CERAMIC SHOT
ENHANCEMENT OF HIGH STRENGTH STEEL ENDURANCE
APPLICATION TO SPRINGS AND GEARS

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Abstract

This paper will briefly recall some previous research works on ceramic shot, expose latest complementary works, and show their translation into effective industrial applications for the improvement of fatigue behaviour of springs and gears.

Keywords

Fatigue strength, high strength steel, ceramic shot, steel shot, spring, gear, dual shot peening.

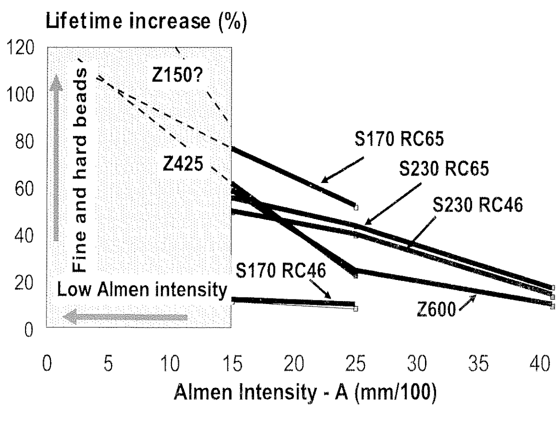
Preliminary research works with ceramic shot in 1986 [2]

In Figure 1, new graphic synthesis of the results helps pointing out two basic conclusions:

1 - The highest fatigue life increase has been obtained when peening under low Almen intensity with fine and hard steel shot or with ceramic shot.

2 - All curve slopes are negative. I.e. whatever are the other peening parameters, low Almen intensity is inducing higher fatigue life time. This was explained by the higher level of compressive residual stress at the surface, combined with smoother surface under low peening intensities.

The left area below 0.15 mm-A was not explored. Very fine ceramic shot was not tested. This was the starting point of further research works.



Test parameters

. Material: high strength steel 300M (1960-2100 N/mm², RC 53-55),
.Torsion test with round specimens diam. 12.7 mm,
. Max stress 1456 N/mm²
. "0" of the y axis as unpeened reference sample.

Fig. 1: Fatigue lifetime of 300M steel versus Almen intensity with steel shot and ceramic shot.

Additional investigations presented in 1996 [4]

For several hardness levels of heat treated steel, single or double peening with steel or ceramic shot were performed, optimising fatigue behaviour of test samples.
All peening operations were carried out with the same optimised parameters:
- Cast steel shot S230 (0.58 mm, 58-64 HRc), Almen intensity 0.30 – 0.40 mm-A, coverage 200 %.
- Ceramic Zirshot Z150 (0.150 – 0.210 mm, 700 HV), Almen intensity 0.10 mm-N, coverage 400 %.

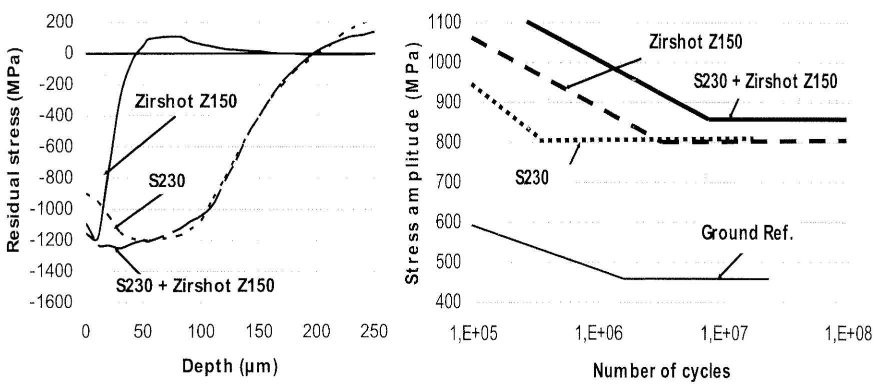


Fig. 2: Residual stress and S-N curves for carbon steel Ck45 hardened 665 HV 10 peened with steel shot, ceramic shot, or combined.

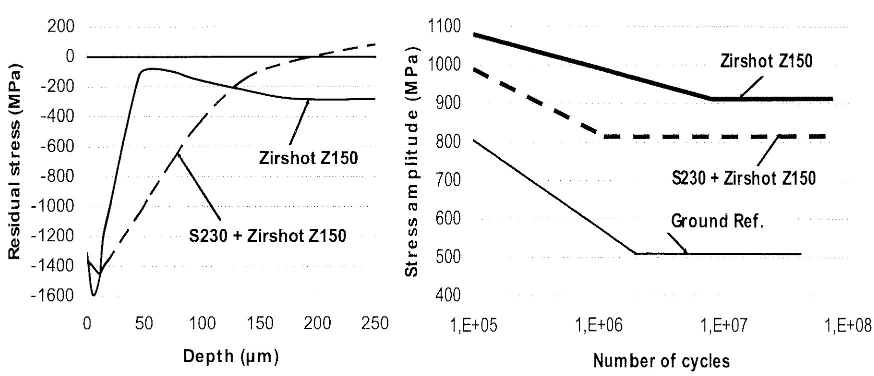


Fig. 3: Residual stress and S-N curves for 16MnCr5, case hardened 1030 HV 0.2, peened with ceramic shot or steel shot + ceramic shot.

Extreme performances are achieved when double peening with steel shot followed by ceramic shot on carbon steel Ck 45 hardened 665 HV 10.

The highest fatigue life and fatigue strength improvements are achieved with single ceramic shot peening on 16MnCr5, case hardened 1030 HV 0,2.

Application to case hardened transmission gears in 1999 [5]

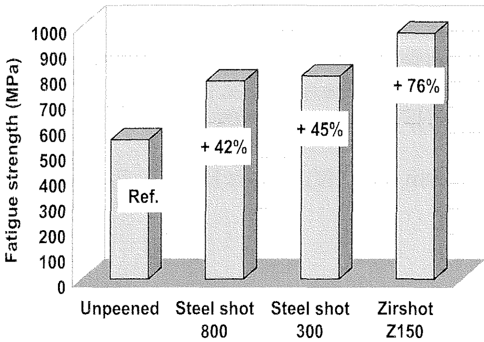


Fig. 4: Fatigue strength results

With the objective to optimise fatigue performance at tooth root location, several case hardening and shot peening treatments with steel or ceramic shot were combined on flat fatigue samples for flexion test.

Austenite transformation rate, micro hardness and residual stress profiles were measured.

In Figure 4, best fatigue strength (10^7 cycles) of 970 MPa is observed after single peening with ceramic shot Z150, in the conditions described previously [4]. The explanation is the high level of compressive residual stress at the surface, combined with the low roughness and the elimination of grinding traces. This confirms previous results.

Latest complementary works in 2002 (**)

Test specimens with a diameter of 16 mm, made of 54SiCrV6 grade of spring steel, hardness 575 HV after austenitization at 920 °C during 18 min under Nitrogen with 9 $l.min^{-1}$ flow rate, oil quenching and air tempering at 400 °C during 1 h. Heat-treatment has been designed in order to reproduce decarburising on coil springs. Hardness profile of test specimen is compared to spring one in Figure 5. The affected depth is about 200 µm.

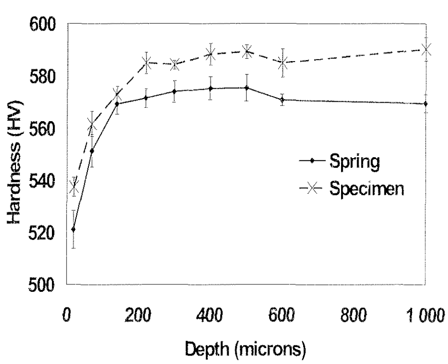


Figure 5 : Micro hardness profiles.

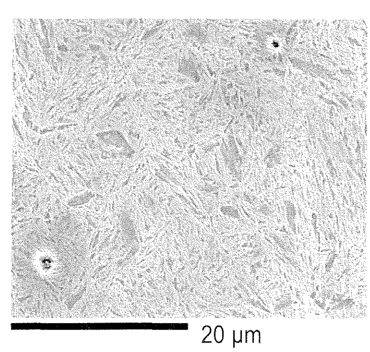


Figure 6 : Tempered martensite microstructure.

Figure 6 shows typical tempered martensite microstructure of material. Tensile tests allowed to estimate Young's modulus about 200 GPa, yield stress about 1600 MPa, ultimate stress about 1900 MPa and ultimate elongation about 10 %. In order to take into account initial roughness effects, specimens have been polished using abrasive paper to obtain Rz = 5.7 µm. Rz roughness criteria has been used in order to take into account the notch effect, important parameter in the fatigue behaviour.

Shot peening parameters:
Shot speed was calculated as function of air pressure, shot size and density [3]. Distance nozzle/sample: 150 mm. Impact angle: 85 °. Automatic translation of the nozzle allowed homogeneous coverage. Coverage rate was determined by optical observation. Ceramic shot Z150 (150 – 210 µm), Z210 (210 – 300 µm), Z300 (300 - 425 µm) and Z425 (425 – 600 µm) were chosen in the Zirshot® range with some cycles of pre-use to simulate an industrial working load. Steel cut wire (400 and 800 µm) was conditioned (5000 cycles). Hardness was about 640 HV for SCCW and 700 HV for ceramic shot.

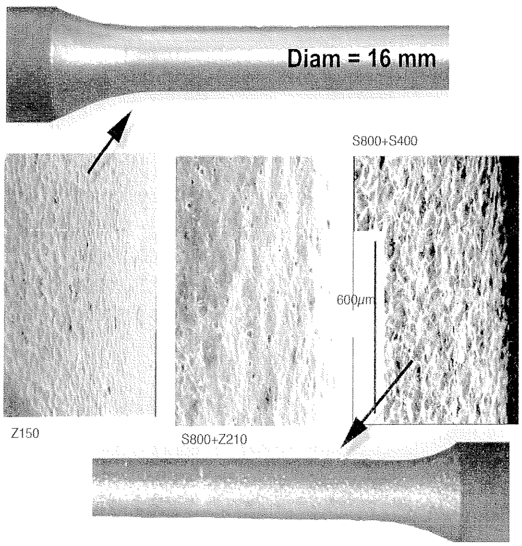


Fig. 7: Influence of shot type and shot peening parameters on surface condition of fatigue coupons

Items designation:
Xxxx/yyy/zzz, where
X = "S" for steel shot;
X = "Z" for ceramic shot;
xxx = shot size (µm);
yyy = shot velocity (m/s);
zzz = coverage rate (%).

In Figure 7, visual differences appear clearly. Double peening S800 + S400 using only steel shot gives the highest roughness; Rz ≈14 µm. The use of ceramic shot Z210 for the second shot peening improves the surface quality notably; Rz ≈10 µm. SEM images show a significant smoothening of the surface when ceramic shot is used.

In figure 8, roughness after peening with ceramic shot is almost identical, even slightly lower, than initial roughness for affected depth up to 150 µm.

The use of steel shot (S800) is increasing the affected depth, but generates systematically higher roughness than the ceramic shot (Z425).

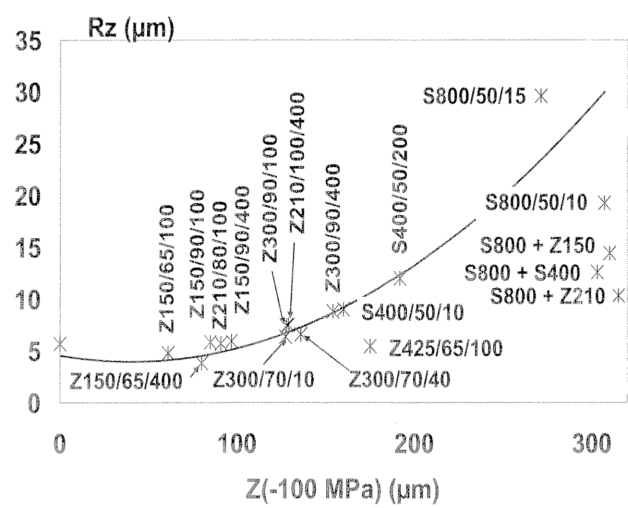


Fig. 8: Surface roughness (Rz) versus depth where compressive stress is 100 MPa (Z-100 MPa)

Double peening, first with steel shot followed by ceramic (S800 + Z210) maintains a low roughness level and provides the same affected depth as steel shot S800, even versus double peening with steel shot (S800 + S400).

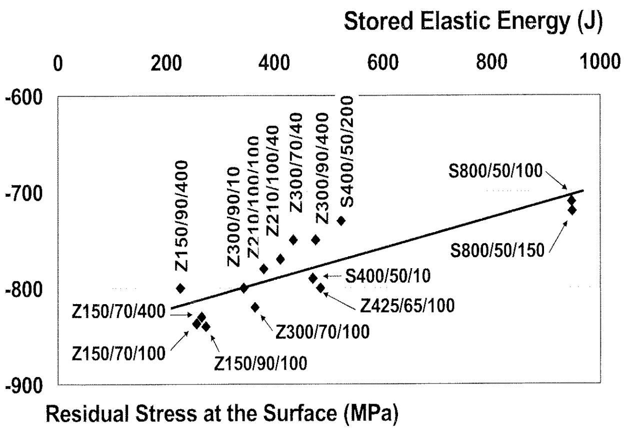


Fig. 9: Influence of the amount of stored elastic energy (*EV*) on residual stress at the surface (σ_S).

In Figure 9, the amount of stored elastic energy *EV*, can be evaluated by integral calculation on the volume:

$$\int_V \sigma.\varepsilon.d\varepsilon$$

Where σ is the stress, ε is the strain and v is the volume. This can be directly linked to the area contained under the residual stress distribution curve.

The increase in residual stresses at the surface due to the stretching effect and the strong cyclic plastic deformations of this one [1] is more significant for shot peening with ceramic shot than for peening with steel shot.

This explains why ceramic shot does not increase roughness, in a significant way, when the shot peened depth increases. In parallel the residual stresses of surface remains appreciably constant.

In case of early failure starting from the surface, the affected depth by the shot peening is not the first issue. For better fatigue behaviour, it is preferable to seek a low roughness with in-depth compressive residual stresses. Therefore ceramic shot is more advantageous than steel shot.

With regards to local fatigue concept [1] [4], in case of heavy loading, depth of residual stress profile should be adapted and combined with the lowest roughness as possible. If necessary, double shot peening (steel + ceramic shot) can be used. In other cases, for current load, single ceramic peening can be advantageously applied.

Industrial application of ceramic shot for automotive springs (***)

Trying to respond to specific performance issues on automotive springs, the company started its program with ceramic peening in 2002. The challenge was to increase the durability of highly stressed compression and torsion springs.

Sample springs processed with ceramic shot gave encouraging results. The next step was to develop the full scale production process that would insure repeatable results.

The industrial shot-peening of springs is performed in a batch type equipment where a centrifugal wheel is used to propel the shot. A machine normally working with steel shot was adapted to work with ceramic shot. The main modifications to the equipment were the control of the mass flow with ceramic shot and adjustment of the wheel rpm.

By using ceramic versus steel shot in a double peening process, an increase of 25% of durability for 90% reliability has been achieved on highly loaded torsion springs.

Even after the optimal shot configuration and intensity are established for a given application, it was also possible in some cases to achieve the same or better durability with a single ceramic peening versus duplex peening with steel shot or even duplex peening with steel followed by ceramic.

Because of the very high residual stresses that can be achieved at the surface without increasing the roughness, ceramic shot is especially efficient in applications where the fatigue failure actually starts at the surface of the spring wire.

Conclusion

During more than 10 years, the research works described through this paper represent some hundreds of residual stress measurements, fatigue tests, and other analysis, combining a wide range of parameters, involving different research teams worldwide.

As a consequence, the use of ceramic shot for the improvement of high strength steel endurance is now proven to be of high efficiency by smoothening the surface and bringing high level of compressive residual stress at the surface, avoiding crack initiation and propagation from the surface, and thus solving most of the fatigue troubles.

In case of high level of solicitation, for lightening purpose for instance, combining double peening, first with steel shot, followed by ceramic shot, allows to compensate the effect of deep tensile solicitation without degrading surface layer.

In some industrial cases, single peening with ceramic shot can produce the same, or even better fatigue performance, compared with double peening.

References

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