COEXISTENCE OF FATIGUE SOFTENING AND FATIGUE HARDENING IN QUENCHED PLUS TEMPERED CARBURIZED CARBON STEEL

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The phenomena of fatigue hardening in soft materials and fatigue softening in hardened materials are well-known. By using microstructural analysis, micro-hardness measurements and fatigue plus tensile tests it is shown that fatigue softening and fatigue hardening can coexist in a quenched plus tempered carburized 0.06 (wt)% carbon steel. There is a transition zone which devides the whole cross section of a round specimen into two parts : the softening part outwards and the hardening part inwards. Further, it is shown that with the increase of stress level and number of cycles, the effect of fatigue softening and hardening is also increased.

1. INTRODUCTION

In fatigue of metals, both fatigue hardening and softening are important processes, which occur before crack initiation. The behaviour of a metal in these processes is determined by the motion of dislocations, their mutual interaction and their interaction with other lattice defects, i.e. precipitates, foreign particles, grain boundaries, etc. During fatigue, dislocation substructure and density, and distribution and morphology of other obstacles can be changed.

Fatigue hardening commonly happens in soft materials, especially in annealed ones. Because of fatigue loading, the dislocation density increases with the number of cycles and tends to a saturation (1), so do other properties of materials such as flow stress (2). Much research is concerned with the interpretation of fatigue hardening in soft materials. Several models have been presented, e.g. models given by C.E. Filtner (2), P.B. Hirsch and J.S. Latty (3), J.R. Hancock and

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J.C. Grosskreutz (4), D. Kullman-Wilsdorf and C. Laird (5) as well as C.E. Feltner and C. Laird (6). All the models are related to the dislocation behaviour in the studied metals. In contrast, fatigue softening commonly occurs in hardened materials either by cold working or by other methods, e.g. precipitation, solid solution, martensitic transformation and so on (2). In this field, only a few models were presented to deal with the softening mechanism. In general, fatigue hardening and fatigue softening occur in different materials separately, or even in the same materials but not at the same time. However, the present study shows that both fatigue hardening and softening can exist simultaneously in a given specimen.

2. MATERIAL AND ITS TREATMENT

The starting material used to prepare the fatigue specimens is 0.06 (wt)% C steel, patented and drawn in the form of a bar of 8 mm diameter. The grain size of this material in the as-received state is ASTM 6.5 near the surface and ASTM 9.5 in the center. After machining, however, no difference in the grain size exists at the surface and in the center of the gauge length. The geometry of the specimens (non-notched) is shown in figure 1. The specimens are pack carburized at 930°C for 6 hours in order to get 1.0 mm case depth, or, 2 hours to get 0.4 mm case depth. Then, the specimens are cooled slowly. Next, the specimens are individually retreated in a protective argon atmosphere at 860°C for 110 minutes for 1.0 mm case depth, or, 40 minutes for 0.4 mm case depth, followed by a quenching in tap water. Finally, a tempering is done at 180°C for 105 minutes and cooled quickly in tap water. Near the surface, the microstructure of the present steel is martensite plus residual austenite, with traces of decarburization. In the core we find free ferrite plus traces of lath martensite. The microstructure of the as-received material consists of ferrite and traces of pearlite. The microstructure of the near surface and the core of the present steel is shown in figure 2.

3. EXPERIMENTAL METHOD

All fatigue tests were done on a Schenck fatigue machine in a laboratory atmosphere. The tests are of a tension-tension type, with a stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.1. The frequency for the present tests is 20 Hz. Two methods were used to check and make sure the possible degree of fatigue hardening and softening of these carburized steel specimens, i.e. microhardness tests and tensile tests.

3.1. Microhardness Tests

Using a Leitz microhardness tester, the microhardness distribution along the cross sections before and after fatigue tests was determined. In order to decrease the effect of grinding and polishing on the microhardness value, an etching method is used to minimize the mechanical stress due to the sample preparation process. The microhardness was measured along two mutually perpendicular diameters on the cross section of a sample. The load for the measurement is 200 grams. The distance between two successive indentations is 0.2 mm for the samples with 1.0 mm case depth, it is 0.15 mm near the surface and 0.2 mm in the core for the samples with 0.4 mm case depth. The microhardness of the core material after fatigue is taken from the mean value of the microhardness measured at places deeper than 2.0 mm for 1.0 mm case depth and deeper than 1.0 mm for 0.4 mm case depth.

3.2. Fatigue Plus Tensile Test

This test is especially useful to estimate the influence of fatigue on the yield strength and ultimate tensile strength of the core material. For this, some 0.06 (wt)% C steel specimens in the same geometry as figure 1 were treated in such a way that they have a thermal history similar to that of the specimens with 0.4 mm case depth. After these specimens survived at a stress level below but near the fatigue strength at 10^6 of the material, they were further tested in tension on an Instron tensile testing machine. Table 1 shows the heat treatment history, the type of tests and the results of these specimens.

4. RESULTS

The mean tensile strength values of specimens No. 511, 512 and 513 are taken as reference. The effect of fatigue loading on the tensile strength is shown in table 1 and more clearly in figure 3, where 1 and 1' denote the strength properties before fatigue testing and 2 and 2' after fatigue testing. Obviously, after a test for 10^6 cycles, the yield strength is increased up to 524 MPa and the tensile strength up to 677 MPa. The strength increment goes up with the fatigue stress level. Because of the similar heat history, these informations can be considered as the basic hardening data of the core material of the present carburized steel.

TABLE 1 : Heat Treatment History, Types of Testing and Result of the quenched 0.06 (wt)% Steel

Sample No.	Heat History	Type of Testing	$\sigma_{0.2}$ MPa	σ_{UTS} MPa	Note
511	Heated from R.T. to 930°C for 2 h; Austenitized at 860°C for 1/4 h; Tempered at 180°C for 1 3/4 h.	Tension	311	543	
512			304	509	
513			334	487	
501F	Heated from R.T. to 930°C for 2 h; Austenitized at 860°C for 1/4 h and quenched.	Fatigue + Tension	511	636	σ_{max}=427.1MPa N_f=1.0x10^6
508F			471	604	σ_{max}=416.4MPa N_f=1.0x10^6
510F			524	677	σ_{max}=437.8MPa N_f=1.0x10^6

The microhardness results of the carburized steel specimens are shown in figures 4 to 8. From these data it can clearly be seen that :

a) fatigue softening in the case and fatigue hardening in the core coexist in the present carburized steel specimens. The effect of the softening and hardening can be expressed by a softening-hardening band;
b) in general, the higher the applied stress level (figures 4 and 5) or, the higher the number of cycles (figures 6, 7 and 8) the higher the degree of both fatigue softening in the case and fatigue hardening in the core of a round specimen is;
c) under the present experimented conditions, the effect of increasing applied the stress level is similar to that of increasing number of cycles for both fatigue softening and fatigue hardening;
d) there is a transition area, which divides the whole cross section of a round specimen into two parts : the softening part outwards and the hardening part inwards. The transition area is in the vicinity of the case depth of the carburized steel.

5. DISCUSSION

The coexistence of fatigue softening and fatigue hardening is an interesting phenomenon in the present material. Its occurrence depends on two major factors, i.e. material characteristics and stress conditions.

As mentioned above, this low carbon steel was carburized followed by quenching and tempering. After this heat treatment, its fatigue strength at 10^6 cycles, in tension-tension with a stress ratio of 0.1 is 536 MPa for 1.0 mm case depth and 481 MPa for 0.4 mm case depth. The microhardness of the case can be as high as $HV_{0.2}$ = 880 - 915. On the other hand, the yield strength and the ultimate tensile strength of the core material of the carburized steel is 316 MPa and 513 MPa, respectively and the microhardness of the core is just $HV_{0.2}$ = 160. Obviously, this carburized steel forms a system which consists of a very hard case with martensite plus austenite, and a very soft core with ferrite matrix plus lath martensite. These characteristics of the material provides a prerequisite for occurrence of the coexistence phenomenon because it is a fact that fatigue softening is typical for materials hardened by martensitic transformation and fatigue hardening is typical for materials such as carbon steel with ferrite matrix, even though they are not annealed. For the specimens of the present study, on the other hand, all the applied stresses in the tests are near or even higher than the fatigue strength of the carburized steel and considerably higher than the yield strength of the core materials. These high stresses, making the core deform plastically prior to the case, are the necessary conditions to make the coexistence phenomenon show up. The behaviour of the present carburized steel during fatigue can be explained as follows. For the core, it is clear that its yield strength is lower than the applied fatigue stress, it is possible for the core to deform plastically prior to the case. In this case, according to Feltner (2), even during the first cycle, strain hardening occurs. At the same time, prismatic dislocation loops create by moving screw dislocations. On each subsequent cycle, these loops act as obstacles to continued dislocation line motion. Screw dislocations circumventing the debris obstacles by cross-slip will create additional loops which increase the obstacle density further. As a results, fatigue hardening occurs. Or, according to Hirsh and Lally (3), and Hancock and Grosskreutz (4), the dislocation loops emitted from sources on nearly parallel planes interact so that the edge components trap one another to form bundles and the screw components annihilate by cross slip. This interaction, leads, in the vicinity of edge bundles, to formation of the faulted dipoles, which serve to stabilize the bundles against long range movement. Cycling, causing a multiplication of the dislocation bundles, decreases average slip distance and increases mobile dislocation density to accomodate the imposed strain limit. Therefore, the back stress on active dislocation sources as well as the necessary applied stress are increased. As cycling proceeds, on secondary glide planes, dislocations are activated and cut through the primary bundles which act as obstacles. So, bundles of secondary dislocations are formed and an even higher stress is needed.

For the case of the carburized steel, after quenched plus tempered, it is hardened by several mechanisms, the most important of which are interstitial solid solution from carbon (dislocation locking) and precipitation of small particles on dislocations. During fatigue, the case can be softened by the gradual elimination of different obstacles for dislocation movement or by the possible diffusion of some elements or by other mechanisms. It was proved (7) that when a dislocation passes a coherent or partly coherent particle, because of the repeated shearing effect from the to-and-fro motion of dislocations, the particle is split into two parts, and then more parts until it disappears. It was also found that carbon in martensite experiences a diffusion during fatigue (8). As a result, the carbon content in martensite decreases and hence the tetragonality and distortion of martensite lattice decreases too.

6. CONCLUSION

Both for fatigue softening or hardening, the key factor is dislocation movement. The intensity of dislocation movement and the dislocation density are increased with the applied stress. Also, dislocation movement as well as the diffusion process is time-dependent. Therefore, with the increase of applied stress, or the increase of the number of cycles, the degree of fatigue softening and fatigue hardening is increased.

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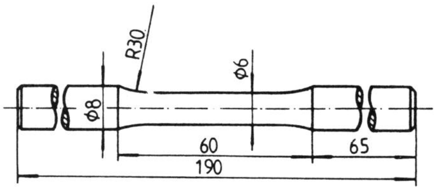

Fig. 1 Geometry of the testing specimens

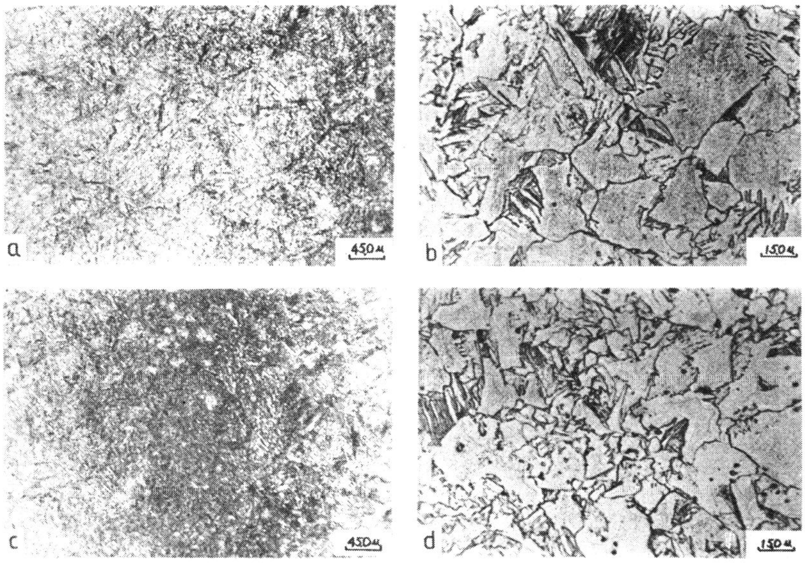

Fig. 2 Microstructure of case (a) and core (b) of the specimen with 1.0 mm case depth and of case (c) and core (d) of the specimen with 0.4 mm case depth

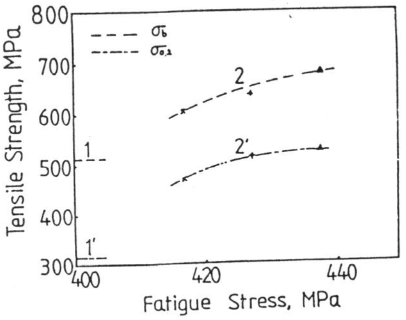

Fig. 3 Relationship between tensile strength and fatigue stress for the quenched 0.06 (wt)% C steel

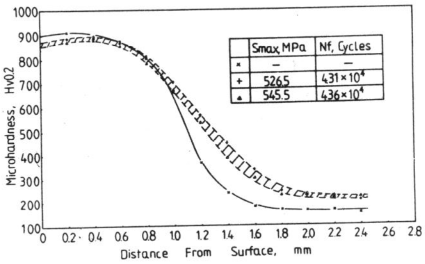

Fig. 4 Microhardness of the failed specimen (at about 4.3 x 10^4) with 1.0 mm case depth

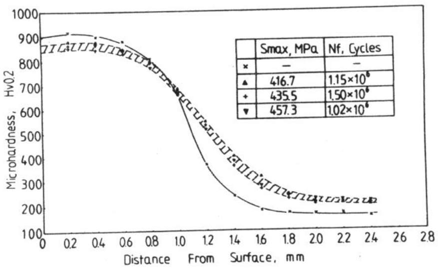

Fig. 5 Microhardness of the survived specimens (at 10^6 cycles) with 1.0 mm case depth

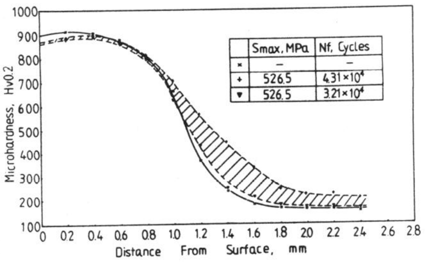

Fig. 6 Microhardness of the failed specimens (at 526.5 MPa) with 1.0 mm case depth

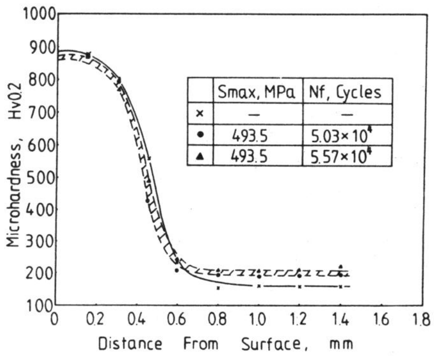

Fig. 7 Microhardness of the failed specimens (at 493.5 MPa) with 0.4 mm case depth

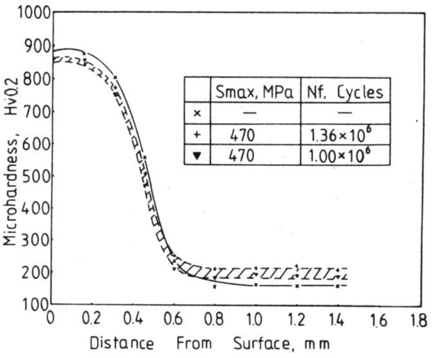

Fig. 8 Microhardness of the survived specimens (at 470 MPa) with 0.4 mm case depth