INVESTIGATION ON THE MICROSTRUCTURE IN SHOT-PEENING SURFACE STRAINING LAYER OF MATERIALS

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ABSTRACT

The microstructure in shot-peening surface plastic straining layer of several metals are investigated. It was found that this plastic deformation is not the same as the simple monotonic plastic deformation. As a result of cyclic plastic deformation, material in the surface layer is subjected to "cyclic hardening" or "cyclic softening" as it occurs in the strain fatigue test. The appearance of cyclic hardening or cyclic softening is dependent on the initial microstructure of the material.

KEYWORDS
Shot-peening, fatigue (materials); cyclic softening and hardening; microhardness; breadth of diffraction line; subgrain; lattice distortion.

INTRODUCTION

The structural changes of metals after cold working (uniaxial tension or compression) and its effect on the mechanical properties of materials have been investigated extensively by metallography, X-ray analysis and mechanical testings (Keh, 1965; Low, 1963; Bullen, 1952; Shuji, 1968, 1968; Nakanishi, 1972; Conrad, 1963; Austin, 1945).

For annealed steel, austenite stainless steel as well as precipitation hardening alloys, after monotonic tension or compression, the following microstructural changes are usually observed: the deformation of grain, the fragmentation of subgrain, the increase of misorientation of subgrain, the increase of distortion of crystal lattice and the increase of dislocation density. All these changes depend on the initial state of microstructures and the degree of plastic deformation. As for martensitic hardening (including low temperature tempered) steel, the lattice distortion can be recovered in certain degree by cold working (БАЙМЕР, 1972).

The microstructural changes of materials which undergo cyclic straining can take place correspondingly, but the mechanism of changes was different from that of monotonic loading. For annealing softening materials, with an increase of the number of cyclic strain, the subgrain size is decreased, lattice distortion and dislocation density are increased, hence, "cyclic hardening" of materials occurs. As for hardening (or low temperature tempering) steel and cold work hardening materials, during cyclic straining the growth of subgrain, and the decrease of lattice distortion and dislocation density take place. Consequently, "cyclic softening" of materials is developed.

The shot-peening is a process in which the shots successively impact on the surface of a material. In the shot-peening process, the occurrence of plastic strain on surface layer may be considered as a kind of cyclic straining. The tendency of changes of the microstructure in the surface layer applied
shot-peening is analogous to the microstructure changes which occurs in the fatigue process. But the applied alternative strain is a compressive cyclic strain in this case, it has, of course, its intrinsic features. In this paper, the microstructural changes in shot-peening straining layer are discussed.

MATERIALS AND EXPERIMENTAL PROCEDURES

To obtain materials having different microstructures, five kinds of steels (30CrMnSiNi2A, 18Ni, Cr17Ni2A, 18CrNiWA, 40CrNiMoA) two kinds of aluminium alloys (LY12, LC4) were used. The

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>W</th>
<th>Cu</th>
<th>Mg</th>
<th>Zn</th>
<th>Fe</th>
<th>Al</th>
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<tbody>
<tr>
<td>30CrMnSiNi2A</td>
<td>0.3</td>
<td>1.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.6</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>18Ni</td>
<td>0.02</td>
<td>0.09</td>
<td>0.07</td>
<td></td>
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<tr>
<td>18CrNiWA</td>
<td>0.17</td>
<td>0.27</td>
<td>0.40</td>
<td>1.50</td>
<td>4.2</td>
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<tr>
<td>40CrNiMoA</td>
<td>0.4</td>
<td>0.27</td>
<td>0.65</td>
<td>0.75</td>
<td>1.4</td>
<td>0.2</td>
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</tr>
<tr>
<td>Cr17Ni2A</td>
<td>0.14</td>
<td>0.8</td>
<td>0.8</td>
<td>17</td>
<td>2.0</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>LY12</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.3</td>
<td>1.5</td>
</tr>
<tr>
<td>LC4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.7</td>
<td>2.3</td>
</tr>
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</table>

Table 1. Chemical Compositions

chemical compositions of experimental materials were listed in Table 1. The mechanical properties and the microstructures of materials were illustrated in Table 2.

The X-ray diffraction profiles were recorded on D2-C diffractometer using MoKα radiation and reflecting planes (310), (222), (321), but the diffraction profile of (211) and the residual stresses were measured on 2903 type strain diffractometer using CrKα radiation. The subgrain size, D,

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength (MNm⁻²)</th>
<th>Yield stress (MNm⁻²)</th>
<th>Elogation (%)</th>
<th>Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>30CrMnSiNi2A</td>
<td>1700</td>
<td>1350</td>
<td>9</td>
<td>tempered martensite</td>
</tr>
<tr>
<td>18Ni</td>
<td>1790</td>
<td>1735</td>
<td>5</td>
<td>martensite</td>
</tr>
<tr>
<td>18CrNiWA</td>
<td>1150</td>
<td>835</td>
<td>11</td>
<td>tempered martensite</td>
</tr>
<tr>
<td>40CrNiMoA</td>
<td>1080</td>
<td>930</td>
<td>12</td>
<td>sorbite</td>
</tr>
<tr>
<td>Cr17Ni2A</td>
<td>1080</td>
<td>835</td>
<td>10</td>
<td>martensite + ferrite (~10%)</td>
</tr>
<tr>
<td>LY12</td>
<td>420</td>
<td>275</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>LC4</td>
<td>490</td>
<td>410</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Mechanical Properties

and lattice distortion, Δa/a, were calculated from reflection lines (110) and (220) by using FeKα radiation. The amount of residual austenite was calculated by using the (200) reflection of CoKα radiation.

The microhardness in shot-peening surface layer was performed on PMT-3 microhardness tester using 100 gram load.
The dependence of integrated breadth of diffraction line on the depth distance from the surface was measured successively by removing surface layers from the specimen. The shot-peening of the specimens was carried out by an air-blast machine. Variations of shot-velocity, shot size and coverage were carried out in order to obtain different intensity $I_H = 0.33 \sim 0.55 \text{mm}$ (it is equivalent to 13A-2 \sim 22A-2 for Almen gages).

EXPERIMENTAL RESULTS

(1) The dependence of integrated breadth on depth distance from the surface. The dependences of integral breadth on the depth distance from the surface for different materials are plotted in Fig. 1. According to the different initial microstructure of materials, there are two modes of the variations of breadth with depth distance; firstly the breadth, $b$, with depth was decreased gradually and finally reached to a plateau level extending well into the bulk material (Fig. 1, a, b, c, d); secondly, the rapid decline of the $b$ with depth to about 150$\mu$m, and beyond this distance the $b$ increased again to a plateau level of the virgin material (Fig. 1, e, f, g, h, i).

For a giving shot-peening intensity, the depth profiles of $b$-curves, in fact, were changed gradually with the shot-peened time. The $b$ in the different depth distance, $\delta$, were changed gradually with increasing shot-peened time. The variations of depth profiles of $b$-curves of 30CrMnSiN2A hardening steel are shown in Fig. 2. The resulting kinetic process of variations of $b$-curves for hardening steels with increasing shot-peened time, as a matter of fact, can be shown schematically in Fig. 3. Hence, the depth profiles of $b$-curves for this kind of materials can be divided into three distinct zones, virgin material zone-A zone, B zone and C zone (Fig. 3). It was found that with increasing shot-peened intensity $b$ in C zone decrease at the beginning, and then increase gradually. Whereas $b$ in B zone decrease gradually in the whole peening period.

(2) Dependence of microhardness($H_V$), subgrain size ($D$) and lattice distortion ($\Delta a/a$) on depth distance from the surface. The variations of the microhardness $H_V$ with $\delta$ from the surface for 30CrMnSiN2A and 18CrNWA hardening steels are plotted in Fig. 4. It was found that the variation tendency of $H_V$-$\delta$ curve was in agreement with the variation tendency of $b$-$\delta$ curve (Fig. 1, f, h, i). Consequently, B zone and C zone in Fig. 3 may be considered as the softening and rehardening zones respectively.

The relations between $D$, $\Delta a/a$, the amount of residual austenite and the $\delta$ for both 30CrMnSiN2A and 18CrNWA hardening steel are shown in Fig. 5.

It can be seen from Fig. 5 that the amount of residual austenite is increased from 5.4% at
to 3.5% at center of the specimen. Obviously, the variations in the amount of residual austenite is monotonic, hence it seems not responsible to the change of hardness.

(3) Variation of \( \beta \) with \( \delta \) in the plastic zone of fatigue crack tip. It is well known that the cyclic plastic zone size ahead of a fatigue crack tip increases with increasing crack length. After fatigue fracture of a specimen, the variation of \( \beta \) with the depth distance from fracture surface at different fatigue crack length, \( a \), for both annealing softening and hardening steels (30CrMnSiNi2A) are measured, and all testing results are shown in Fig. 6. The variation of \( \beta \) for annealed softening steel with depth distance is just opposite to the variation of \( \beta \) for hardening steel. According to the variation of \( \beta \) with depth distance, it is evident, that cyclic hardening in the plastic zone ahead of fatigue crack tip is observed only for annealed softening steel (Fig. 6, a). As for the hardening steel, the cyclic strain under fatigue can only produce cyclic softening in the plastic zone (Fig. 6).

(4) Microscopic study on different depth distance from the surface.

The microstructure of 30CrMnSiNi2A hardening steel are shown in Fig. 7. The microstructure at depth distance of about 17 \( \mu \)m appears to be a heavy deformation structure (Fig. 7, a). But on the depth distance about 170 \( \mu \)m where pronounced softening occurs, no considerable

Fig. 1. b. Depth profiles of \( \beta \) with \( \delta \) of the hardening materials.

Fig. 2. Variations of depth profiles \( \beta - \delta \) curves with different shot-peened time or intensity (\( P \) is the air pressure, \( \tau \) is shot-peened time, sec) for hardening steel 30CrMnSiNi2A, carrying out X-ray analysis with CrK\( \alpha \) radiation.
change of the microstructure can be observed.

**Discussion**

(1) For hardening or low-temperature tempered steel
For this kind of steels, the dependence of $\beta$ on $d(\beta-\delta$ curve) is shown in Fig. 2. Firstly, it is necessary to point out that the variation of $(310)$ and $(321)$ breadth, $\beta$, with $\delta$ does not correlate with the phenomenon of carbon precipitation from the supersaturated martensite, because the depth profile of $(222)$ breadth also exhibits the same variation. The change of crystal axis ratio, c/a, does not affect the $(222)$ breadth. In order to avoid the effect of carbon content on the c/a, low carbon content steel (18Ni) is used. It is found that the tendency of depth profile of $(222)$ breadth exhibits the same variation for $(310)$ and $(321)$ lines. The depth profiles of $(310)$, $(222)$ and $(321)$ with $\delta$ is ascribed, therefore, primarily due to the effect by other structural changes.

For the convenience of discussion, some curves obtained from these tests are summarized in Fig. 8. According to Hirsch (1965), the relationship between excess dislocation density, $D_e$, breadth, $\beta$, and Burgers vector, $b$, may be expressed in the form $D_e = \beta^4/b^6$. The $D_e-\delta$ curve exhibits, therefore, the same tendency of depth profile with $\beta-\delta$ curve. Thus, the $D_e-\delta$ curve is also shown in Fig. 8. The consistency of depth profiles between both $\beta-\delta$ and
When this softening microstructure is subjected further plastic deformation by shot-peening, the hardening produced by refinement of D and increase of D and of Δα/α. It is necessary to emphasize that the strain by shot-peening in the surface layer is not a monotonic tensile (or compressive) strain, but a cyclic strain resulting from rapid moving shots.

The number of cycles can be calculated according to following shot-peening parameters: flow of shots (25 kg/min), diameter of shots (1mm), diameter of indentation at specimen surface (0.05mm), diameter of shot-peened area at specimen (0.6mm) and the shot-peened time (45sec). The calculated impulses of shots on unit surface area is about 80. Hence, the plastic strain produced by shot-peening in the surface layer is, in fact, a cyclic strain under compressive loading. The kinetic process illustrated in Fig.3 also indicates that the change of depth profile of β-δ curve is controlled by the shot-peened intensity (i.e. the number of cyclic strain).

In fatigue crack propagation tests, the straining in the plastic zone ahead of crack tip is, in fact, a push-pull plastic straining. The result indicates that as a consequence of cyclic strain in the plastic zone only cyclic softening occurs (Fig.8,b). The strain fatigue test (strain ranges are 0.7-4%) using 4340 steel which exhibits the same microstructure and tensile strength with 30CrMnSiN2A steel shows that this kind of steel exhibits a cyclic softening materials (Dowling, 1973). Obviously, this experimental result is in agreement with the present result. Besides, in the condition of push-
pull strain fatigue, the $\beta$-$\delta$ curve consists of A and B zones only, but without C zone (Fig.6,b). It may be stated that the softening of materials in the plastic zone ahead of crack tip is gradually developed during the push–pull cyclic strain process, and the push–pull cyclic strain may be not enough to produce rehardening of material in the plastic zone before the specimen is fractured. Whereas in shot–peening process, the cyclic strain subjected by the surface layer is, in fact, a compressive strain. In this condition, initial cyclic softening which is similar to the fatigue condition is a "cyclic softening" (Fig.2, a, b, c, d, e). With successively applied compressive strain, this softening material gradually transforms into "cyclic rehardening" (Fig.2, g, h), but the later feature does not appear in the fatigue test condition. Hence, after shot–peening, the surface layer may be a cyclic rehardening layer, and the subsurface is a cyclic softening layer. Such microstructures in the surface layer may be beneficial to the improvement of fatigue properties of hardening steels. For this kind of shot–peened specimens, the fatigue crack often initiates in the subsurface which would be associated with the appearance of softening microstructures (Starker, 1979). As it is well known, besides microstructure factor, the shot–peening residual compressive stress is also another important factor for improvement of fatigue properties of materials (Wang, 1979).

2. For annealed or high-temperature tempered steel and aluminium alloys, most of fatigue test results have indicated that for annealed softening steels and aluminium alloys with the increase of straining amount and the number of cyclic strain, the breadth of diffraction lines, $\beta$, gradually increases (The 2nd Division, 1970; Weiss, 1979; Pangborn, 1979). This phenomenon can also be seen from Fig.6, a. This variation of $\beta$ is shown that the dislocation density is gradually increasing, and the fragmentation of subgrain is gradually taking place during fatigue process (Grosskreutz, 1983). As it has been said before, the shot–peening process is similar to the fatigue process. The $\beta$-$\delta$ curves shown in Fig. 1, a, b, c, d, are successively decreased with $\delta$. This appears to be a function of shot–peening straining amount which is gradually decreased with $\delta$. The consistence of $\beta$ variation tendency with the variation tendency occurred in fatigue illustrates that the similar variation of microstructure occurred in both cases. But it should be pointed out that the plastic deformation produced by fatigue is not homogeneous because of inhomogeneous slips. These inhomogeneous slips could produce fatigue crack initiation (Wood, 1959; Kramer, 1974). Whereas shot–peening plastic deformation in the surface layer is homogeneous. In the shot–peening condition, the crystal slips are homogeneous, and it may produce the fragmentation of subgrain and the increase of dislocation density, hence, all these can promote the strengthening of microstructures in the surface layer. This strengthening microstructures may be beneficial to the improvement of fatigue properties of materials in ambient and high-temperatures (Wang, 1981).

5. Conclusions
(1) The shot–peening process is a process in which the cyclic plastic strain is taken place in the surface layer.
(2) For cyclic hardening materials, there are very high dislocation density and very fine subgrain
formed in the surface straining layer after shot-peening.

(3) For cyclic softening materials (for example hardening steel), the surface straining layer consists of softening and rehardening zone formed by shot-peening. In the softening zone there are lower dislocation density and larger subgrain size, whereas in the rehardening zone there are higher dislocation density and fine subgrain size.

(4) The microstructures having high dislocation density and fine subgrain size in the surface layer formed by shot-peening for any materials are, obviously, beneficial to the improvement of fatigue properties.

REFERENCES