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Study of the effects produced by shot peening on the surface of quenched and tempered steels: roughness, residual stresses and work hardening

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ABSTRACT

Shot peening induces important effects on the surface of materials, both positive and negative, the correct balance between them being the key to success.

Roughness, impact mark size, compressive residual stress and work hardening of six steel grades obtained from an AISI 4340 steel were studied to explain their evolution according to the Almen intensity and their mechanical properties. A linear relationship between the impact diameter, the kinetic energy of the balls and the Almen intensity was found. Moreover, under full coverage, the surface and the maximum compressive stresses only depend on the mechanical properties of the steels, whereas the depth subjected to high compressive residual stresses and the total depth subjected to compressive residual stresses depend on the mechanical properties of the steel and the Almen intensity. Furthermore, several mathematic expressions were formulated to predict the residual stress profiles using the Almen intensity and the mechanical properties of the steels.

1. Introduction

Conventional shot peening (SP) is a cheap surface treatment that consists in projecting very hard, tiny, spherical ceramic or metallic balls ($0.3 < Ø < 1.6$ mm) at high speed onto the surface of the component to treat. These impacts produce local surface plastic deformation, the expansion of which is constrained by the adjacent deeper material, giving rise to a uniform surface compressive residual stress field (Fig. 1), along with other important effects. These include modification of the roughness and appearance of the surface in addition to work hardening, which, if properly controlled, can significantly improve the final properties of metallic components [1–4]. The aforementioned effects provided by shot peening treatments cannot be called merely positive or negative, as this role depends on the purpose of each treatment.

Shot peening has many applications: for instance, it can be used to improve the fatigue life of industrial components [5–8], obtain a specific surface finishing [9], enhance the wear resistance [10] or prevent stress corrosion cracking [11,12]. Consequently, it is necessary to control the shot peening parameters, mainly the Almen intensity and the coverage degree, according to the mechanical properties of the material treated, to obtain the best combination of the aforementioned effects and, hence, maximize the performance of the product. Coverage is the ratio of the area covered by the shot impacts to the entire surface of the treated sample, expressed as a percentage, whereas the Almen intensity is a measure of the energy of the shot stream, which depends on the projection velocity and also on the shot density, mass and size [13,14].

However, although shot peening is a relatively old technology, even now, most companies are not able to employ it optimally, and this means that they are not able to take full advantage of it. The main reason is the complexity of the process, due to the different parameters that must be simultaneously controlled to attain the optimal balance among effects.

It is worth to remember here the existence of other surface treatments which are based in similar concepts as conventional shot peening, but they have some specific differentiating characteristics. For instance, severe shot peening (SSP), which employs more intense parameters, usually very high coverage degrees [15]; laser peening, which uses laser-generated shock waves to introduce high level of surface compressive stresses deeper in the workpiece [16]; roller burnishing, which rub the metal surface with a smooth hard roller under a sufficient pressure [17] or surface mechanical attrition treatment (SMAT), where shots are resonated by vibration using an ultrasonic transducer [18–20], as well as vibration

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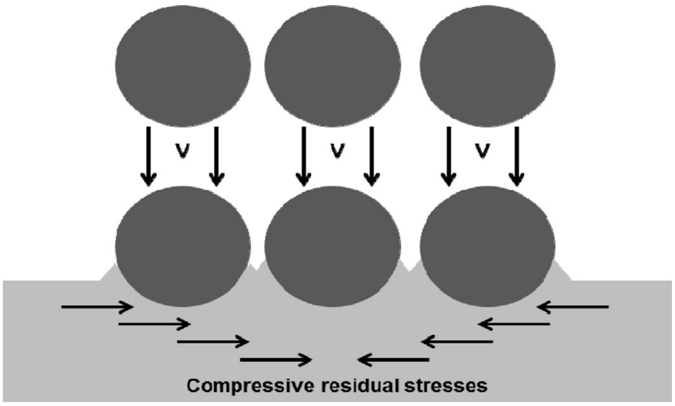


Fig. 1. Schematic illustration of the shot peening process.

Table 1
Chemical composition of AISI 4340 alloy steel.

Element	C	Mn	Si	P	S	Cr	Ni	Fe
wt%	0.410	0.710	0.260	0.013	0.024	0.870	1.920	Balance
Element	Mo	V	Cu	Al	Sn	Ti	Nb	
wt%	0.235	0.005	0.210	0.016	0.011	0.004	0.003	

polishing, vibration peening or grinding [21]. In relation to these surface treatments, shot peening is usually cheaper, versatile, effective enough and very easy to be implemented in most workshops.

Anyway, in order to attain the final goal on these surface treatments and specifically in the case of shot peening, it would be convenient to have a tool able to foresee the main effects of any treatment in order to select the most appropriate parameters for optimizing it. Numerous experimental and theoretical studies have been performed along these lines to improve the state of knowledge of shot peening and better understand its effects [9,22–28].

This paper focuses on the analysis of the evolution of the main effects induced by conventional shot peening treatments (surface finish modification, surface work hardening and compressive residual stress fields), in different quenched and tempered steel grades presenting a relatively broad range of mechanical properties submitted to different shot peening intensities. The main objective of the experimental study was to understand the role played by the mechanical properties of the treated steel and the applied Almen intensity on the main effects induced by shot peening treatments. Furthermore, several simple, practical expressions are proposed to predict the impact diameter and some characteristic values of the residual stress profiles. These expressions may be used in a practical way to predict the effects induced by shot peening treatments on industrial components, being an effective tool to select the correct parameters to satisfy the requirements fixed by the final client in an easy and fast way.

2. Materials and methods

2.1. Steel and mechanical properties

This study was carried out on samples of AISI 4340, a commercial heat treatable low-alloy steel widely employed in the automotive and aircraft industries for the manufacture of gears, shafts and other structural components due to its favorable combination of strength, toughness and ductility. The steel was supplied in the form of rolled bars with a diameter of 16 mm, and its chemical composition is given in Table 1.

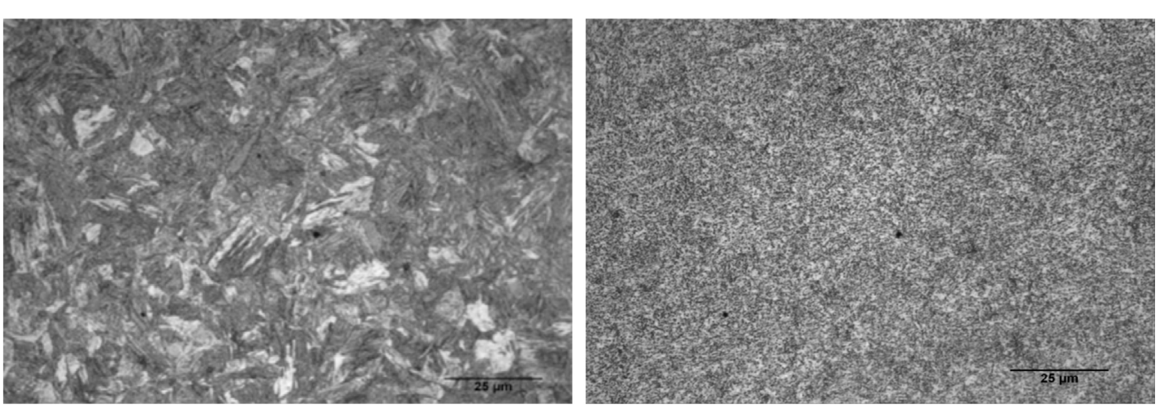
This steel was subjected to different heat treatments in order to obtain six different steel grades. The treatments consisted in austenitizing at 850 °C for 45 min, water quenching (Q), plus different tempering treatments (T), ranging from 200 °C to 680 °C, during 150 min. The use of different tempering temperatures allowed us to obtain a wide range of mechanical properties, as can be seen in Table 2, which shows a representative range of the mechanical properties of typical martensitic steels employed in the metal industry.

Fig. 2 shows the steel microstructure obtained after two of these heat treatments (Q + T200 and Q + T680).

Table 2
Hardness and tensile properties of quenched and tempered AISI4340 steel (Vickers hardness, HV, yield strength, σ_{ys}, ultimate tensile strength, σ_{uts}, and elongation, *E*).

Steel	Tempering temperature[a] (°C)	HV (31,25 kg)	σ_{ys} (MPa)	σ_{uts} (MPa)	E (%)
Q + T200	200	552	1604	2057	10.5
Q + T425	425	424	1364	1426	10.6
Q + T540	540	350	1123	1201	13.7
Q + T590	590	325	983	1123	14.6
Q + T650	650	255	863	897	19.3
Q + T680	680	226	626	764	24.7

[a] All tempering times were 150 min, except 10 h in Q + T680.



(a) (b)

Fig. 2. Steel microstructures (nital etched). (a) Q + T200; (b) Q + T680.