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 appearence 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; 1966, 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 (БАЛМЕР, 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 1. Chemical Compositions

Material	Chemical compositions (%)											
	C	Si	Mn	Cr	Ni	Co	Mo	W	Cu	Mg	Zn	Fe	Al
30CrMnSiNi2A	0.3	1.0	1.2	1.0	1.6	—	—	—	—	—	—	Balance	—
18Ni	0.02	0.09	0.07	—	18.6	8.0	5.1	—	—	—	—	Balance	—
18CrNiWA	0.17	0.27	0.40	1.50	4.2	—	—	1.0	—	—	—	Balance	—
40CrNiMoA	0.4	0.27	0.65	0.75	1.4	—	0.2	—	—	—	—	Balance	—
Cr17Ni2A	0.14	0.8	0.8	17	2.0	—	—	—	—	—	—	Balance	—
LY12	—	—	0.6	—	—	—	—	—	4.3	1.5	—	—	Balance
LC4	—	—	0.4	—	—	—	—	—	1.7	2.3	6.0	—	Balance

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 D9-C diffractometer using MoK_α radiation and reflecting planes (310), (222), (321), but the diffraction profile of (211) and the residual stresses were measured on 2903 type strain diffractormeter using CrK_α radiation. The subgrain size, D,

TABLE 2. Mechanical Properties

Material	Mechanical Properties			Microstructure
	Tensile strength (MNm^{-2})	Yield stress (MNm^{-2})	Elogation (%)	
30CrMnSiNi2A	1700	1350	9	tempered martensite
18Ni	1790	1735	5	martensite
18CrNiWA	1130	835	11	tempered martensite
40CrNiMoA	1080	930	12	sorbite
Cr17Ni2A	1080	835	10	martensite+ferrite (~10%)
LY12	420	275	11	
LC4	490	410	5	

and lattice distortion, $\Delta a/a$, were culculated from reflection lines (110) and (220) by using FeK_α radiation. The amount of residual austenite was calculated by using the (200) reflection of CoK_α radiation.

The microhardness in shot-peening surface layer was performed on ПMT-3 microhardness tester using 100 gram load.

The dependence of integrated breath 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 f_{II}=0.33~0.55mm (it is eqivalent to 13A-2~22A-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, β, 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 β with depth to about 150μm, and beyond this distance the β 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 β-δ curves, in fact, were changed gradually with the shot-peened time. The β in the different depth distance, δ, were changed gradually with increasing shot-peened time. The variations of depth profiles of β-δ curves of 30CrMnSiNi2A hardening steel are shown in Fig. 2. The resulting kinetic process of variations of β-δ 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 β-δ 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 β in C zone decrease at the begining, and then increase gradually. Whereas β in B zone decrease gradually in the whole peening period.

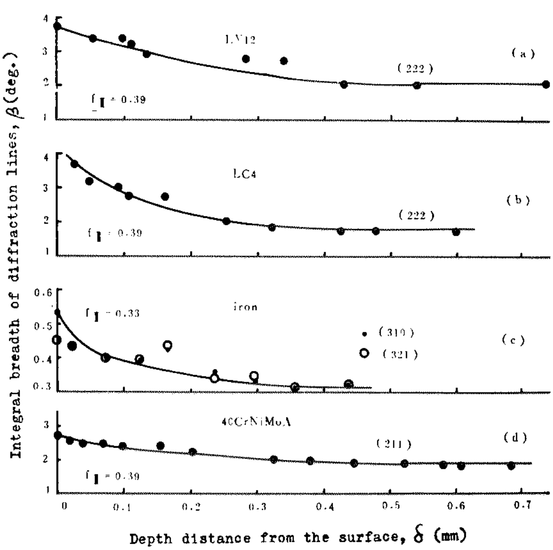


Fig. 1 a. Depth profiles of β with δ of the softening materials.

(2) Dependence of microhardness(Hv), subgrain size (D) and lattice distortion (Δa/a) on depth distance from the surface.
The variations of the microhardness Hv with δ from the surface for 30CrMnSiNi2A and 18CrNiWA hardening steels are plotted in Fig. 4. It was found that the variation tendency of Hv-δ curve was in agreement with the variation tendency of β-δ curve (Fig. 1, f, h, i). Consequntly, B zone and C zone in Fig.3 may be considered as the softening and rehardening zones respectively.

The relations between D, Δa/a, the amount of residual austenite and the δ for both 30CrMnSiNi2A and 18CrNiWA 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 surface

to 8.5% 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.

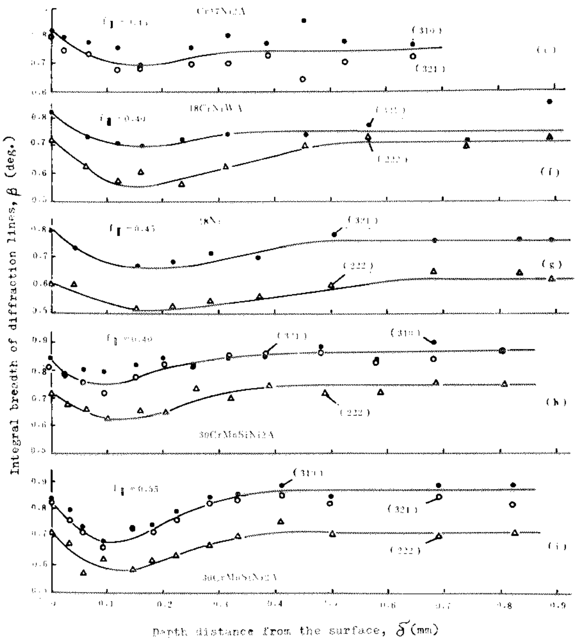


Fig.1, b. Depth profiles of β with δ of the hardening materials.

(3) Variation of β with δ 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 β 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 β for annealed softening steel with depth distance is just opposite to the variation of β for hardening steel. According to the variation of β 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

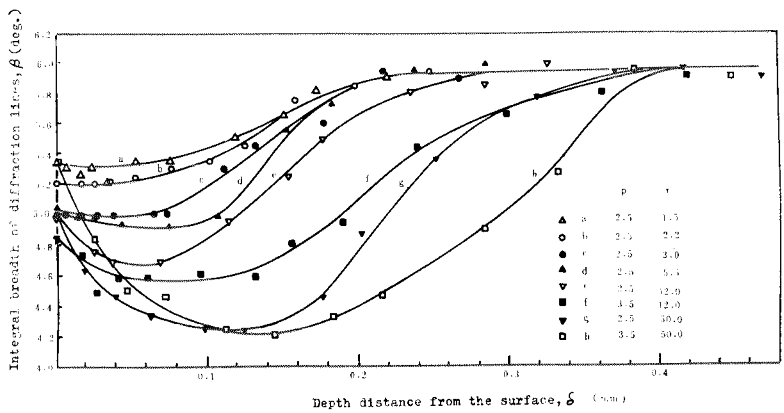


Fig. 2. Variations of depth profiles β-δ curves with different shot-peened time or intensity (P is the air pressure, bar; τ is shot-peened time, sec) for hardening steel 30CrMnSiNi2A, carring out X-ray analysis with CrK_{α} radiation.

The microstructure of 30CrMnSi Ni2A hardening steel are shown in Fig. 7. The microstructure at depth distance of about 17 μm appears to be a heavy deformation structure (Fig. 7, a). But on the depth distance about 170 μm where pronounced softening occurs, no considerable

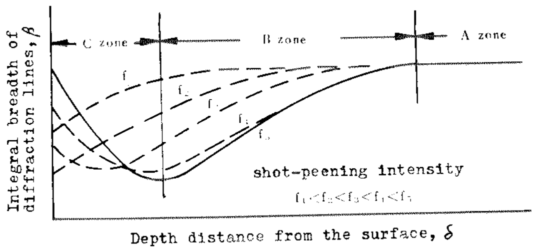


Fig. 3. Schematic of kinetic process of variation of β-δ curves for shot-peened hardening steel.

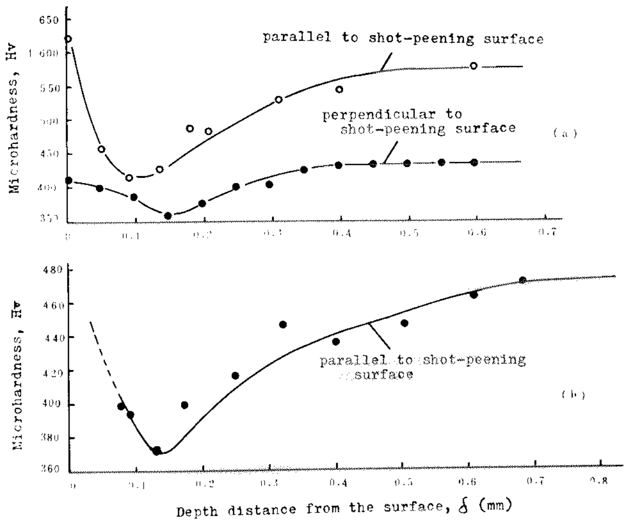


Fig. 4. Variation of Hv with δ from the surface of 30CrMnSiNi2A (a) and 18CrNiWA (b) hardening steels.

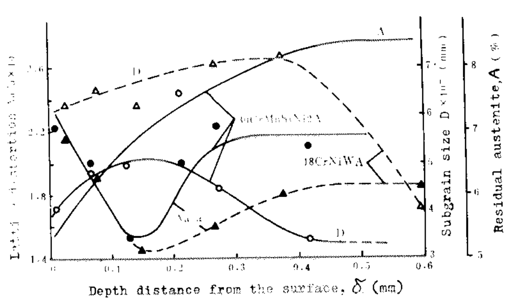


Fig. 5. Variation of D, Δa/a and A amount (only for 30CrMnSiNi2A) with δ for both 30CrMnSiNi2A and 18CrNiWA shot-peened hardening steels.

change of the microstructure can be observed.

DESCUSSION

(1) For hardening or low-temperature tempered steel

For this kind of steels, the dependence of β on δ(β-δ curve) is shown in Fig. 2. Firstly, it is necessary to point out that the variation of (310) and (321) breadth, β, with δ does not correlate with the phenomenon of carbon precipitation from the supersaturated martensite, because the depth protile 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 δ 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, De, breadth, β, and Burgers vector, b, may be expressed in the form $De = \beta^2/9b^2$. The De-δ curve exhibits, therefore, the same tendency of depth profile with β-δ curve. Thus, the De-δ curve is also shown in Fig. 8.

The consistency of depth profiles between both β-δ and

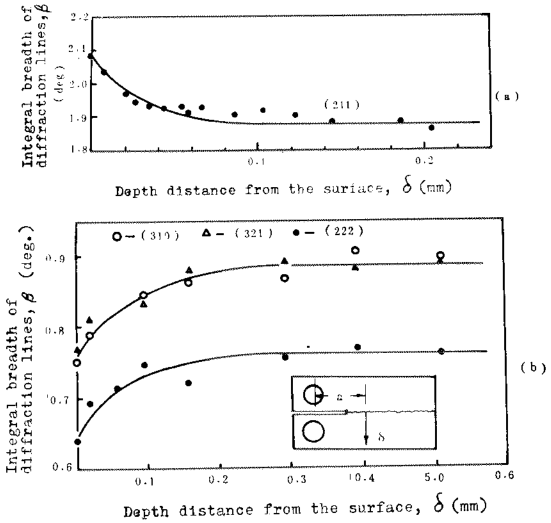


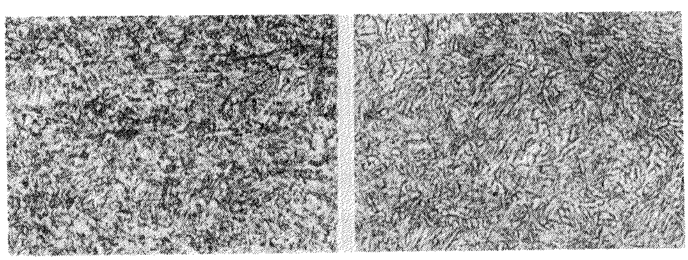
Fig. 6 Variation of breadth, β, with depth distance, δ, from fatigue fracture surface for annealed (a) and hardening (b) steels (30CrMnSiNi2A) .

Hv-δ curves (Fig.4) permit us to draw the following conclutions; B zone is a softening zone as compared with virgin material (A zone) ; C zone is a rehardening zone as compared with B zone; B and A zones are formed gradually during shot-peened process. The kinetic process of formation was shown in Fig.3.

Softening or rehardening in the shot-peened straining layer are correlated with the change of D and Δa/a in the different zone (Fig.5) .The martensite of hardening (or low temperature tempered) steel exhibits a microstructure with very fine subgrain size, high lattice distortion and high dislocation density. In the plastic deformation during shot-peened process, some excess dislocations may be annihilated by each other during sliping or by other ways. All these processes promote the decrease of microhardness resulting from a decrease of lattice distortion and an increase of subgrain size.

When this softening microstructure is subjected further plastic deformation by shot-peening, the rehardening is produced by refinement of D, and increase of De and of Δa/a.

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.



(a) (b)

Fig. 7 Microphotographs at the depth distance about 17μm (a) , about 170μm (b) of 30CrMnSiNi2A hardening steel, 500×.

The number of cycles can be calcutated according to following shot-peening parameters; flow of shots (25 kg/min) , diameter of shots (1mm) , diameter of indentation at specimen surifaceA(0·35mm), diameter of shot-peened area at specimen (60mm) 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 consequeuce of cyclic strain in the plastic *zone only cyclic softening occurs (Fig.6.b) . The strain fatigue test (strain ranges are 0.7–4%)* using 4340 steel which exhibits the same microstructure and tensile strength with 30CrMnSiNi2A 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-

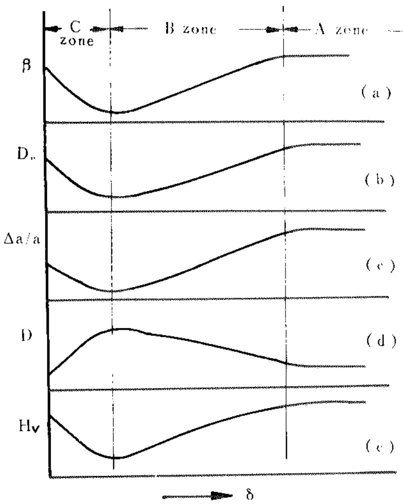


Fig.8 Variations of β(a), De(b), Δa/a(c), subgrain size D(d), and Hv(e) with δ from the surface of hardening steel.

pull strain fatigue, the β-δ 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 gradnally 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 appearence of softening micrstructures. (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, β, gradually increases (The 2nd Divisicn, 1970; Weiss, 1979; Pangborn, 1979). This phenomenon can also be seen from Fig.6, a. This variation of β is shown that the dislocation density is gradually increasing, and the fragmentation of subgrain is gradually taking place during fatigue process (Grosskreutz, 1963). As it has been said before, the shot-peening process is similar to the fatigue process. The β-δ curves shown in Fig. 1, a, b, c, d, are successively decreased with δ. This appears to be a function of shot-peening straining amount which is gradually decreased with δ. The consistence of β 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 becouse 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 homogeneaus, 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. Conclutions

(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.

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