Plastic Deformation Behavior of Rail Steels under Cyclic Impact Blows

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In order to demonstrate clearly the damaging mechanism on rail surfaces at the joint subjected to impact blows by train wheels, cyclic impact blow tests and low cycle fatigue tests have been performed using 0.75 % C rail steel with different hardness values and microstructures.

The results are summarized as follows:

1. Under cyclic impact blow, a cyclic softening occurs at an early deformation stage in tempered martensite, but only a hardening occurs following surface cracking afterward in pearlite.

2. Under low cycle fatigue conditions, a cyclic softening at a small strain amplitude gives place to a hardening as the strain amplitude increases in pearlite, although only a cyclic softening occurs more extensively in tempered martensite.

3. The fact that dislocation structures formed under cyclic impact blows correspond to the structural changes observed under cyclic plastic straining suggests that the fatigue behavior under impact blows can be roughly estimated using low cycle fatigue tests.

KEY WORDS: rail steel; cyclic impact blow; low cycle fatigue; cyclic hardening; cyclic softening; heat treatment; microstructure.

1. Introduction

The repeated impact blows given by a passing train cause plastic flow and sometimes horizontal cracking in the heads of rail ends at the joints, as shown in Fig. 1. In order to prevent this type of damage, an End-Hardened rail (EH rail), which has a fine pearlite structure formed by slack quenching with hardness values ranging from HV320 to HV372 has come to be widely used.

Although the effectiveness of the EH rail has been confirmed by field tests, greater durability has come to be required of rails with the increase in train speed and frequency. Furthermore, a Head-Hardened rail (HH rail) and a New-type Head Hardened rail (NHH rail) also have come to be used for the purpose of decreasing the gauge corner wear of outside rails.

On the other hand, the characteristics of plastic flow due to cyclic impact blows have not been clarified from a metallurgical viewpoint in spite of the long time utilization of such rails.

In this study, cyclic impact blow tests and low cycle fatigue tests have been performed using 0.75 % C rail steels with different hardness values and structures in order to throw light on the rail head crushing mechanism.

2. Experimental Procedures

2.1. Specimen and Heat Treatment

Specimens were heat treated after machining (Table 2). In the case of pearlite structure, the hardness depends on inter-lamellar spacing which becomes smaller with a decrease in the pearlite-forming temperature. Therefore, the hardness level was controlled by isothermal transformation using salt baths.

On the other hand, in the case of tempered martensite structure, the hardness level was controlled by the tempering temperature.

2.2. Cyclic Impact Blow Test

The cyclic impact blow test was performed using a Matsumura-type Impact Fatigue test machine (Fig. 3) with a modified impact hammer (HV500). Impact loads were measured by four strain gauges attached symmetrically with respect to the axis of the hammer at a distance of 10 mm from the impact end. Detected impact loading data were stored in a transient memory, and were registered on an X-Y pen recorder. An example of the impact loading curve is illustrated in Fig. 4. The loading frequency is about 67/min.

The characteristics of plastic flow due to cyclic impact blows were evaluated using the decrease in specimen height, \( \Delta H = H_0 - H_N \), and the increase in impact surface diameter, \( \Delta D = D_N - D_0 \), where \( H_N \) and \( D_N \) are specimen height and impact surface diameter after the \( N \)-th blows, respectively, and \( H_0 \) and \( D_0 \) are their initial values. Furthermore, the change in hardness distribution on the impact surface with number of loading cycles was measured. The impact surface and subsurface flow structure were observed using SEM and TEM.
2.3. Low Cycle Fatigue Test

The cyclic push–pull loading test was carried out under the following condition; total strain amplitude was constant and the strain rate was $7 \times 10^{-4}/s$ using an Instron low cycle fatigue test machine. Strain was detected by a clip-on-gauge placed on the section with parallel sides of the specimen.

3. Experimental Results

3.1. Cyclic Impact Blow Test

Fig. 5 shows the relation between $\Delta H$ and number of impact blows $N$ for various hardness values. In the case of pearlite structure (a), the increase rate of $\Delta H$ is large in the early stage, but gradually decreases as $N$ increases and $\Delta H$ finally approaches a constant value. The higher the initial hardness value, the more quickly $\Delta H$ becomes constant. A similar ten-

![Fig. 1. A crushed head at rail end.](image1)

Table 1. Chemical composition of specimens. (wt%)

|   | C  | Si | Mn | P  | S   |
|---|----|----|----|----|-----|
|   | 0.75 | 0.25 | 0.93 | 0.022 | 0.006 |

![Fig. 2. Dimensions of specimens.](image2)

Table 2. Heat treatments of specimens.

| Structure               | Heat treatment          | Hardness | Interlamellar spacing | Reference |
|------------------------|-------------------------|----------|-----------------------|-----------|
|                        | Austenitize             | Isothermal transformation |           |           |
| Pearlite 850°C×20 min  | 300°C×2s → 550°C×20 min → water cooled | HV375     | 0.12 µm               | NHH rail  |
|                        | 575°C×20 min → water cooled | HV335     |                       | EH rail   |
|                        | 625°C×20 min → water cooled | HV295     |                       |           |
|                        | As rolled               |           |                       |           |
| Tempered martensite 850°C×20 min | 525°C×60 min → water cooled | HV390     |                       | HH rail   |
|                        | 575°C×60 min → water cooled | HV340     |                       |           |
|                        | 600°C×60 min → water cooled | HV300     |                       |           |
|                        | 625°C×60 min → water cooled | HV285     |                       |           |

![Fig. 3. Impact blow test machine.](image3)

![Fig. 4. Impact loading curve.](image4)
tendency is observed in the case of the tempered martensite (b), but a point of inflection (● in Fig. 5) appears at an early stage. That is, the increase rate of $\Delta H$ increases with $N$ until $N$ reaches nearly 10,000, but afterwards, it decreases and $\Delta H$ approaches a constant value. It seems that the deformation of tempered martensite is considerably smaller than that of pearlite for the same hardness value.

Fig. 6 shows the relation between $\Delta D$ and the number of impact blows $N$. The behavior of $\Delta D$ is similar to that of $\Delta H$, but is more marked. If the hardness exceeds HV300, the increase rate of deformation decreases rapidly and $\Delta D$ soon levels out. In such a case, the final value of $\Delta D$ in pearlite is almost the same as that in tempered martensite.

Fig. 7 shows the change in diametral hardness distribution on the impact surface with $N$. In the case of the pearlite structure (a), hardness increases monotonically as $N$ increases. The increase rate is large in the early stages and decreases gradually. In contrast, in the case of the tempered martensite (b), hardness decreases with $N$ in the early stage, but when $N$ exceeds nearly 10,000, it increases conversely. The value of $N$ at which this change occurs almost coincides with $N$ corresponding to the point of inflection in Figs. 5(b) and 6(b). The final hardness depends only on the initial hardness value regardless of the structure. In the early stages, there comes a sharp peak of hardening or softening at the center of the specimen. But it tends to gradually become constant all over the surface with the increase in $N$.

### 3.2. Low Cycle Fatigue Test

Determining the cyclic stress-strain curve from the multiple step tests consists in cycling a single specimen at several levels of strain amplitude. The number of cycles taken at each level should be large enough for the hysteresis loop to become stable but small enough to avoid any serious fatigue damage. With the stable hysteresis loops superimposed, the cyclic stress-strain curve is obtained by drawing a smooth curve connecting the tips of the loops.17

Fig. 8 shows the 1st and the 1,000th stress-strain hysteresis loops for both medium pearlite and tempered martensite. In medium pearlite, the flow stress increases as the number of cycles increases, but in tempered martensite, it decreases remarkably.

Fig. 9 shows cyclic stress-strain curves obtained from hysteresis loops and monotonic stress-strain curves. In fine pearlite (HV365), only a cyclic soft-
Softening occurs in this strain range. Maximum softening occurs at a 0.4% strain amplitude, and the softening decreases as the strain amplitude further increases. However, in medium pearlite (HV275), a cyclic softening occurs at strain amplitudes less than 0.5%, while a cyclic hardening occurs at those above 0.5%. Even in fine pearlite, if the strain amplitude increases further, a cyclic hardening will occur. On the other hand, in tempered martensite (b), only a cyclic softening occurs at every hardness level. Softening increases with higher initial hardness values. Comparing Figs. 9(a) and 9(b), it can be seen that softening in tempered martensite is more marked than that in pearlite.

Monotonic stress-strain curves are expressed by the equation

$$\sigma = K\varepsilon^n$$ .................................. (1)

where, $\sigma$: the stress

$\varepsilon$: the plastic strain

$K$: the monotonic strength coefficient

$n$: the monotonic strain hardening exponent.

And cyclic stress-strain curves by

$$\Delta\sigma/2 = K'(\Delta\varepsilon/2)^{n'}$$ .................................. (2)

where, $\Delta\sigma/2$: the stress amplitude

$\Delta\varepsilon/2$: the plastic strain amplitude

$K'$: the cyclic strength coefficient

$n'$: the cyclic strain hardening exponent.

Applying these equations to the results obtained gives the parameters shown in Table 3. For the same hardness value, the 0.2% offset yield stress in tempered martensite is larger than that in pearlite. The cyclic strain hardening exponent $n'$ is larger than the monotonic strain hardening exponent $n$ in every specimen. Fig. 10 shows representative relations between the stress amplitude $\Delta\sigma/2$ and the number of cycles $N$. In the case of a 0.4% strain amplitude, only a cyclic softening occurs in each structure and hardness. But in the case of a 0.8% strain amplitude, a cyclic hardening occurs only in medium pearlite (HV275). The stress amplitude in pearlite becomes stable more quickly than that in tempered martensite.

4. Discussion

4.1. Deformation Behavior under Cyclic Loading

Fig. 11 shows the relation between $\Delta D$ and the hardness at the center of the impact surface, which can be roughly classified into three stages: an initial transition stage (I in Fig. 11), a rapid hardening stage (II) and a gradual hardening stage (III). In the case of pearlite, hardening occurs in stage I. While for tempered martensite, softening occurs in medium pearlite

![Medium pearlite and tempered martensite](image)

Fig. 8. Stress-strain hysteresis loops.

![Monotonic and cyclic stress-strain curves](image)

Fig. 9. Monotonic and cyclic stress-strain curves.

![Relation between stress amplitude $\Delta\sigma/2$ and number of cycle $N$.](image)

Fig. 10. Relation between stress amplitude $\Delta\sigma/2$ and number of cycle $N$.
this stage. Stage III appears clearly in pearlite, and especially in medium pearlite (HV275). In stage III, many cracks like those shown in Fig. 12(a) are observed on the impact surface of a pearlite specimen. On the other hand, they are rarely observed in tempered martensite. It seems that the stage III appearing in pearlite is caused by cracking and crack opening.

Fig. 13 shows the change in the deformation increment \( \Delta d \), \( (=d(JD)/dN) \), obtained from the data displayed in Fig. 6. Klesnil et al. 19 have obtained similar results from low cycle push–pull loading at a constant stress amplitude. That is, depending on the microstructure, only a cyclic hardening occurs or a cyclic softening gives place to a hardening as \( N \) increases. These facts suggest that the deformation behavior in steels under cyclic impact blows and under low cycle fatigue can be thought of as essentially identical.

Fig. 13. Relation between \( \Delta d \) and \( N \).

In the impact blow tests, results indicating monotonic hardening in pearlite, and an initial softening stage followed by a subsequent hardening in tempered martensite have been obtained. On the other hand, the low cycle fatigue tests have revealed a softening stage at a small strain amplitude followed by a subsequent hardening at a large one in pearlite, and monotonic softening in tempered martensite. These contradictory results can be explained as follows: in the case of the impact blow test, the loading is compression only, and this induces the localization of softening and hardening at the end surface, as shown in Fig. 7, while in the case of low cycle fatigue, push–pull loading causes uniform softening and hardening over the length of the specimen. Furthermore, the strain amplitude and the number of cycles are quite different in both tests. Consequently, softening in an early cyclic stage can not be easily observed in the impact blow tests.

According to the results of low cycle fatigue tests, Table 3, if the initial hardness value is about the same, both of the monotonic and cyclic yield stress are much larger in tempered martensite than in pearlite. So the final deformation (see Figs. 5 and 6) is smaller in tempered martensite than in pearlite even though the former shows noteworthy softening.

4.2 Structural Change under Cyclic Loading

Figs. 14 and 15 show the subsurface microstructures and dislocation structures, respectively. The dislocation structure depends on the distance from the impact surface.

In the case of pearlite, the microstructure is heavily deformed in a region just under the impact surface (Fig. 15(a)). In this region, the dislocations were localized in the ferrite causing the cementite to crack (\( \infty \)). However, the cracking did not extend over the whole colony. In the region (Fig. 15(b)), cell structures developed without any cementite cracking, but they are more difficult to detect in fine-pearlite. In the inner region far from the impact surface (Fig. 15(c)), there are recognized a few cell structures in medium pearlite, but only isolated dislocations can be seen in fine pearlite. In the case of tempered martensite, an increase in dislocation density and dislocation tangling takes place in the heavily deformed region (Fig. 15(a)), while a uniform distribution of isolated dislocations in the inner region takes place in martensite laths.

Such structural changes can be considered to correspond to deformation stages shown in Fig. 11. Namely, the deformation behaviors in the regions (a), (b) and (c) correspond to the stages III, II and I, respectively. So the deformation process can be explained as follows:

In the pearlite structure, dislocations are rearranged into cell structures in ferrite lamellae at stage I, and hardening occurs rapidly due to dislocation tangling at stage II. As a strain further increases,
cementite cracking occurs locally leading afterward to micro-cracking. On the other hand, in the tempered martensite structure, cyclic softening occurs due to generated mobile dislocations and the annihilation of dislocations at stage I, because both dislocation density and hardness are relatively high before impact blows. As strain increases, dislocation blocking due to tangling becomes predominant following intensive hardening at stage II. However, even more straining can not induce cementite cracking because of the globular structure. So the final deformation is smaller in tempered martensite than in pearlite.

From these results, it can be said that tempered martensite structure is superior to pearlite one in the effect of preventing plastic deformation of rail by impact blows. However, what causes damage to rails are not only plastic deformation and cracking in the heads but also wear, shelling, etc. Pearlitic structure is prominently effective to prevent wear on rail surface. So the EH rails should not necessarily be rejected for use, and the optimum structure of rail must be sought from all angles.

5. Conclusions

Cyclic impact blow tests and low cycle fatigue tests were performed using 0.75% C rail steels with different hardness values and structures.

The results are summarized as follows:
(1) The deformation caused by cyclic impact blows is larger in pearlite than that in tempered martensite. In the case of tempered martensite, a cyclic
softening occurs at an early deformation stage. In contrast to this, only a hardening occurs in the case of pearlite. At a stage of heavier deformation, many cracks appear on the impact surface in pearlite, while there is no such cracking in tempered martensite.

(2) In low cycle fatigue tests, a cyclic softening occurs at a small strain amplitude in pearlite structure. As the strain amplitude increases, the softening gives place to a hardening. This transition tends to occur at a smaller strain amplitude in medium pearlite than in fine pearlite. On the other hand, in tempered martensite, it seems that only a cyclic softening occurs and more extensively than is observed in pearlite.

(3) The dislocation structures formed under cyclic impact blows depend on the distance from the impact surface and correspond to the structural changes seen under cyclic plastic straining. This fact suggests that the fatigue behavior in cyclic impact blow tests can be roughly estimated using low cycle fatigue tests.

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