Deformation Behavior of Rail Steels

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The cyclic deformation behavior of three rail steels was determined under conditions of uniaxial plane-strain compression. Two loading programs were used: (a) one load (simple loading) for the entire test and (b) two loads (split loading) in which the load was increased at set intervals during the test. The results for simple loading showed that the steel softened under cyclic compression; i.e., for a constant stress, compressive cyclic loading caused an increase in strain. Increasing the applied stress increased both the rate and the amount of softening. Rails with higher hardness and yield strength showed an increase in deformation resistance. Split loading produced either increased or decreased resistance to deformation, depending on the type of steel. An equation is presented that can be used to predict the expected amount of plastic flow in rail in service.

The deformation behavior of rail steels has taken on great importance with the increasing severity of service conditions. The average weight of a carload has risen 20 percent in 10 years, and train speeds have also increased (1). Consequently, rails are wearing and failing at higher than expected rates. Research into this problem is being done by several agencies, including Battelle Memorial Institute and the Association of American Railroads (AAR).

Research at Battelle showed that fully reversed cyclic straining caused softening of standard rail steel at low strain levels and hardening at strain levels greater than 0.6. However, when the steel was cycled with a mean tensile or compressive strain, softening occurred over the entire strain range. In addition, the softening rate, or relaxation rate, was the same for both mean strains. The results of the Battelle studies indicated that tests made with fully reversed strain amplitudes may not accurately duplicate the straining of rail in service (2).

Because rails undergo compressive loading, Marich and Curcio (3) proposed that deformation tests on rails should be made in compression, thus eliminating the Bauschinger effect and approximating more closely actual service conditions. Their work on rails tested in monotonic plane strain compression showed that, as the yield strength of the rail increased, the depth of deformation in the railhead decreased, thus decreasing the occurrence of shelling and transverse defects. In addition, the work-hardening behavior of a hot-rolled pearlitic steel was related to dislocation processes occurring in the ferrite lamellae, a decrease in the interlamellar spacing, and dislocation tangles in the cementite.

As an initial part of this study, the deformation pattern and microstructure of rails that had undergone 468 million-662 million gross Mg (515 million-728 million gross tons) of traffic were evaluated to characterize service-induced deformation behavior. The resulting hardness profiles and microstructures serve as standard to ensure that laboratory experiments are reproducing service conditions.

This present investigation is part of the AAR's effort to increase research and development on the improvement of rail performance. The purpose of this project is to study the deformation behavior of several rail steels under cyclic uniaxial plane strain compression.

OBSERVED BEHAVIOR IN RAILS REMOVED FROM SERVICE

Three rails removed from service on the Union Pacific Railroad were used to characterize rail work hardening attributable to plastic flow and the change in microstructure that accompanies deformation. Two of the rails had undergone 468 million gross Mg (515 million gross tons) of traffic, and one of the rails had undergone 662 million gross Mg (728 million gross tons) of traffic. Figure 1 shows the results of two Vickers microhardness test surveys made at the gage corner of the rail. The rails typically had been work hardened to 85-95 Vickers hardness above the base hardness [Vickers microhardness numbers are approximately equivalent to Brinell hardness numbers (BHN)]. It is important to note that, between 6 and 8 mm (0.24 and 0.31 in) in depth, a zone of work-softened material exists. It has been shown, by Leis (2) for rail steel and Park and Stone (4) for wheel steels, that these pearlitic steels work soften under cyclic strains of less than 0.6 percent.

There are also dramatic changes in the microstructure that may be associated with work hardening. Figures 2-4 show scanning electron microscope photomicrographs of the same rail specimen, after 662 million gross Mg (728 million gross tons) of service, at depths of 2.25, 6.75, and 7.5 mm (0.09, 0.27, and 0.30 in), respectively. At 2.25 mm (Figure 2), the material has been work hardened to 320 BHN and exhibits a very heavily deformed microstructure within which the cementite plates either have become kinked (in a wavelike pattern) and cracked or have thinned out. The difference in deformation behavior could be associated with the orientation of the cementite plates within individual cells relative to the applied load. In the work-softened zone, the cementite is either straight with some cracking or slightly deformed in a sinusoidal pattern. In the base material at 7.5 mm (Figure 4), the cementite plates are in their normal straight and undeformed condition. Several investigators have observed the same microstructure as that shown in Figure 2 in cold-drawn, high-carbon steel wire (5, 6).

TESTING PROCEDURE

Materials

Three rail steels were tested: (a) hot-rolled carbon steel, (b) heat-treated carbon steel, and (c) pearlitic chromium-molybdenum (CrMo) alloy. Their compositions and mechanical properties are given in Table 1.

The hot-rolled carbon steel had a fully pearlitic microstructure. The heat-treated carbon steel was also pearlitic but had a smaller grain size. The alloyed pearlitic rail was also fine grained.

Samples were cut from the railhead with the deformation face parallel to the running surface (Figure 5). The samples were 6.35 mm (0.25 in) thick and, except for the heat-treated samples, which had a width of 23.8 mm (0.9375 in), were 25.4 mm (1 in) wide.

Because the hardness of rails varies with depth from the surface, the average hardness of each sample was determined and any sample that varied more than 2 points Rockwell C from the average was discarded. The hardness values given in Table 1 are thus the average of the samples tested.

Mechanical Testing

The compression test used in this project was designed by Watts and Ford (7) for testing steel sheet and strip. The test consists of applying a compressive load to the sample by means of two parallel indenting dies (see Figure 6). The width b of the dies was equal to the thickness t of the samples. It has been found that the true yield stress is achieved only when t is an integral multiple of b. By keeping b small in comparison with sample width w, the deformed region of the sample is constrained in the width dimension by the undeformed material on either side. Thus, the sample deformed under plane strain conditions. This test approximates the loading conditions experienced by rail in service, especially in tangent track and on the low rail of curves.

Figure 1. Hardness profiles of standard carbon steel rail in the high rail of a 1° curve after 468 million gross Mg (515 million gross tons) of service.

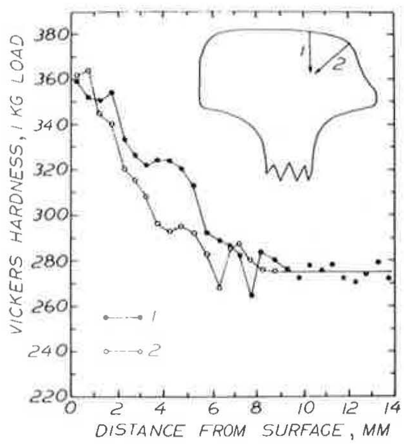


Figure 2. Microstructure of rail specimen 2.25 mm (0.9 in) below running surface (4900X etched in Nital).

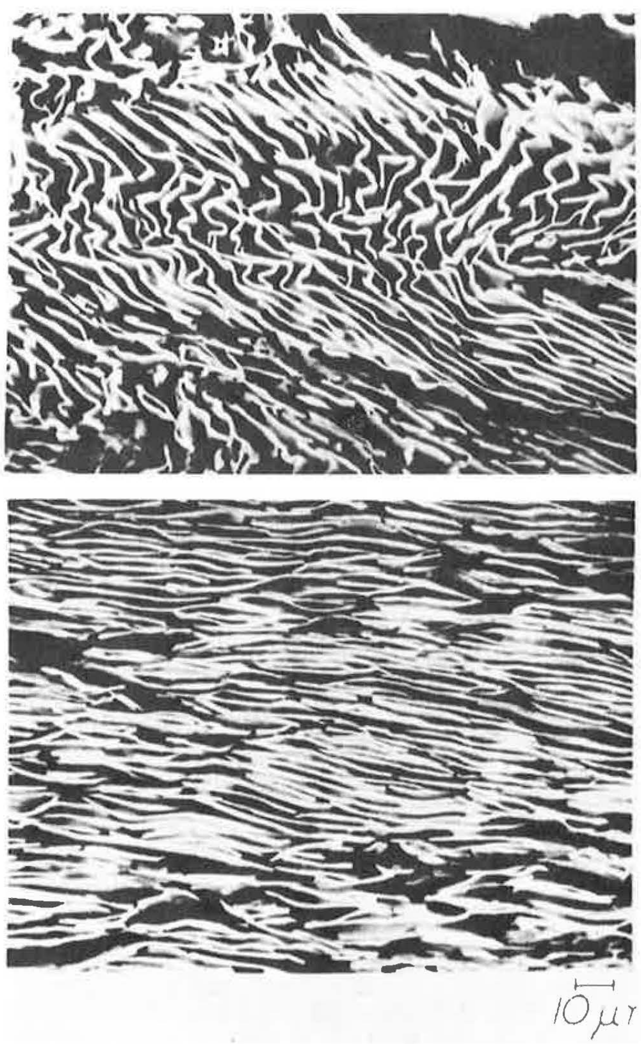


Figure 3. Microstructure of rail specimen 6.75 mm (0.27 in) below running surface (4900X etched in Nital).

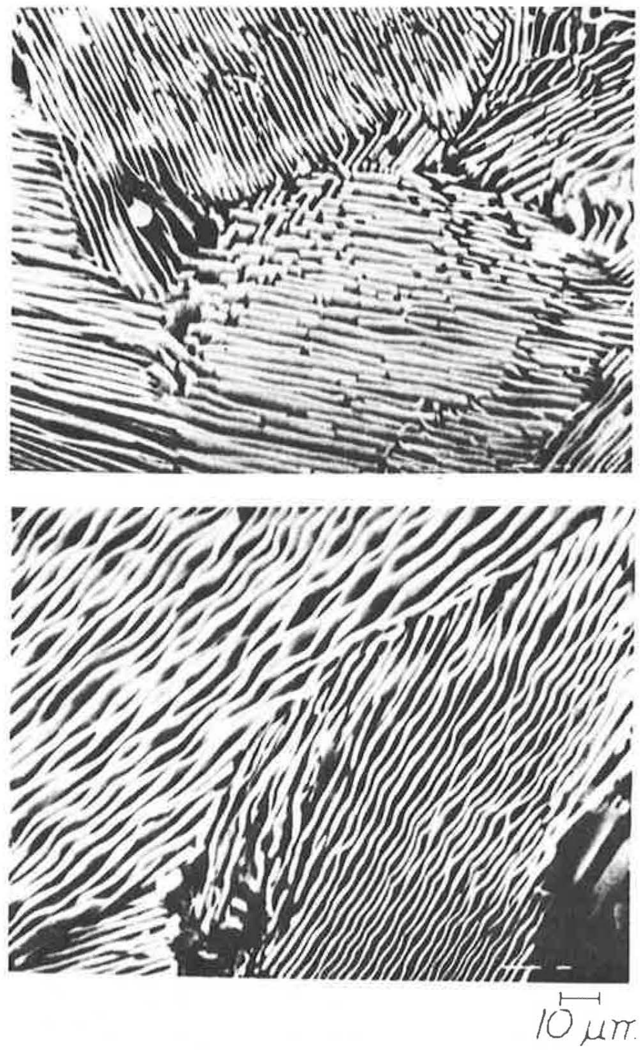


Figure 4. Microstructure of rail specimen 7.5 mm (0.3 in) below running surface (4900X etched in Nital).

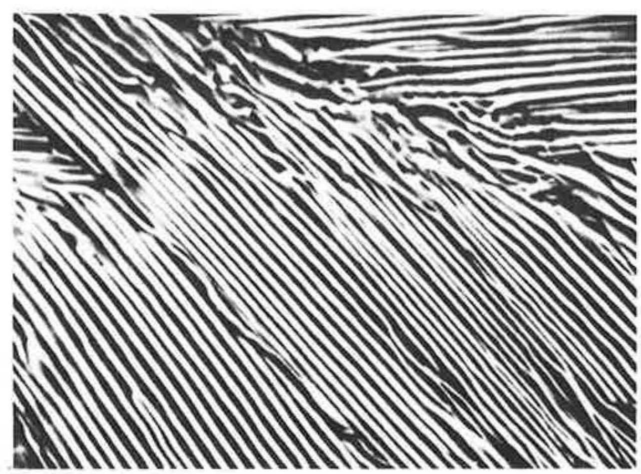


Table 1. Composition and mechanical properties of rail steels.

Type of Rail Steel	Composition (%)	Yield Strength (MPa)	Rockwell C Hardness
As-rolled carbon steel	0.69-0.82 carbon, 0.7-1.0 manganese, 0.04 max phosphorus, 0.05 max sulfur, 0.1-0.25 silicon	517	22-23
Heat-treated carbon steel	0.69-0.82 carbon, 0.7-1.0 manganese, 0.04 max phosphorus, 0.05 max sulfur, 0.1-0.25 silicon	827	38-39
CrMo steel, pearlitic	0.78 carbon, 0.84 manganese, 0.22 silicon, 0.72 chromium, 0.19 molybdenum, 0.026 phosphorus, 0.022 sulfur	752	35-36

Note: 1 MPa = 145 lbf/in².

Figure 5. Test sample as taken from the head of a rail.

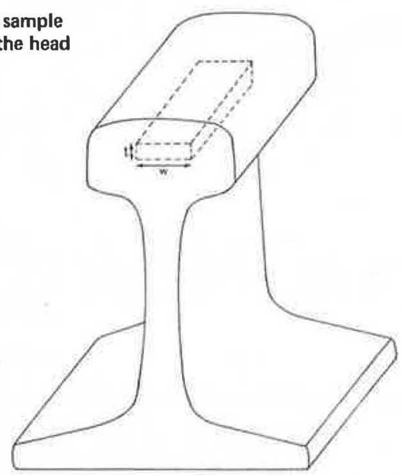
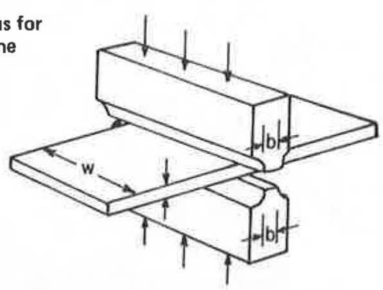


Figure 6. Apparatus for testing uniaxial plane strain compression.



Testing was done on a Material Testing System electrohydraulic close-loop machine in load control (cyclic deformation tests are usually run in strain control, but in this case load control was the simpler mode).

The ideal loading is zero to P_{max} (compressive). However, because of the instability of the samples at zero load, samples were loaded from -13 kN (-3000 lbf) to P_{max}. Loads were applied following a sine wave function at frequencies from 6 to 18 Hz. P_{max} varied from 110 to 200 kN (25 000-45 000 lbf).

To reduce friction effects, the contact surface of the specimens was covered with Teflon tape. In order to record the progressive deformation behavior, the reduction in sample thickness was measured by a micrometer to the nearest 0.002 54 mm (0.0001 in) after a set number of cycles. To facilitate plotting on logarithmic paper, thickness was measured after 1, 2, 5, 10, 20, 50, and 100 cycles, up to 100 000 cycles or 10 percent reduction in thickness, whichever came first. After each measurement, the surface was again covered with Teflon tape. In replacing the samples, care was taken to align the indentation with the dies. The load was then applied again for the next cyclic increment.

Two loading patterns were used. The first pattern (simple loading) consisted of cycling at the same load for the entire run. Simple loading was done for a range of loads to observe the effect of increasing stress on deformation behavior. The second loading pattern (split loading) consisted of cycling the sample at one load for 100, 1000, or 10 000 cycles and then finishing the run at a higher load. Split-loading tests were run after the simple-loading tests so that the low loads could be chosen for little or no cyclic deformation and the high loads for marked cyclic softening behavior. One split-loading set (three runs) was done for each rail type.

Calculations

The axial compressive stress for plane strain compression in this case is simply the applied load divided by the area being deformed:

$$\sigma = P/wb \qquad (1)$$

Each measurement of sample reduction was converted to true strain by the following formulas (derived from the Von Mises yield criterion): For percentage reduction in thickness,

$$(t_0 - t)/t_0 = \epsilon_\epsilon \qquad (2)$$

For plane strain,

$$\ln(1 - \epsilon_\epsilon) = \epsilon_\rho \qquad (3)$$

For true strain,

$$(2/\sqrt{3})\,\epsilon_\rho = \epsilon_t \qquad (4)$$

Graphs of true strain versus cycles were thus obtained for the rail steels for simple and split loading.

TESTING QUALIFICATIONS

Frequency Effect

The frequency of the wheels of a train going over a section of rail is about 3 Hz. Tests previously run at AAR were conducted at a low frequency (6 Hz) to approximate service conditions. Because of time limitations, however, the current tests were conducted at higher frequencies. The effect of frequency on strain was therefore examined.

The curves produced by progressive cyclic loading of hot-rolled carbon steel rail at 6, 12, and 18 Hz and at 827 MPa [120 000 lbf/in² (120 kips/in²)] are shown in Figure 7. From these curves, it was concluded that there was no significant frequency effect and the tests could be run at 18 Hz. This result was not unexpected. In this range, steels generally do not show a frequency effect. If the magnitude of the strain range were great,

Figure 7. Effect of frequency on compressive cyclic softening of rail steel.

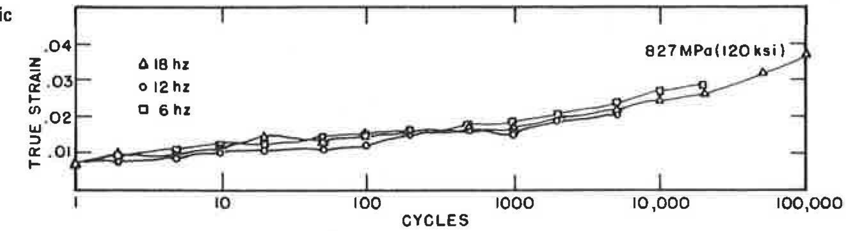
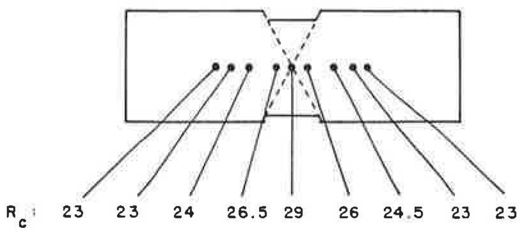


Figure 8. Schematic of hardness traverse (values in Rockwell C hardness numbers) across deformed region of standard rail steel specimen [σ = 1102 MPa (140 000 lbf/in^2)].



or if the tests were run in an aggressive environment, a frequency effect could be expected.

Extent of Deformation

Because more than one region of each sample was used for tests, it was desired to determine how much material on either side of a deformation region was affected. A hardness traverse was therefore made across the deformed area of a specimen (see Figure 8). The results showed that the hardening effect was well confined directly under the dies.

RESULTS AND DISCUSSION

Simple Loading

The results for the hot-rolled carbon steel rail are shown in Figure 9. At all stress levels, strain increased as the number of cycles increased, which indicated that the steel was softening. As the stress level increased, so did the rate of softening and the total amount of softening.

It appears that, at 896 MPa (130 000 lbf/in^2) or less, the softening behavior would eventually stabilize if the cycling were continued beyond 100 000 cycles. However, above 896 MPa, the metal appeared to soften continuously. Cycling at the higher stresses was not continued to 100 000 because the sample thickness had been reduced 10 percent and cracks were forming. It was presumed that those samples would fail before the softening stabilized.

The other steel types also showed increased softening with increasing stress (see Figures 10 and 11). Note, however, that the effect is less severe for the heat-treated rail and the softening effect is even more damped for the pearlitic CrMo steel.

The increasing deformation resistance is probably partly a function of the increasing hardness and yield strength of the steels. However, the heat-treated carbon steel had slightly greater hardness and yield strength than the pearlitic CrMo steel but exhibited worse deformation behavior. Therefore, other factors must be considered in the deformation behavior. The alloying additions in the CrMo steels might increase deformation resistance by inhibiting dislocation movements.

Split Loading

The results of the split-loading tests are less clear than those for simple loading. In the case of the hot-rolled carbon steel, preloading at a lower stress caused an increase in the softening rate at the higher stress (see Figure 12). For the heat-treated rail (see Figure 13), preloading improved the deformation resistance at 100 and 10 000 cycles and decreased deformation resistance when the load was increased after 1000 cycles. Preloading the pearlitic CrMo steel improved its deformation resistance at the higher stress (see Figure 14).

The reasons for the variable effects of preloading on the different steels are not clear. Preloading of the plain carbon steel may promote dislocation movement in the pearlite, whereas the alloying additions in the other steels may inhibit dislocation movement and thus improve deformation resistance at the higher loads. The heat-treated rail, at 1000 cycles, must reach some critical dislocation arrangement that promotes the increased softening behavior. Further study is under way to explain this behavior more fully.

Microstructure of Deformed Specimens

The microstructure of a deformed specimen 0.5 mm (0.02 in) below the surface is shown to be comparable to that of service-deformed rail steel (see Figure 15).

Prediction of Plastic Flow

Deformation as a function of stress, number of cycles, and microstructure can be calculated by a modified form of an equation developed by Langford (8) for deformation caused by cold rolling. Langford's equation for axisymmetric compression of pearlite is

$$\sigma = \sigma_0 + (k/\sqrt{2d}) \exp(\epsilon_p/2) \tag{5}$$

where

σ = compressive stress,
σ_0 = friction stress (76.4 MPa),
k = Hall Petch constant (0.5 to 0.68 MN/m$^{3/2}$),
d = pearlite spacing, and
ϵ_p = plane strain.

Rearranging terms,

$$\epsilon_p = 2\left\{\ln\left[(\sqrt{2d}/k)(\sigma - \sigma_0)\right]\right\} \tag{6}$$

and, from Equation 4,

$$\epsilon_t = (4/\sqrt{3})\left\{\ln\left[(\sqrt{2d}/k)(\sigma - \sigma_0)\right]\right\} \tag{7}$$

Figures 9-14 show that ϵ_t is made up of the strain after one cycle ϵ_1 and the cyclic strain ϵ_c if more than one cycle is considered. In addition, each increment of ϵ_c is accompanied by the log of a cycle of stress. Therefore, for more than one cycle of stress, Equation 7 can be modified as follows to fit the curves presented:

Figure 9. Cyclic deformation behavior of standard hot-rolled plain carbon rail steel.

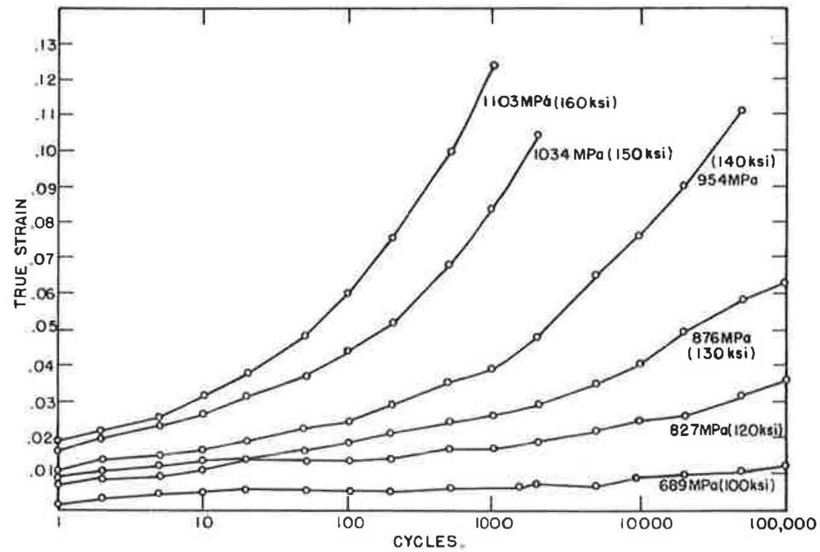


Figure 10. Cyclic deformation behavior of fully heat-treated plain carbon rail steel.

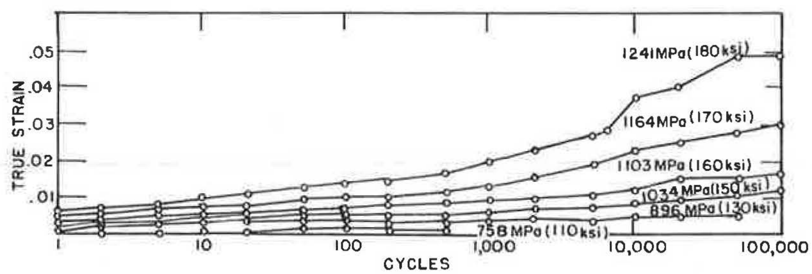


Figure 11. Cyclic deformation behavior of pearlitic CrMo rail steel.

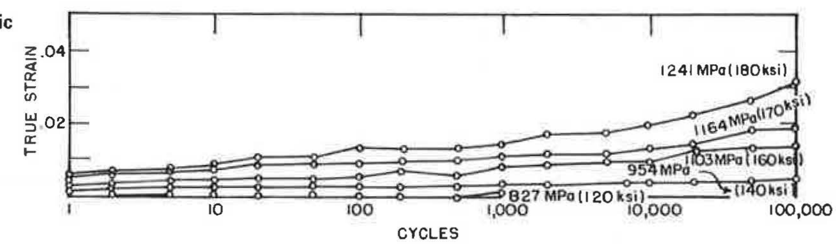


Figure 12. Effect of split loading on deformation resistance of standard carbon rail steel.

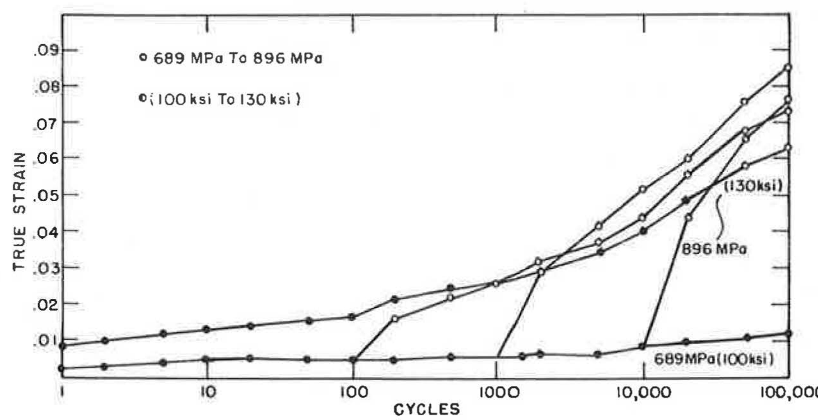


Figure 13. Effect of split loading on deformation resistance of heat-treated carbon rail steel.

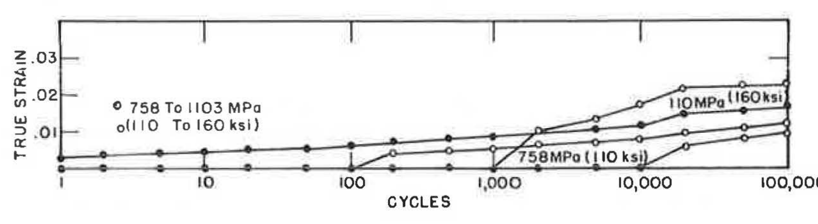


Figure 14. Effect of split loading on deformation resistance of pearlitic CrMo rail steel.

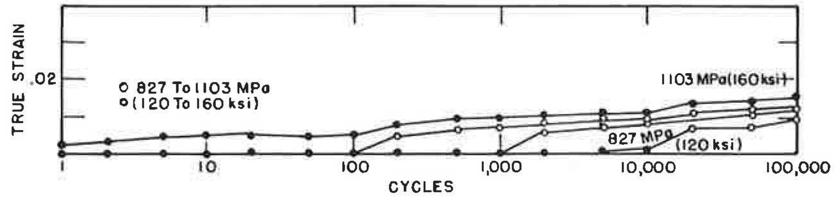
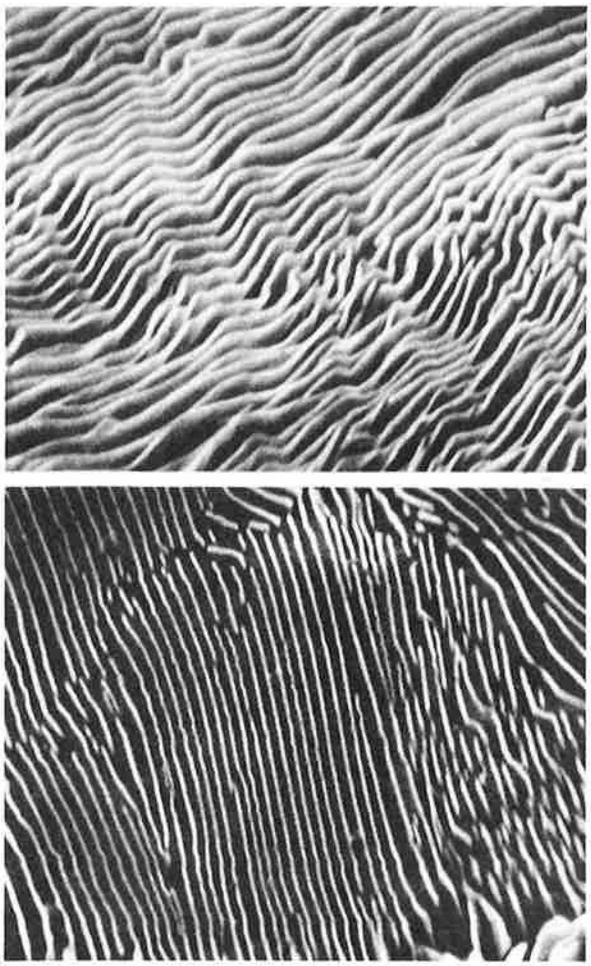


Figure 15. Microstructure of standard rail steel specimen 0.5 mm (0.02 in) below deformed surface (4900X etched in Nital).



$$\epsilon_c + \epsilon_i = (4/\sqrt{3})\, A \ln N \left\{ \ln \left[(\sqrt{2d}/k)(\sigma - \sigma_0) \right] \right\} \quad (8)$$

Evaluation of the curve, for 689 MPa (100 000 lbf/in^2) in Figure 9, gives a mean value of 0.17 MN/m (11 680 lbf/ft) for A, and Equation 8 reduces to

$$\epsilon_c - \epsilon_i = 4.27 \times 10^{-3} \ln N \left\{ \ln \left[(\sqrt{2d}/k)(\sigma - \sigma_0) \right] \right\} \quad (9)$$

A set of experiments was performed by Code (9) in which brass pins were inserted in railheads that were then placed in service. The rails were removed after varying amounts of traffic load and were sectioned, and the deformation of the pins was measured. For two pins, after 68 million gross Mg (75 million gross tons) of traffic, the average true strain can be calculated from Code's data as 0.023 and 0.017. In 1951, the average freight carload was 38 t (42 tons); adding 28 tons for the empty car weight gives a gross load of 63 Mg/car (70 tons/car). This provides an estimate of 4.3 million cycles for the duration of Code's test (number of cars times four axles). Substituting this value into Equation 9 gives a strain of 0.016. This value is in close agreement with the values measured in the field, which run from a maximum of 0.046 at the surface to 0 at a distance of 8 mm (0.34 in) below the surface.

CONCLUSIONS

1. When cycled in plane strain compression, plain carbon steels, heat-treated steels, and CrMo steels exhibit softening. The rate and the amount of softening increase with increasing stress.
2. Deformation resistance increases with increasing hardness and yield strength of the steel.
3. The behavior of steels under split loading varies depending on steel type. The reason for the difference is not clear.
4. The wavy pearlite microstructure developed in rails during service is duplicated in laboratory specimens.
5. The average flow in rails can be predicted if stress, microstructure, and number of cycles are known.

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