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The effect of the cementite phase on the surface hardening of carbon steels by shot peening

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ABSTRACT

This study investigates the effect of the cementite phase on the surface hardening of carbon steels when they are shot-peened. Three carbon steels were used in this study: 0.1% C, 0.45% C, and 0.8% C steels. The results show that the surface hardness after shot peening is proportional to its carbon content. Grains at the surface were transformed into grains with lamellar structures. The cementite was spheroidized by energy generated from the severe plastic deformation at the surface, the ferrite grain size was refined noticeably, and the carbon dissolved in the ferrite. The higher the carbon content in the ferrite, the higher the degree of grain refinement was observed. The primary reason for the noteworthy enhancement of surface hardening likely originates from both the grain refinement and supersaturation of the carbon in the ferrite following cementite dissolution.

1. Introduction

Shot peening, a cold working process generating a high plastic strain on the surface of metals, has been applied to the metal parts (components) that require a high level of surface hardness and an elevated resistance to fatigue failure in service. Since an intense plastic deformation on a metal surface draws a microstructure change on the surface layer, different types of shot peening techniques, derived from the original shot peening have been proposed. With diverse grades of metals and the derivative shot peening techniques, many research groups [1–5] have made an attempt to examine the effect of shot peening on the microstructural change and mechanical properties on its surface.

Liu et al. [1] applied a high-energy shot peening (HESP) technique to low carbon steel (0.11% C). They reported that a nanostructured surface layer with a thickness of about 20 nm was synthesized and that the average grain size in the surface layer is a few nanometers. Its yield strength after HESP was significantly enhanced without a considerable degradation of ductility and toughness. Tao et al. [2,3] fabricated a nanocrystalline surface layer by applying a surface mechanical attrition treatment (SMAT) technique and ultrasonic shot peening (USSP) to a pure Fe. Tao et al. [2] showed that, after USSP treatments, the initial coarse-grained structure in the surface layer was refined into equiaxed ultrafine grains (about 10 nm) with random crystallographic orientations. Tao et al. [3] also showed that high strains with a high strain rate (10^3–$10^4\ s^{-1}$) in the top surface are necessary for the formation of nanocrystalline during intense plastic deformation.

Using SMAT, Zhou et al. [4] studied the strain-induced microstructure evolution of spheroidized steel (at 1053 K for 3 h) with chemical composition (in mass%), as follows: 1.0% C, 1.5% Cr, 0.31% Mn, 0.24% Si, 0.08% Ni, 0.15% W, and balanced Fe. They investigated the nanocrystallization mechanism of both phases (ferrite and cementite), as well as the dissolution of cementite into ferrite. The ferrite refinement process was greatly facilitated by the presence of dispersed cementite particles, as the cementite/ferrite interfaces are effective nucleation sites for dislocations and are also barriers for dislocation motions. Meanwhile, Umemoto et al. [5] applied particle impact (PI) and a conventional air blast shot peening technique to a silicon steel (Fe–3.29% Si, 0.01% Mn in mass%), a 590 MPa class high tensile strength steel (Fe–0.05% C, 1.29% Mn in mass%), and an eutectoid carbon steel (Fe–0.80% C, 0.20% Si, 1.33% Mn in mass%) with a spheroidite structure. They examined necessary conditions to produce nanocrystalline regions, i.e., the amount of strain and the strain rate, the temperature, the magnitude of the repetitive deformation, impurities and/or alloying elements, and the second phase.

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Those works [1–5], however, mainly focused on the nanocrystallization mechanism of a grain on the steel surface due to the intensive plastic deformation by shot peening but did not link the nanocrystallization to its surface hardening. They [2–5] used carbon steels with spheroidite structures as the specimens. Hence, there was a limit to study the effect of the cementite phase on the surface hardening since the specimen employed in the experiment, i.e., shot peening, was spheroidized in advance.

This study investigates the effect of the cementite phase on surface hardening when shot peening is applied to carbon steel. For this purpose, three carbon steels (0.1% C, 0.45% C, and 0.8% C) were chosen and shot-peened. Note that the carbon steels used in this study were not spheroidized beforehand. Before and after shot peening, we measured the surface hardness and observed the microstructural change. We then examined how the cementite phase plays a role in grain refinement and how it has an influence on the surface hardening in the course of shot peening.

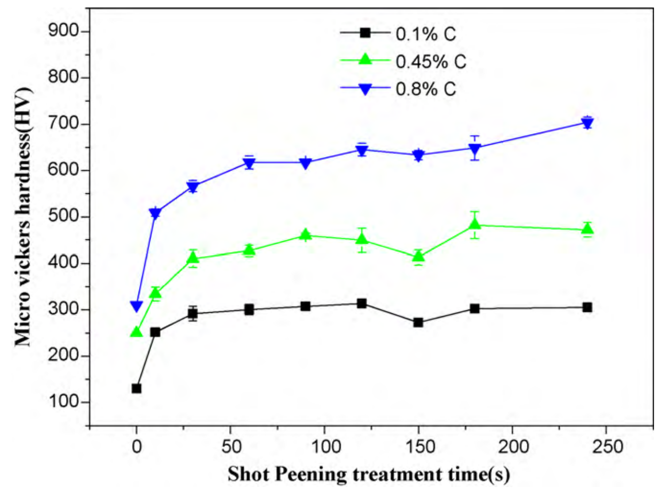

Fig. 1. Surface hardness profiles of the three carbon steels as a function of the shot peening treatment time, i.e., exposure time.

2. Experimental

We selected three carbon steels: 0.1% C (AISI1010), 0.45% C (AISI1045), and 0.8% C eutectoid carbon steels. Rectangular plate specimens (50 mm × 50 mm) with thicknesses of 10 mm were cut from these three steels and used in the shot peening test. A normalizing treatment was given to the specimens to relieve the residual stresses in the specimens generated during rolling and machining.

Rounded cut wire (RCW) balls were used in the shot peening test. The hardness of a shot ball was about 760 HV, and its diameter was 250 μm. The Almen intensity after shot peening was 0.06 mmA. The shot ball impacted the specimens perpendicularly with a pressure of 0.6 MPa. The hardness after the shot peening was measured with a microVickers hardness tester (Future Tech FM-7). The applied load was 0.2 kg with a duration of 10 s. An optical microscope and a transmission electron microscope (TEM, JEOL 2100) were used to observe the microstructure evolution. The specimens for the TEM were prepared with a focused ion beam (FIB, Helios Nanolab). Hereafter, the word 'specimen' is replaced with 'steel' for convenience.

3. Results and discussion

Fig. 1 shows the measured surface hardness profiles of the three carbon steels as a function of exposure time (duration time). The surface hardness before shot peening was 130 HV for the 0.1% C steel, 250 HV for the 0.45% C steel, and 310 HV for the 0.8% C steel. At the initial stage of the shot peening, i.e., up to approximately 15 s, the surface hardness increases sharply. After 15 s, the slope of the surface hardness increment becomes low. The surface hardness profile becomes almost flat when the exposure time reaches about 60 s. We observe that, as the carbon content of the steels increases, the surface hardness also increases. In the case of the 0.1% C steel, the surface hardness is about 300 Hv. The surface hardness for the 0.45% C and 0.8% C steels are about 440 Hv and 640 Hv, respectively.

We know that the surface hardness of the three steels roughly reaches a maximum about 60 s. Hence, we decided to shot-peen the steels for 60 s to examine their microstructural evolution behav-

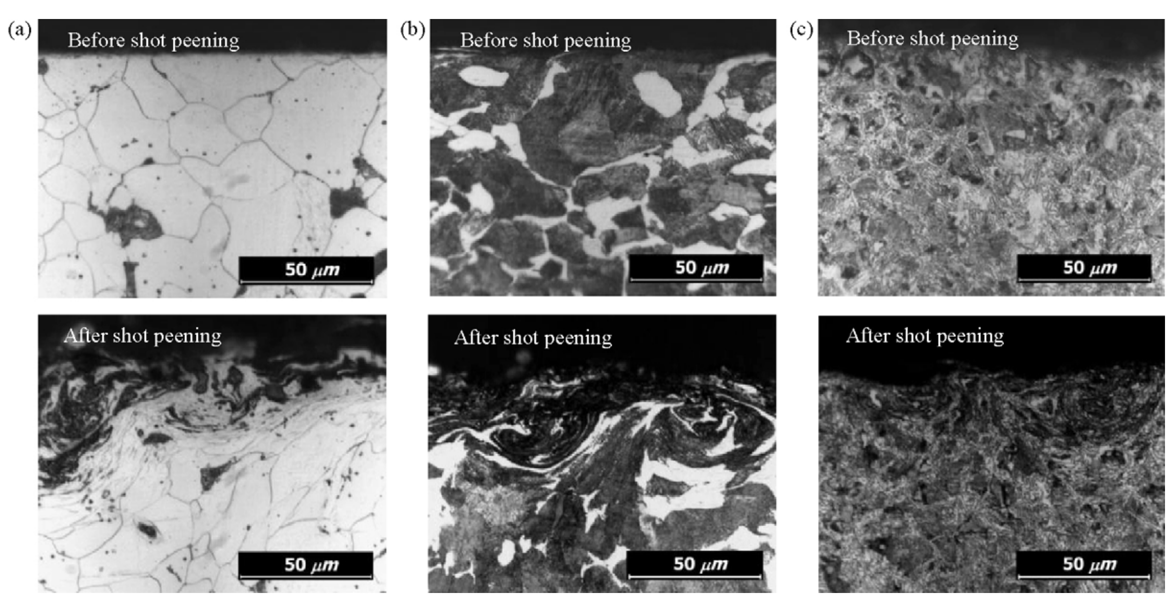

Fig. 2. Cross-sectional optical micrographs showing the microstructural evolution before and after shot peening for 60 s: (a) 0.1% C (b) 0.45% C, and (c) 0.8% C steels.