of microstructure. After some microcracks has occurred away from the nucleation site, a more regular crack grow is observed. This is the beginning of the real crack grow period [2].

Thus, fatigue life until failure consists in two periods:

- the crack initiation period
- the crack propagation period.

Different phases of the fatigue life are indicated in figure 6.

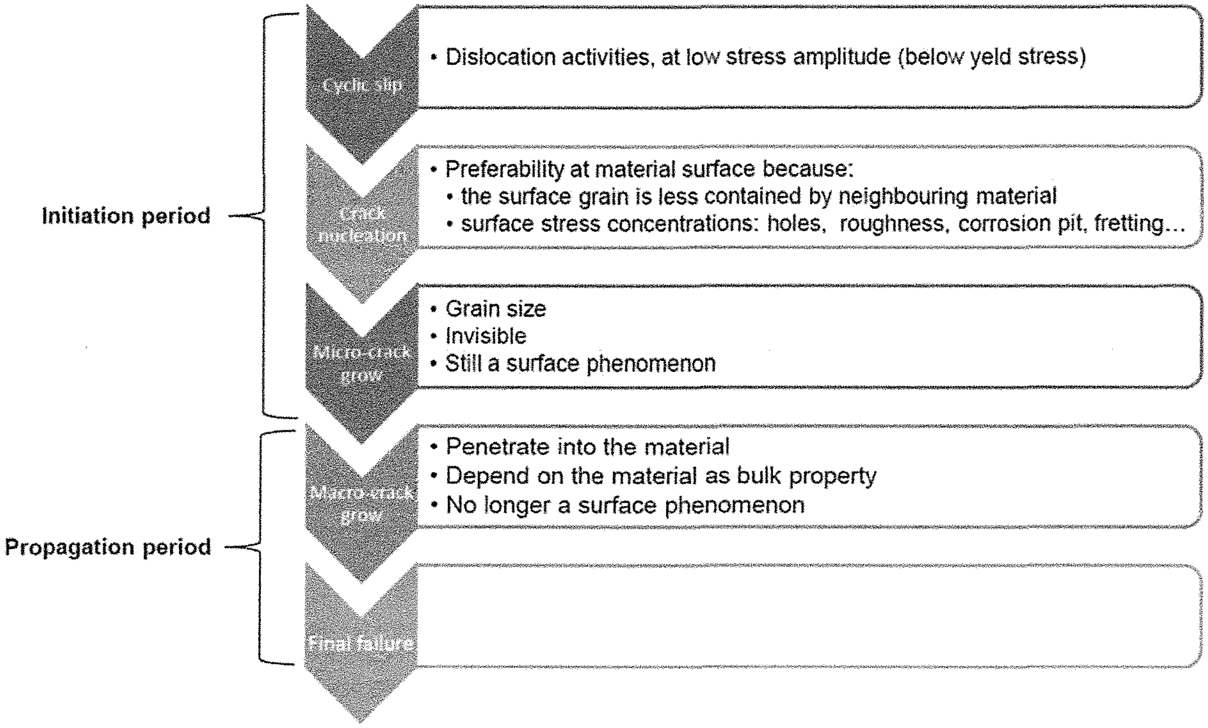

Figure 6: different phases of the fatigue life.

S-N, or Wöhler curve, represent the end of the propagation period, when the part fails.
Now, let's imagine we could detect, and plot the end of the initiation period: it's the French curves (figure 7).
On logarithmic chart the gap between two curves tend to zero as long as the number of cycles: in High Cycle Fatigue domain (HCF) the percentage of the crack propagation period in the total life is very small, and this percentage increase in Low Cycle Fatigue (LCF).

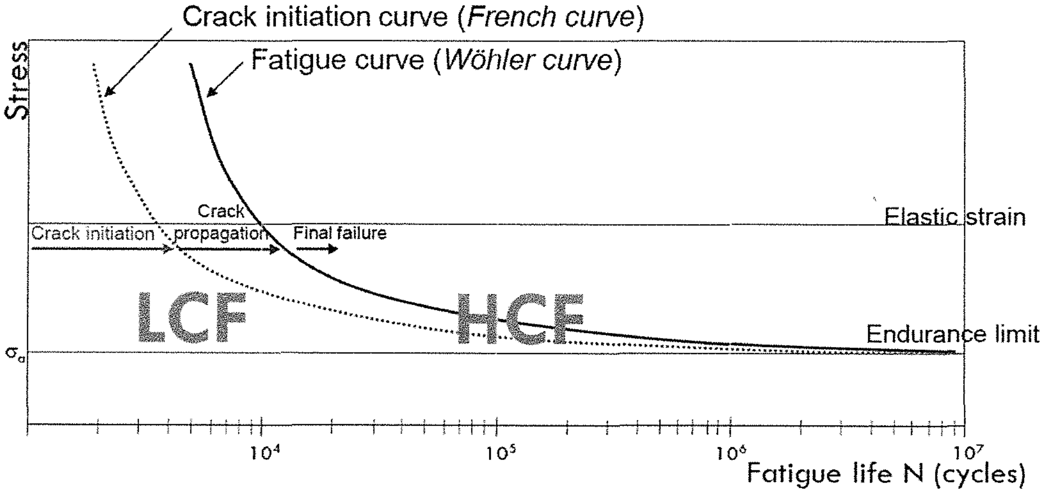

Figure 7: French curve, representing the crack initiation area, and Wöhler curve, representing the crack propagation time; assuming non deteriorating environment.

It's important to remember that:

- Crack initiation period represent a big percentage of the total fatigue life of a structure.
- Crack initiation is a material surface phenomenon

- Crack propagation period is material bulk properties dependent.

Now, let's see how residual stress profile, surface roughness and cold work influence the fatigue properties.

3- Engineering of residual stresses, surface roughness and cold work

3-1 Engineering of residual compressive stress

Assuming non deteriorating environment such as Foreign Object Damage (FOD) or corrosion, big depth of residual compressive stress is beneficial in LCF only, where crack propagation period is a significant percentage of the total fatigue life (figure 8).

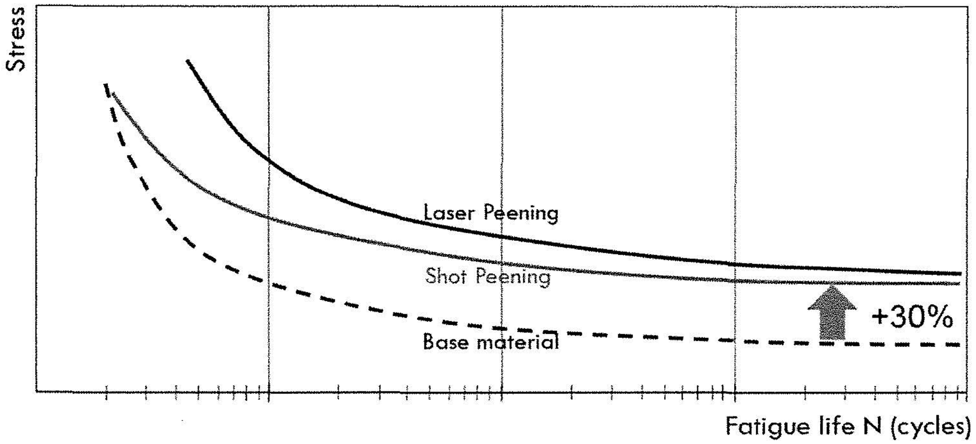

Figure 8: comparison of SP and LP: effect of residual stresses only in <u>non-deteriorating</u> environment

Assuming deteriorating environment, the low depth of residual compressive stress from SP can be insufficient to increase significantly the fatigue properties (figure 9).

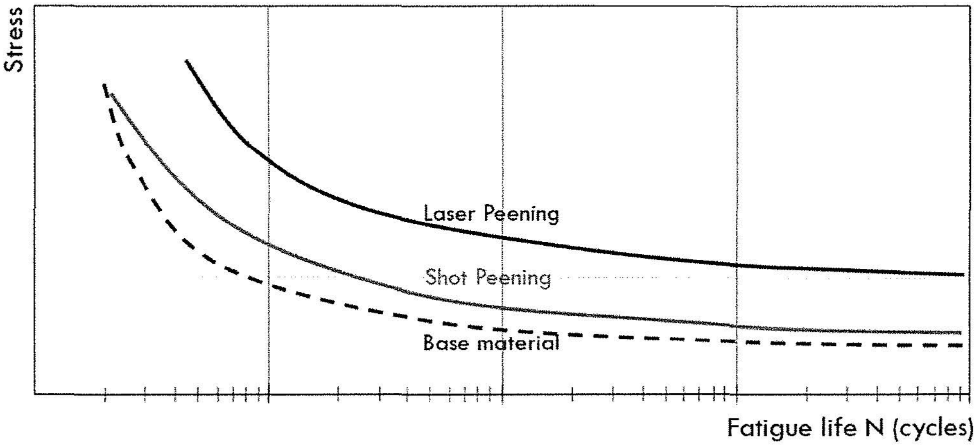

Figure 9: comparison of SP and LP: effect of residual stresses only in <u>deteriorating</u> environment

3-2 Engineering of surface topography

Surface roughness from shot peening is characterized by peaks and valleys.

In HCF application, the roughness increase resulting from SP has a negative effect because it will most often increase the surface Kt, and increase cracks nucleation; this effect is even more detrimental when surface roughness before SP is smooth, and when material is notch sensitive.

In LCF, this effect is less significant because crack propagation is not a surface phenomenon

In fretting-fatigue and fretting-corrosion applications, peaks from shot peening have a positive effect because they reduce the friction factor; valleys have also a positive effect because the help in neutralizing fretting fragments at the bottom of craters. So, surface roughness from SP is beneficial.

In contact fatigue applications, peaks have negative influence because they increase stress concentration at the surface; on the opposite valleys have positive influence because they improve lubrication. So, increase of surface roughness can be beneficial or detrimental depending on surface topography and application (micro or macro-pitting).

3-3 Cold work

Cold working, when hardening the material (typically changing austenite into martensite in austenitic stainless steels, or in gears after carburizing), will be very positive in HCF applications because it will:

- reduce the grain size and delay micro-crack propagation,
- improve the mechanical properties of the material,
- increase the magnitude of residual compressive stress.

But on the other side is has been demonstrated that work hardening increase the residual stress relaxation. So, work hardening can be detrimental in LCF application, and thermal fatigue applications.

Conclusion

The fatigue life consists of two periods, the crack initiation and the crack propagation. In most of the applications the crack initiation period, which is a surface phenomenon, is a big percentage of the total fatigue life. There is no need in deep residual compressive stress but surface integrity is important to preserve.

LP is complementary to shot peening in some specific applications such as LCF, FOD, CGR where SP is inefficient because crack propagation period is a significant percentage of the total fatigue life.

Also, even if control and repeatability of SP becomes more and more precise when using new generation of robotic machines, the process control of LP is unequalled and allow more securely designers to take the credit of fatigue improvement in the design.

References

[1] *Shot Peening Applications*, Eight Edition, Metal Improvement Company
[2] Jaap Schijve, *Fatigue of Structures and Materials,* Second Edition, Springer, pp 14-15