Correlation of shot peening parameters to surface characteristic.

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Abstract
Compressive residual stress is one of the surface characteristic resulting from shot peening, but it can be an error to focus only on it.
Depending on the application (fatigue, pitting, micro-pitting, fretting, stress corrosion cracking) there are others characteristics which must be considered with attention when we specify shot peening parameters (shot nature, shot size, shot hardness, Almen intensity, shot angle, coverage). These surface characteristics are elimination of tool marks or surface defects, modification of surface roughness, work hardening, surface elongation, contamination, surface damages. This paper describe the most important of them.

Introduction
Fatigue performance of metallic parts depend on three factors : metallurgy, surface geometry, and residual stress. Performance can also been affected by damages during process manufacturing or in service.
Shot peening has potentially positive and sometimes negative effects on all these factors: creation of residual compressive stress, work hardening, surface roughness and tribological properties modification, delay of micro-cracks propagation in service.

Depending of fatigue type shot peening effects which must be considered are not the same:
- for fatigue applications, characteristics are residual stress, roughness and notch effect, work hardening, surface damages
- for pitting and fretting applications there is also to consider tribologic properties of surfaces in contact which are also modified by shot peening.

We detail these effects and see the influence of shot peening parameters.

A- Redistribution of residual stress in the part.

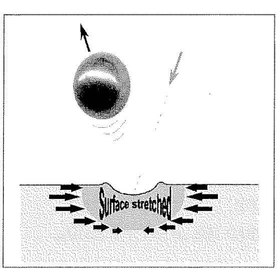

Figure 1 : compressive residual stress generation.

Compressive residual stress are the result of a difference of plastic deformation between surface and sub-surface.
Every shot strike create a dimple. The surface and a small volume under the dimple are stretched (figure 1).The rest of the part try to restore this area to his original shape, stressing this area in compression. Overlapping dimples develop an uniform layer of compressive residual stress [1].

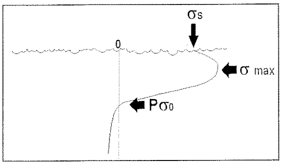

Figure 2 : typical residual stress profile

The three characteristics points of a compressive residual stress profile are (figure 2) :
σ_{max} : maximum compressive residual stress, normally just bellow the surface. If shot peening is processed in good conditions it reach 70% of material yield strength after cold working.
σ_S : surface stress, usually less than σ_{max} .
$P\sigma_0$: depth of compressive layer.

A-1 Two mechanisms drive the generation of compressive residual stress : Hertz pressure and skin elongation.

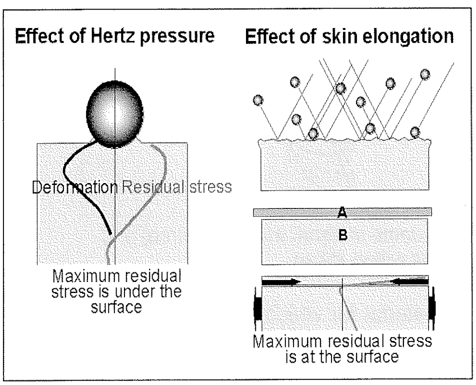

Figure 3 : residual stress generation mechanisms.

1- Hertz pressure
Deformation induced by big shot is maximum under the surface, at the Hertz pressure depth. Then maximum compressive stress σ_{max} is under the surface, at this depth (figure 3). Difference between σ_S and σ_{max} increase when shot size increase: with a small shot, σ_S value is close to σ_{max}, as soon as with a big shot magnitude of σ_S decrease.

2- skin elongation.
Shots strikes acts as rolling pin which elongate a thin layer A on the surface of the part. (figure 3). If layer A was free, it would be longer than the rest of the part B. But A and B are linked and B do not allow permanent deformation of A. As a result we get compressive residual stress in A with maximum stress σ_{max} on the surface, and small depth affected.
This residual stress profile is typically generated by small steel shots, glass beads and ceramic shots.

High depth of compressive residual stress $P\sigma_0$ are required when fatigue cracks initiate under the surface, and/or to increase crack growth resistance

A-2 Amplitude of compressive residual stress depend on shot direction angle.

Amplitude of compressive residual stress is maximum (about 60/70% of yield strength after cold working) when the shot direction is perpendicular to the surface of the part, and amplitude will decrease when angle will increase.
This aspect characterise the quality of the process: strike impact direction badly oriented, or badly controlled during the process, will induce poor amplitude of compressive residual stress compared to the potential of the material.

B- shot peening is a cyclic cold working process which can modify material mechanical characteristics.

Shot peening is a cyclic cold working process. At 100% coverage each point of the part is in average stricken 13 times; at 200% each point is in average stricken 26 times, ect...

After cold working some material will harden, some others will soften (figure 4). For example austenitic stainless steel hardness will increase dramatically, as soon as for some aeronautical aluminium will soften. On spring steel, cyclic cold working has no influence.

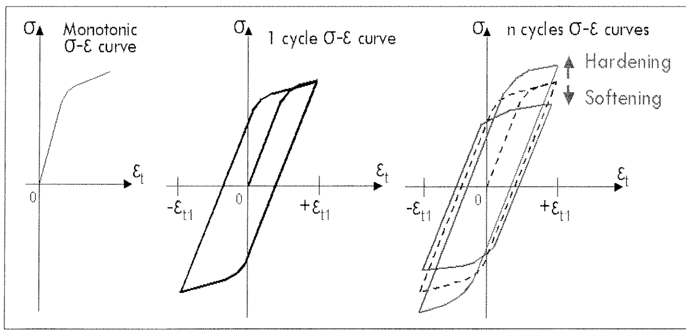

Figure 4 : under cyclic cold working some material will harden (red) and some others will soften (blue).

Then we can specify high coverage on material for which cold working has positive effect; we specify low coverage (100 or 125%) on material for which it is negative and/or we specify a maximum coverage.

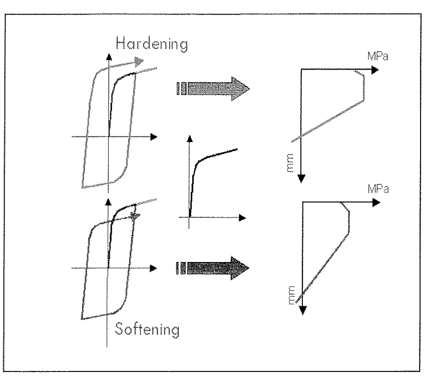

Figure 5 : influence of work hardening on residual stress profile

As a consequence residual stress profile will be influenced by cold working and coverage rate because magnitude of compressive residual stress is directly linked to mechanical characteristics of the material (figure 5). When material hardness increase, magnitude of compressive stress will increase, and soon as when material hardness will decrease magnitude of compressive stress will decrease, and depth of compressive stress will increase.

C- Tribologic and surface effects

It's a important aspect which is often ignored during shot peening parameters specification, qualification process, and production control.

C-1 Elimination of tools marks, surface isotropy.

Fatigue performance is influenced by surface topography resulting from process manufacturing. Depending on notch sensitivity of the material, this influence is more or less important.

For example:

- Machining, grinding, shaving...generate grooves. The bottom of these grooves, most of the time oriented in the main loading direction, are stress concentrations.
- Stamping a metal sheet produce burs and cracks in the area where material is pulled up.
- Casting skin present surface defects, more or less important depending on casting process (investment, sand, mould...)

Shot peening can eliminate or soften the damaging effect of surface defects, if the shot size is correctly adapted to the surface topography. If shot size is too big it can't remove tool marks and shot peening performance is poor. Figures 6 to 9 show surface tool marks prior and after shot peening.

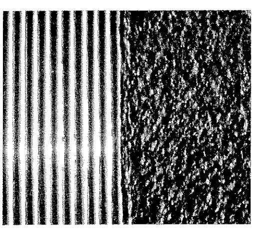

Figure 6 construction steel prior / after shot peening: elimination of tool marks.

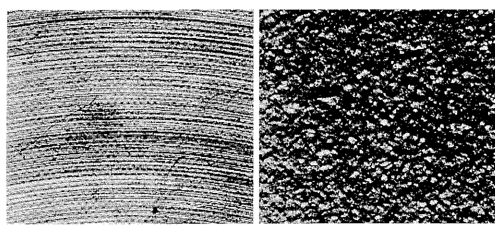

Figure 7 : Udimet machined / shot peened S070H Shot peening create an isotropic surface

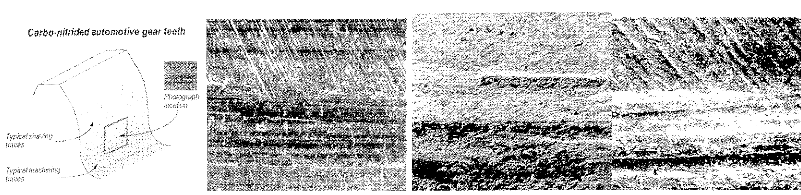

Figure 8: pinion tooth root and flank after machining and shaving (photos 1 & 2 from left to right): tool marks are perfectly visible. Tools marks are eliminated with small S110H shots (photo 3) but not with S230H shots (photo 4).

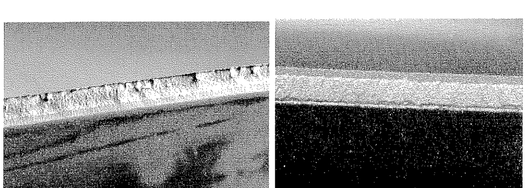

Figure 9 : cutting area of a metal sheet after stamping (left), and after shot peening (right): cracks initiations are limited.

Now, we come against a difficulty when we try to measure this effect.

The easy and intuitive way consist in measuring roughness Ra and considering that the lower roughness Ra is, the bigger fatigue life is. It is often true if we compare two surfaces with the same manufacturing process, but it can be incorrect if we compare different manufacturing process. In particular it is incorrect if we compare a machined area, and the same surface after shot peening.

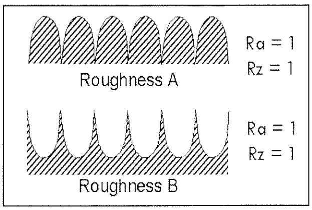

Figure 10 : roughness comparison of two surfaces A and B

Example on figure 10 is exaggerated but allow to understand. Everybody intuitively feel that fatigue performance of surface B is better than this on of surface A because stress concentration at the bottom of A gorges are much more higher than at the bottom of B valley. But nevertheless A and B have the same Ra, and the same Rt roughness.

Coming back to more concrete concepts, we can consider that shot peening will be efficient if shots strikes bottom of the defects, and if residual roughness is isotropic. The eye + magnifying grass or microscope are good tools to evaluate this effect.

But it is not always possible to check every shot peening area with a microscope, and it is impossible in production. It is why fluorescent tracer method like PeenScan® is very useful. We can immediately detect if tools marks are not correctly peened. This control is also very important in production because sometime surface topography can change because machining process has changed, and fluorescent tracer control ensure that shot peening process remain adapted to the part from this point of view.

But micro-cracks and stress concentration elimination is not the only geometrical positive effect of shot peening.
Shot peening surface topography is characterised by succession of peaks and valley: lets see their influence in fretting and pitting applications.

C-2 Roughness influence in fretting applications.

Fretting occurs when two highly loaded members have common surface where sliding takes place. Adhesive forces cause cold welding of opposite asperities, and relative movement of microscopic amplitude cause detachment of metal particle which further contribute to scoring the surface. Other failure mechanism, such as fretting corrosion and fretting wear commonly accompany fretting failure.
Typical roughness resulting from shot peening reduce the fretting.

C-2 a) Positive influence of shot peening peaks.

If we consider two machined surfaces, there are in reality few contact points, causing very high contact pressure at this points (figure 11) [2].
When we peen one of the two surfaces, number of contact points increase (figure 11) and thus pressure contact decrease.

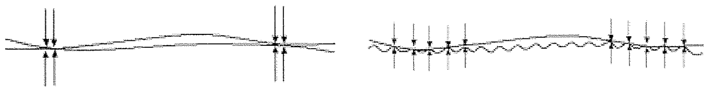

Figure 11: unpeend (left) and peened (right) conditions: contacts points increase, and then contact pressure decrease after shot peening one surface.

Bearing capacity is considerably modified, sliding factor is reduced, and risks to create micro cold welding is reduced.
For the same reason this roughness resulting from shot peening is efficient against galling.

In addition the elasticity of the peaks or contact points on which the surface is carried plays an important role.
When there is a relative movement between both surfaces, peaks will be in a first time elastically deformed without sliding on the contact point. So, if we stay in this conditions, there is no risk of detachment of particle [2].

C-2 b)- Positive influence shot peening valleys.

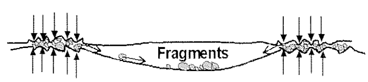

Figure 12 : neutralization of fretting fragments in the shot peening crater

Fretting generate some particle called third body. These particle are usually very hard and aggravate the degradation process as soon as they stay in the contact area.
Shot peening craters help to collect the fragments and keep its out of the contact areas (figure 12).

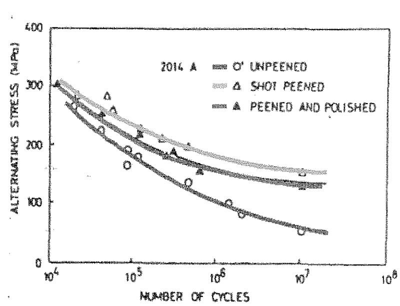

Figure 13 S-N curves on 2014 aluminum alloy

Figure 13 shows results on a 2014 aluminium [3], and allow to distinguish the contribution of residual stress, and roughness.
Testing conditions are: pressure contact 32 MPa, frequency 50 Hz, shot peening parameters S330, 12-16A, 125% controlled PeenScan®.
Compared to unpeened condition (blue curve), shot peening (green curve) increase fatigue strength from 50 to 150 MPa.
Then, if we remove the roughness induced by shot peening, keeping compressive residual stress, fatigue strength decrease from 150 Mpa to 125 MPa (red curve). We can conclude that the difference is the contribution of roughness.

As a conclusion, even if compressive residual stress is the major shot peening effect of shot peening to retard fretting, typical roughness (peaks and valley) resulting from shot peening has also significant positive effect.

C-3 Roughness influence in micro-pitting applications.

Pitting occurs on gears flanks and others components involved with rolling and sliding contacts.
This time roughness peaks have an negative influence because loadings and stress reach higher levels and surface finishing prior shot peening is better.

C-3 a) Negative influence of shot peening peaks.

Roughness peaks in red on figure 14 induce high amplitude stress concentration on the surface of the part (figure 15) where micro-pitting can initiate. Micro-cracks can also propagate and reach the Hertz pressure depth and generate big pits (figure 16).

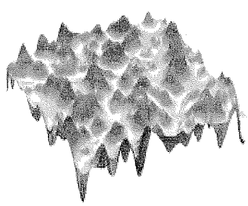

Figure 14 : 3D surface topography [4]

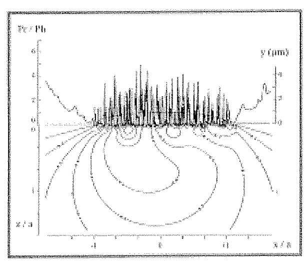

Figure 15 : pressure and stress fields [4]

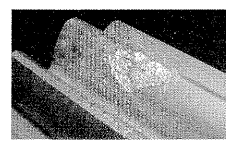

Figure 16 : pitting on a pinion tooth flank.

C-3 b) Positive influence shot peening valleys.

Figure 17: dimples act like lubricant reservoirs.

Roughness valley have positive effect because they act like lubricant reservoirs. (figure 17), and they will help lubrication of the contact.

Hybrid roughness parameters Rk, Rpk, Rvk were specially designed for measuring these criteria.
We have seen that for pitting problems, ideal surface consist in absence of peaks, and lubricant reservoirs; it is what proposes the C.A.S.E® process (Chemically Assisted Surface Engineering): it is a chemical assisted tumbling after shot peening, which allow to erode the shot peening peaks, keeping the dimples valley (figure 18).

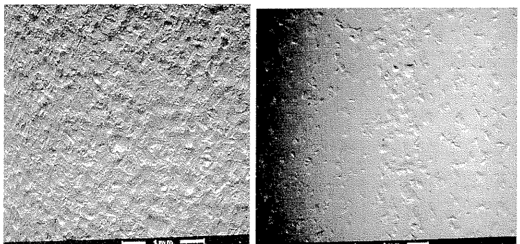

Figure 18 : surface shot peened (left) and shot peened + C.A.S.E process (middle) on a EN36 58-60HRc case harden steel : shot peening peaks are removed but not the dimples useful for lubrication.

C-4 Creation of damages : burrs, cracks, broken shots incrustations.
Different types of surface damages can occur during shot peening operation if shot peening parameters are not adapted to the material and part geometry, figure 19.

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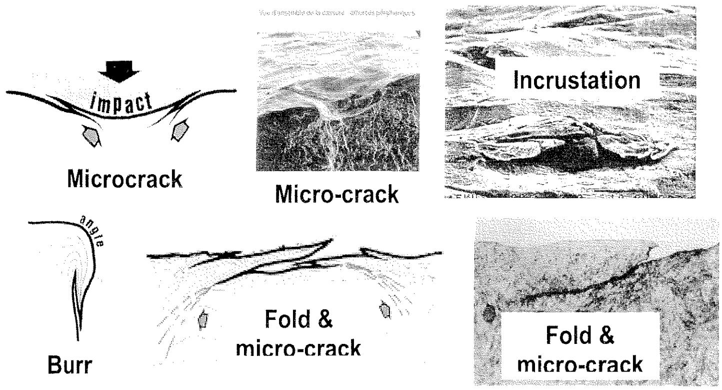

Figure 19 : different type of shot peening damages.

- Micro-cracks around the impact can occur when shot velocity (i.e Almen intensity) is too much important compared to the mechanical characteristics of the material,
- Incrustation can occur with bad quality of shots, and bad quality of shots can be the consequence of a bad process which break down the shots and do not eliminate its.
- Burrs can occur if the shot diameter is too big compared to the radius peened,
- Folds + micro-cracks are the consequence of excessive high Almen intensity, very high coverage, bad quality shots.

Conclusion
This non exhaustive list of shot peening effects emphasize that optimization of shot peening parameters is a complex process.
To a great extent this optimization is empirical because shot peening effects are difficult to measure (elimination of tool marks, peaks and valley effects in pitting and fretting applications,...) and it is not possible to replace expensive and long fatigue tests on parts or on samples by computer modeling which are still at the early development stages.

References
[1] Metal Improvement Company, "Shot Peening Application", eighth edition.
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[3] The fatigue of an aluminium alloy produced by fretting on a shot peened surface G. Leadbeater, R. Waterhouse, University of Nottingham, UK.
[4] Philippe Sainsot, Philippe Ville, Laboratoire de Mécanique des Surfaces et des Solides, INSA Lyon.