# Looking for the Optimal Shot Peening Treatment on Quenched and Tempered Steels with Different Hardness Levels

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## Abstract

Bars of a medium-carbon alloyed steel (AISI 4340), with a diameter of 16 mm, were subjected to different heat treatments (quenched and tempered between 200ºC and 680ºC) in order to achieve different mechanical properties. The bars were cut and machined to obtain fatigue specimens that were subjected to different shot peening treatments (diverse Almen intensities under 100% coverage) using cut wire shots of different sizes in a direct compressed air shot peening machine. X-ray diffraction (XRD) combined with electro-polishing techniques were used to obtain the different residual stress profiles induced by shot peening in each steel. Moreover, the specimen roughness was also measured. Finally, fatigue tests were performed in a four-point loading rotating beam testing machine (R= -1) to determinate the fatigue life under a stress slightly higher than the fatigue limit of each steel.

It was observed that every heat treated steel had an optimal Almen intensity in order to attain the best fatigue behavior, which is dependent on its mechanical properties. The optimal Almen intensity is larger for mid-strength steels than for weaker and stronger ones, due to the existing compromise between the extension of the induced compressive residual stress field and the surface damage produced by shot impacts.

**Keywords** Fatigue, residual stress, optimal Almen intensity, quenched and tempered steels.

## Introduction

Shot peening (SP) is a cold surface treatment commonly used in metal industries, mainly to improve the fatigue properties of metallic components, like gears, shafts or springs. It consists in throwing tiny spherical balls, called shots, at high velocity onto the surface of the specimens. Impacts produce the plastic deformation of surface layers and induce compressive residual stresses and work hardening, and the fatigue life of the component can improve significantly, but if the treatment is too strong, surface defects (microcracks) will appear and the fatigue life will decrease strongly. The success of the SP treatment depends on finding the accurate combination of the aforementioned effects in order to achieve the highest fatigue strength.

The purpose of this paper is to analyze 6 steels with different mechanical properties ($226 \leq HV \leq 552$) and several SP treatments ($8A \leq AI \leq 21A$), to understand the way that roughness, surface hardening and residual stress profiles evolve. Finally, the optimal Almen intensity to achieve the highest fatigue life was determined.

## Experimental Methods

An AISI 4340 alloy steel was used to obtain, by means of heat treatments (water quenching from 850ºC and different temperings), 6 different steel qualities with very different mechanical properties (Table 1).

Table 1. Mechanical Properties of Analyzed Steels (AISI 4340, Q+T).

| Tempering temperature (ºC) | HV | E (GPa) | $\sigma_y$ (MPa) | $\sigma_R$ (MPa) | A (%) |
|---|---|---|---|---|---|
| 200 | 552 | 201 | 1604 | 2057 | 10.5 |
| 425 | 424 | 200 | 1364 | 1426 | 10.6 |
| 540 | 350 | 198 | 1123 | 1201 | 13.7 |
| 590 | 325 | 205 | 983 | 1123 | 14.6 |
| 650 | 255 | 202 | 863 | 897 | 19.3 |
| 680 | 226 | 197 | 626 | 764 | 24.7 |

### *Shot peening process*

SP treatments depend on Almen intensity and coverage. Almen Intensity (AI) is related to the kinetic energy transferred from the shots, and it depends on their velocity, weight, hardness and impact angle. Coverage is the amount of surface that is hit by SP. These treatments were performed in a direct compressed air machine (Guyson Euroblast 4 PF) using different steel cut wire shots (CW). An impact angle of 90° and complete coverage (100%) were always used. Table 2 summarizes the SP working parameters.

Table 2. Work Parameters for the Different Shot Peening Treatments.

| Almen intensity | 8A | 10A | 12A | 14A | 16A | 19A | 21A |
|---|---|---|---|---|---|---|---|
| Steel Shots | CW0.3 | CW0.4 | CW0.5 | | CW0.7 | | |
| Pressure (kPa) | 200 | 200 | 200 | 300 | 150 | 300 | 400 |

For convenience, roughness, residual stresses and surface hardening were measured over small slices cut from the bars, whereas fatigue tests were carried out in conventional machined specimens.

### *Surface finish, compressive residual stresses, surface hardening (FWHM) and fatigue life*

Before evaluating the roughness, the samples were ground and polished in order to remove all surface defects. Then, the SP treatments were done and the surface was evaluated by Scanning Electron Microscopy (SEM) looking for microcracks produced in the treatment, and afterwards, a Diavite DH-6 roughness tester ($L_t$=4.8 mm and $L_c$=0.8) was used to obtain $R_a$ and $R_{max}$, the most relevant roughness parameters to assess the surface modification induced by SP.

Residual stresses were determined by X-ray diffraction (XRD), employing the $\sin^2\psi$ method. An X-Stress 3000 G3R device was used, following the recommendations from NPL [1]. Table 3 shows the work parameters selected in this analysis.

Table 3. Work Parameters for X-Ray Diffraction on AISI 4340 Steel [2].

| | | | |
|---|---|---|---|
| X-Ray source | Cr | Wavelength (nm) | $K\alpha_1$=0.22897 |
| Maximum potential (V) | 30 | Filter | Vanadium |
| Exposure time (s) | 20 | Ø collimator (mm) | 2 |
| Miller indices (hkl) | (211) | Diffraction angle (2θ) (°) | 156 |
| E/(1+ν) (MPa) | 168900 | Tilt (°) | 9 points between -45/45 |

The residual stress profiles were obtained after removing material surface layers through electro-polishing, using an electric voltage of 45V and a mixture of acetic acid-94% and perchloric acid-6% [3] as electrolyte. The slight stress relaxation produced by layer removal was also taken into account and corrected in accordance with Sikarskie [4]. Work hardening was analyzed by means of the Full Width at Half Maximum (FWHM) profiles also obtained by XRD. The FWHM parameter is related to the lattice distortion, the dislocation density and the so-called type II micro residual stresses [5] and it provides an indirect measure of the induced surface hardening produced by SP.

Lastly, fatigue tests were carried out on a four point loading R. R. Moore rotating beam fatigue testing system (R=-1; 5700 rpm). Between 3 and 6 samples were tested with each steel and Almen intensity. The applied maximum surface stress was between 50 and 65% of the tensile strength of the steel. Figure 1 shows the geometry of the fatigue specimens.

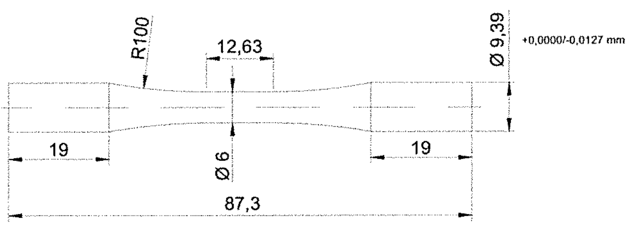

Figure 1. Geometry and Dimensions (mm) of the Fatigue Specimens.

## Experimental Results and Discussion

Figure 2 represents $R_{max}$ evolution with the Almen intensity ($R_a$ also shows the same trend). In general, roughness increase as Almen intensity does, but shot size is also a relevant parameter. A significant roughness decrease was detected when the shot size was increased from 0.5 to 0.7 mm. Moreover, figure 2 also shows how the same SP treatment produces a higher roughness in soft steels that in hard ones.

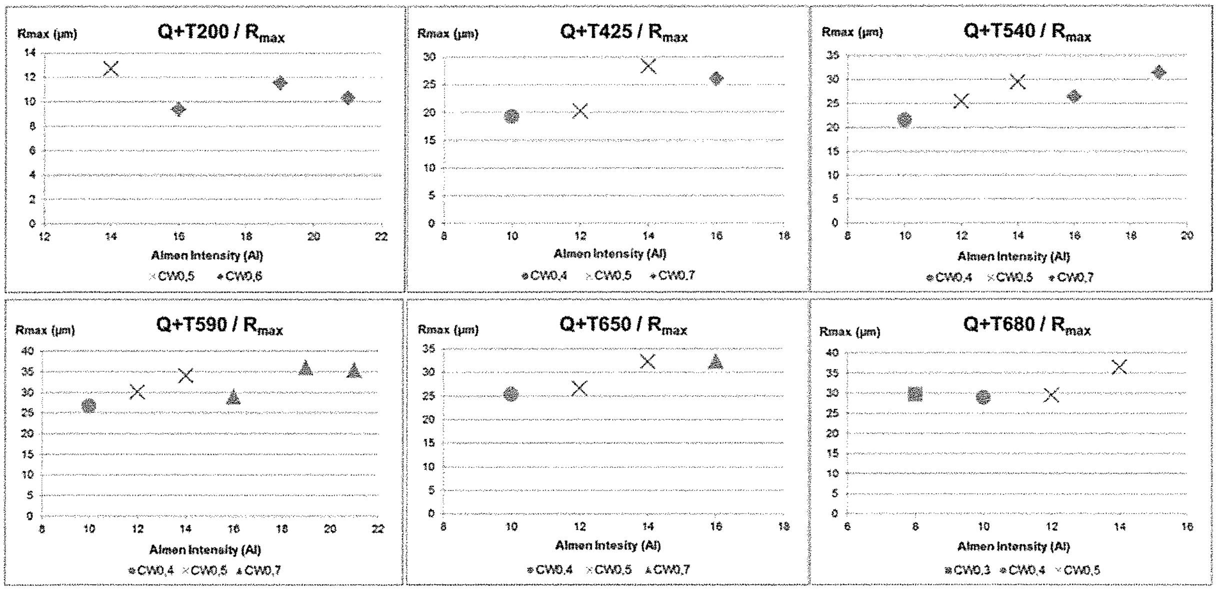

Figure 2. Maximum Roughness ($R_{max}$) versus Almen Intensity for the Different Steels.

The surface analysis was completed with SEM in order to look for the presence of small defects (microcracks) which could work as stress concentrators. Figure 3 shows a microcrack produced by an SP16A treatment on a Q+T650 steel. This SP treatment is too aggressive and gives rise to surface defects that decrease fatigue life under cyclic loading [6].

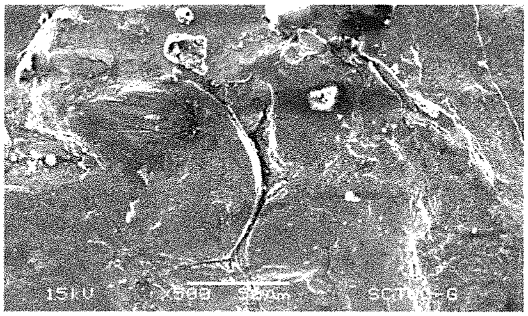

Figure 3. Surface Defect (Microcrack). Q+T650 – 16A. SEM.

### *Compressive residual stresses*

Figure 4 a) shows that the surface and maximum residual stresses are not dependent on shot peening treatment, but the affected depth increases with the applied intensity. On the other hand, figure 4 b) represents the residual stress profiles produced on 5 different steels submitted to the same treatment (Al=14A). It is worth noting that surface and maximum residual stresses grow according to the steel hardness/strength, whereas the depth subject to compressive stresses decreases as the steel mechanical properties grow.

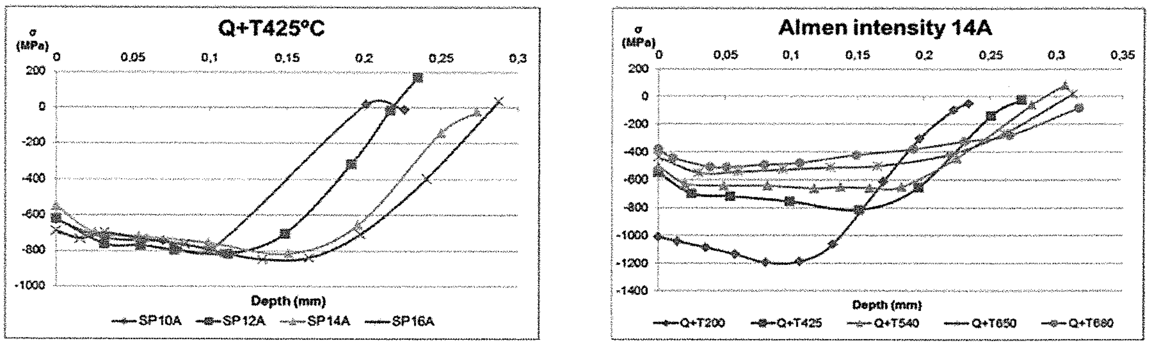

Figure 4. a) Residual Stress Profiles after Different SP Treatments on Q+T425 Steel.
b) Residual Stress Profiles after the Same Almen Intensity (14A) on Different Steels.

### *Surface hardening*

FWHM profiles were analysed for this purpose. Figure 5 is an example where it is noticed the typical trend follow by this parameter. Thus, each steel has a FWHM (internal value), that is dependent on his original hardness, being larger as the steel is stronger. On the other hand, this parameter grows in the surface region, but this increase is larger when the initial hardness of the steel is lower (softer steels have a larger work-hardening capacity).

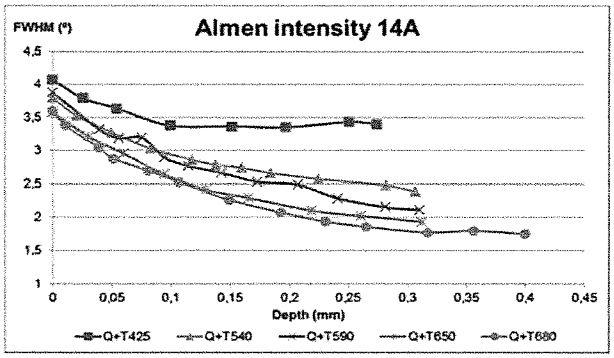

Figure 5. FWHM Profiles of Different Steels with the Same Almen Intensity (14A).

### *Fatigue life*

Finally, fatigue tests on peened (SP) and non-peened samples (NSP) were performed and their results are shown in figure 6. The average of the logarithmic number of cycles was calculated and represented.

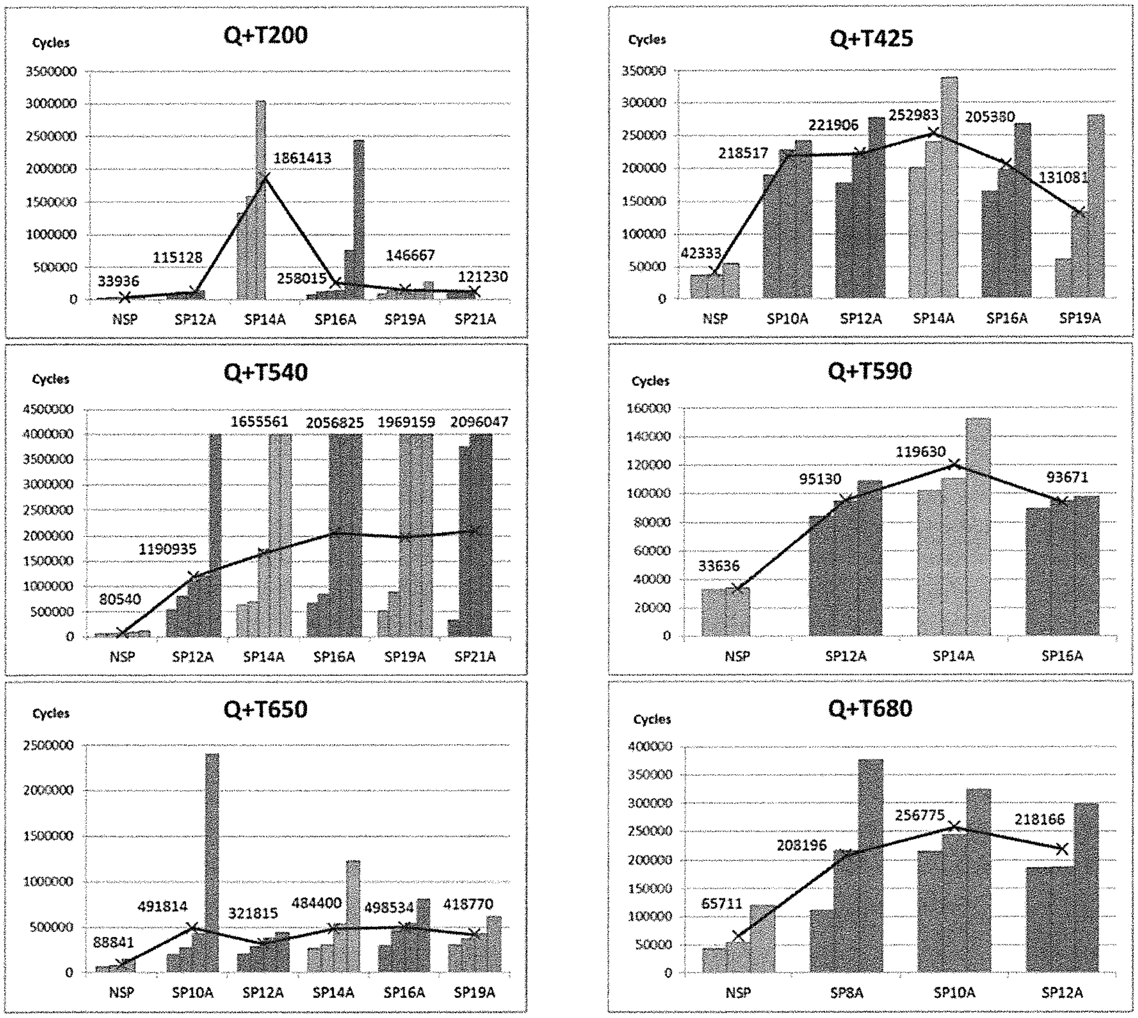

Figure 6. Fatigue Test Results.

All SP treatments significantly improve the fatigue life of these steels. It is also noticed that fatigue life increases as Almen intensity does, until a certain intensity is attained, and then it falls when the treatment is too aggressive. This effect is especially clear in Q+T200 and Q+T425 steels, the hardest ones. On the other hand, in the case of the softest and toughest steels, this tendency is not so obvious. Table 4 shows the optimal Almen intensity and the largest fatigue improvement obtained regarding the non-treated samples.

Table 4. Summary of Fatigue Test Results.

| Steel/HV | Applied maximum fatigue stress (% $\sigma_R$) | IA Optimal | Δ fatigue life |
|---|---|---|---|
| Q+T200 / 552 | 50% | 14A | x55 |
| Q+T425 / 424 | 50% | 14A | x6 |
| Q+T540 / 350 | 50% | 16A–21A | x26 |
| Q+T590 / 325 | 60% | 14A | x4 |
| Q+T650 / 255 | 60% | 10A, 14A and 16A | X6 |
| Q+T680 / 226 | 65% | 10A | x4 |

Finally, figure 7 graphically shows the evolution of the optimal Almen intensity with the hardness of the steels. Undoubtedly, the evident drop of the optimal IA for harder steels is due to their lower toughness that gives rise to like-crack surface defects.

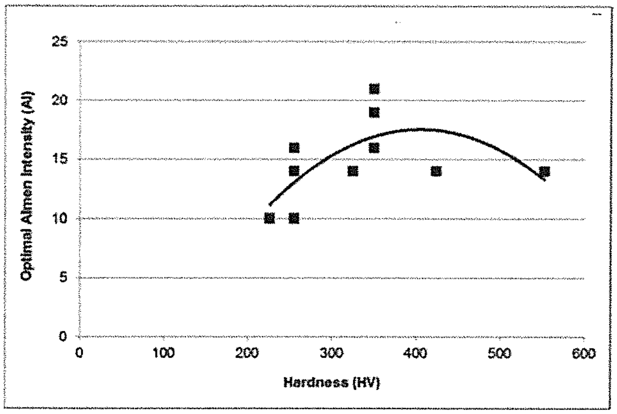

Figure 7. Optimal Almen Intensity (AI) versus Hardness (HV).

## Conclusions

The roughness generated by SP not only depends on the applied Almen intensity but also on the shot size. Moreover, high intensity treatments produce surface microcracks that will reduce the steel fatigue life.

Surface and maximum compressive residual stresses do not depend on the Almen intensity, but they are related to the hardness/strength of the steel. Nevertheless, the depth submitted to compressive residual stresses is larger as IA increases.

The FWHM parameter allows quantifying in an easy way the surface hardness increase produced by SP treatments.

It is finally highlighted that all SP treatments have improved the fatigue life of the different steels compared to the non-treated samples. Nevertheless, it should be pointed out that fatigue life grows according to Almen intensity until a certain optimal value, and then it falls when the treatment is too aggressive and some surface damage is introduced. This fact is especially evident in the case of harder and more brittle steels.

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