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NANOGRAINED STEELS PRODUCED BY SHOT PEENING AND DRILLING

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ABSTRACT

The formation of nanograined structures in steels was studied using air blast shot peening and drilling. Randomly oriented equiaxed nanograins of about 20 nm in diameter were observed. Deformation induced amorphization and mechanically induced nanocrystallization is proposed to be responsible to the formation of nanograins in steels.

1. INTRODUCTION

Large efforts have been devoted to refine grains of materials since ultrafine-grained materials have often superior mechanical and physical properties to those of coarse-grained counterparts. Among various methods proposed to produce nanograined materials (grain size less than 100 nm), severe plastic deformation has received the largest attention due to the simplicity and applicability for all class of materials (Valiev, Islamgaliev and Alexandrov 2000). Fig. 1 shows representative severe plastic deformation processes to produce nanograind structures (Umemoto, Todaka and Tsuchiya 2004): ball milling, high pressure torsion, a ball drop test, particle impact deformation, drilling, sliding wear, ultrasonic shot peening and air blast shot peening. In the present study the microstructure evolutions in steels by air blast shot peening and drilling are investigated. The formation mechanisms of nanograined structure are considered.

2. EXPERIMENTAL PROCEDURES

The materials used in the present study were Fe-3.3Si, Fe-0.55C and Fe-0.80C (in mass %). The details of the experimental conditions were described in our previous paper (Umemoto et al. 2004). For shot peening experiment, Fe-3.3Si with ferrite structure and Fe-0.80C with spheroidite structure were used. For drilling experiment, Fe-0.55C specimens with martensite structure were used. After shot peening or drilling, annealing was carried out at 873 K for 3.6 ks. Specimens were characterized by SEM, TEM observations and Vickers microhardness test.

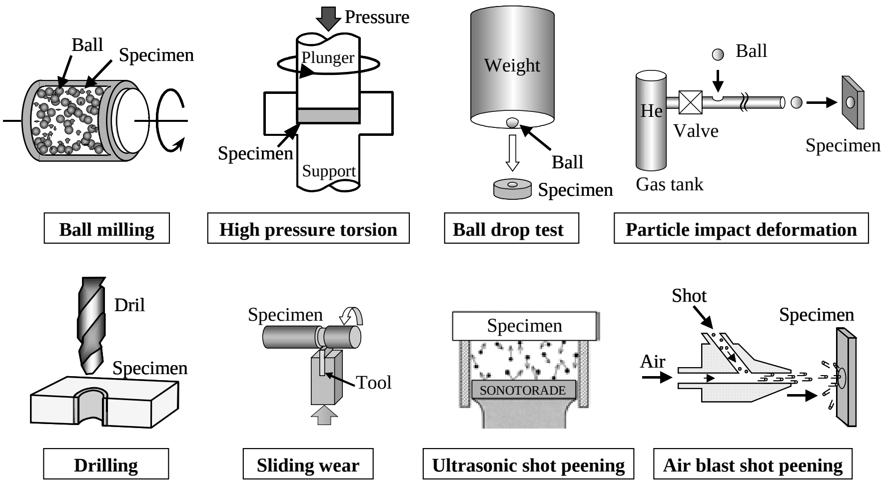

Fig.1 Various severe plastic deformation processes to produce nanograined structures.

3. RESULTS

3.1 Nanocrystallization by shot peening

Fig. 2 shows cross section of the near surface area of shot peened Fe-3.3Si steel. It is seen that the top surface layer with thickness about several μm has different contrast from the matrix Fig.2(a). Fig.2(b) is the TEM micrograph taken from the top surface area. Equiaxed grains about 20 nm are seen. The inserted diffraction (aperture diameter 1.2 μm) rings show uniform contrast, indicates that grains are randomly oriented. Fig. 3 shows cross section of the near surface area of Fe-0.8C specimen (spheroidite structure pre-strained 84% by cold rolling) after shot peening (a) and after annealing (b). Nanograined layer with 5 μm thickness is produced at the top surface. Before shot peening, spherical cementite particles with diameter about 0.5 μm distributed uniformly in the ferrite matrix. After shot peening, cementite particles are not visible in the nanocrystalline surface layer. This indicating that the dissolution of cementite have taken place in the nanograined layer similar to other severe plastic deformation processes (Umemoto 2003). After annealed at 873 K for 3.6 ks, the nanograined layer did not show any detectable change while the deformed regions below the nanograined layer showed a recrystallized structure.

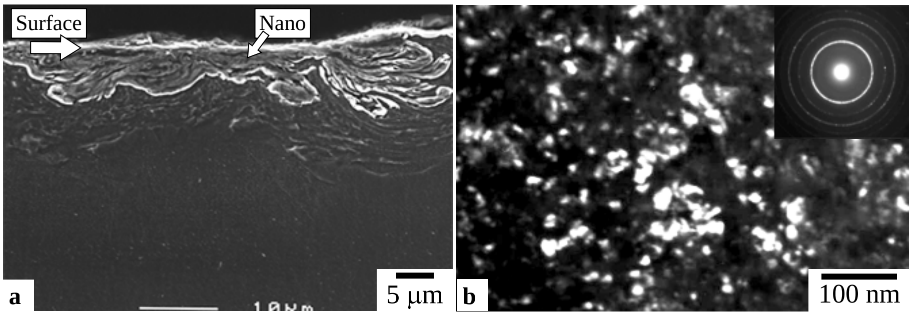

Fig. 2 Micrographs of shot peened Fe-3.3Si steel. (a) SEM and (b) TEM (dark field).

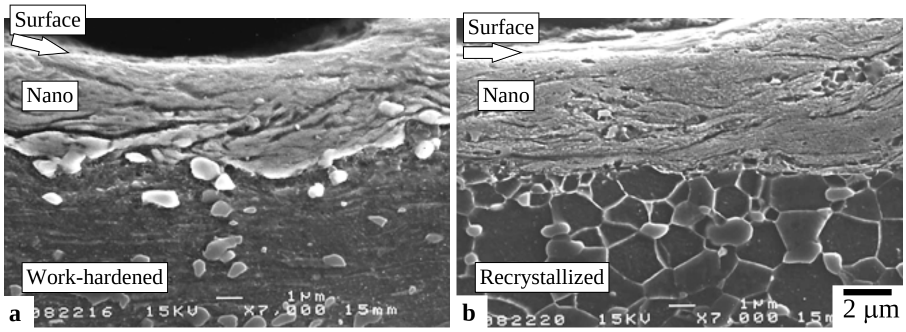

Fig. 3 SEM images of Fe-0.80%C steel with spheroidite structure by shot peening. (a) as shot peened and (b) annealed at 873K for 3.6ks after shot peening.

<u>3.2 Nanocrystallization by drilling</u>

The cross sectional microstructure near a drilled hole in Fe-0.55C steel is shown in Fig. 4. In the picture drilling direction is from top to bottom. Uniform contrast layer is seen near the surface. The hardness near the surface is 11.3GPa, decrease to 5.0 GPa just below the uniform contrast layer and then increase to a constant value of around 6 GPa.

Fig. 5 is the enlarged SEM images of Fig. 4 taken at different depth. (a) is the near top surface area with uniform featureless morphology. (b) is the area about 13 μm from the surface where the lowest hardness is observed. Submicron size equiaxed grains are seen with cementite particles. This structure indicates that initial martensite structure was deformed heavily and recrystallization took place due to the heat induced by deformation. (c) is the area about 30 μm from the top surface. Remaining martensite structure indicates that this area was not deformed. The precipitation of fine cementite particle shows that this area was slightly tempered by the deformation induced heat.

Fig. 6 shows the TEM micrographs near a drill hole. (a) is a dark field image taken from top surface area and (b) is a bright field image taken from the martensite matrix. At the top surface, equiaxed grains of about 20 nm are seen (a). The uniform contrast of inserted diffraction rings indicates the random orientation of grains. These characteristics are similar to those observed in shot peened samples shown in Fig. 2(b).

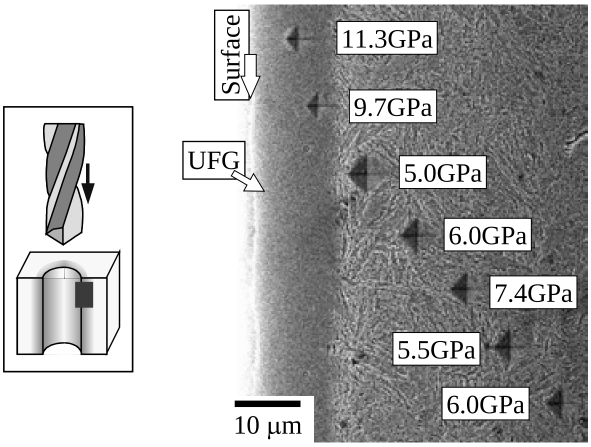

Fig. 4 SEM image of Fe-0.55%C steel (martensite) showing the microstructure of drilled hole surface. Hardness distribution is inserted.

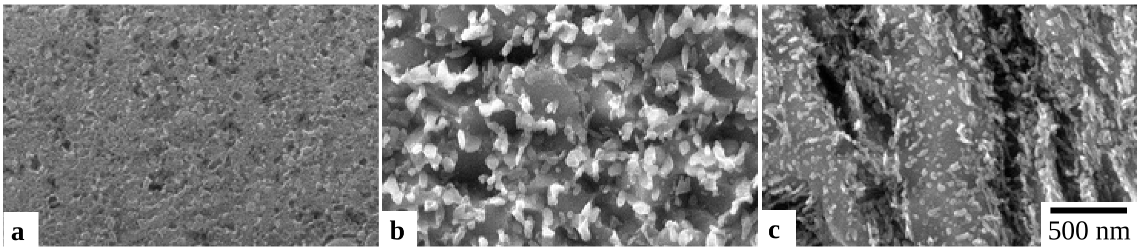

Fig. 5 SEM images of drilled hole surface of Fe-0.55%C steel at different depth. (a) near the top surface, (b) about 13 μm from the surface and (c) about 30 μm from the surface.

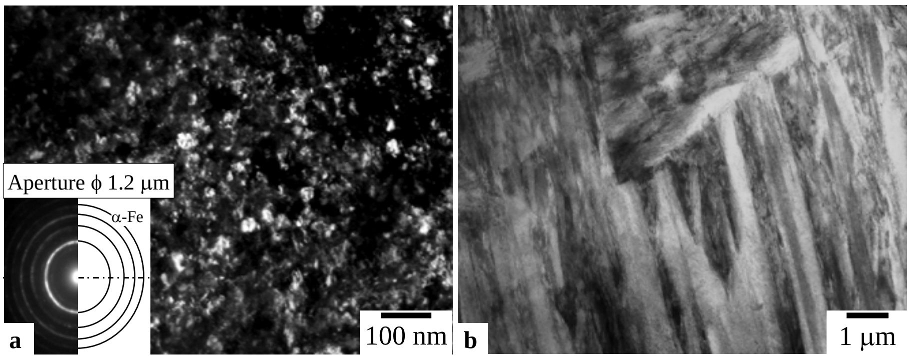

Fig. 6 TEM micrographs of drilled hole surface of Fe-0.55%C steel. (a) near top surface (dark field) and (b) martensite matrix (bright field).

Fig. 7 shows the effect of drilling speed on the thickness of uniform contrast (ultrafine grained) layer. The thickness of uniform contrast layer was found to increase with drill speed.

Fig. 8 shows the cross sectional SEM micrograph of drill hole surface after annealed at 873 K for 3.6ks. In the top surface layer (about 5 μm thick) grains remained fine (less than 100 nm). The grains underneath became large by recrystllization and grain growth and there is a sharp boundary between these areas.

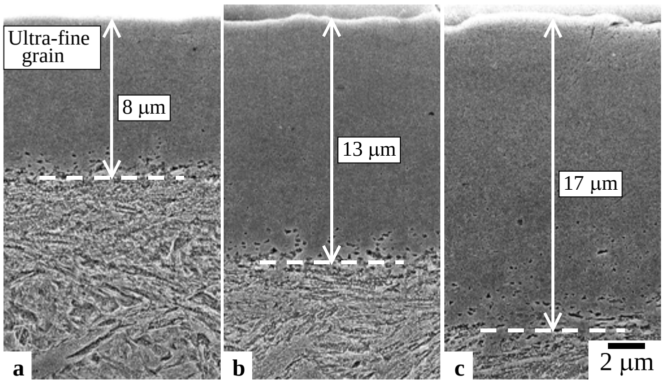

Fig. 7 SEM images of drilled hole surface of Fe-0.55%C steel showing the effect of drill speed. Drill speed increases in the order of (a), (b) and (c).

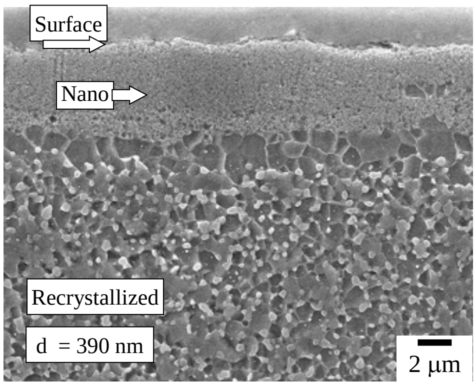

Fig. 8 SEM image of drilled hole surface of Fe-0.55%C steel after annealed at 873 K for 3.6 ks.

4. DISCUSSION

Many studies have been done on the deformation of metals and alloys at ambient temperature. It has been well known that work-hardening occurs up to large strains and grains are refined. A general microstructural evolution at various stages of deformation is as follows. At small strains, original grains are subdivided into cells bounded by dislocation walls with small misorientation. With increasing strain, cell size and cell wall width decrease and geometrically necessary boundaries (GNBs) develop. With further increase in strain, the density of GNBs and the misorientation of GNBs increase. The dislocation density inside grains is low in spite of the large strain imposed (Valiev et al. 2000). When the grains are refined to 10 nm range, the microstructure reaches a steady state since further strains are mainly accommodated by grain boundary sliding (Lu and Lu 2004). The reported structural change by deformation up to submicron sized grains agrees well irrespective of the materials. However, there are two different reports regarding the grain refinement to nanometer range. One is a continuous and another is a sudden decrease in grain size with strain. Former case is mostly observed in ductile materials such as Cu or Ni and grains are elongated substantially along a specific direction due to the influence of deformation direction (Hughes and Hansen 2001). Latter case is observed in ferrous alloys where nanograins are equiaxed and randomly oriented. Nanograins of the latter show no recrystallization and substantially slow grain growth.

The formation mechanism of equiaxed and randomly oriented nano-grains by heavy deformation remains unsolved. In our shot peening experiment in Ni-50.2at%Ti alloy (Nakayama, Tsuchiya, Todaka, Umemoto, Morii and Shimizu 2004), nanocrystalline structure similar to steels was obtained. During shot peening, initial martensite structure changed to full amorphous state and nanograins were nucleated by further shot peening. It has been reported that nanocrystallization takes place when amorphous phase is deformed (Jiang and Atzmon 2003). In steel, amorphization by heavy deformation is reported in hydrogen-charged ferritic steel (Nagumo, Ishikawa, Endoh and Inoue 2003). Although the existence of amorphous phase was not confirmed in the present experiment, one of the possible nanocrystallization mechanisms in steels by heavy deformation is proposed as is shown in Fig.9. In the early stage of deformation, submicron sized grains are formed from dislocation cell structure by dynamic (or in-situ) recrystallization. By applying further deformation, deformation induced amorphization occurs due to high density of vacancies. Finally nano-sized grains are induced mechanically or thermally from amorphous phase.

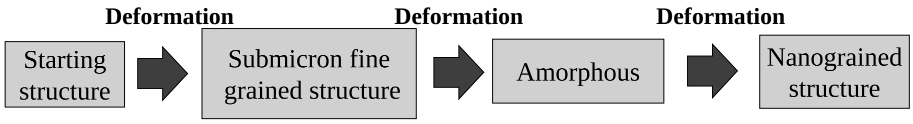

Fig. 9 A proposed structural sequence to reach nanograined structure by deformation.

5. SUMMARY AND CONCLUSIONS

(1) Nanograined structures can be produced in steels by air blast shot peening and drilling. Nano-grains are equiaxed and randomly oriented.

(2) By annealing, nanograined structure showed substantially slow grain growth without recrystallization.

(3) It is suggested that one of the possible nanograin formation is the deformation induced amorphization which is followed by a mechanically induced nanocrystallization.

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