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Research Results

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Fracture and Fatigue Damage Tolerance of Bainitic and Pearlitic Rail Steels

SUMMARY

The Federal Railroad Administration sponsored a research project to investigate the fracture and fatigue damage tolerance of baintic steels. Low carbon baintic steel shows promising potential, especially in critical components such as frogs and switches. The study examined the microstructure – fracture and fatigue damage tolerance relationships of bainitic rail steel in comparison with pearlitic rail steel. It was found that the bainitic microstructure consists of a mixture of tempered martensite and ferrite associated with intralath carbides. The pearlitic microstructure consists of fine lamellar aggregate of very soft and ductile ferrite and very hard carbide. The J6 bainitic steel studied in the present work has ultimate strength, yield strength and elongation to failure of about 1500MPa, 1100MPa and 13% respectively. These values are higher than those for pearlitic steel as shown in Figure 1. The bainitic steel exhibits a higher rate of crack deceleration in the second stage, as indicated by the lower slope of the fatigue crack propagation kinetics curve in comparison with the pearlitic steel. This attests to the superior fatigue damage tolerance of the bainitic rail steel and provides evidence to support the superior rolling fatigue damage tolerance of the bainitic rail steel reported in the literature.

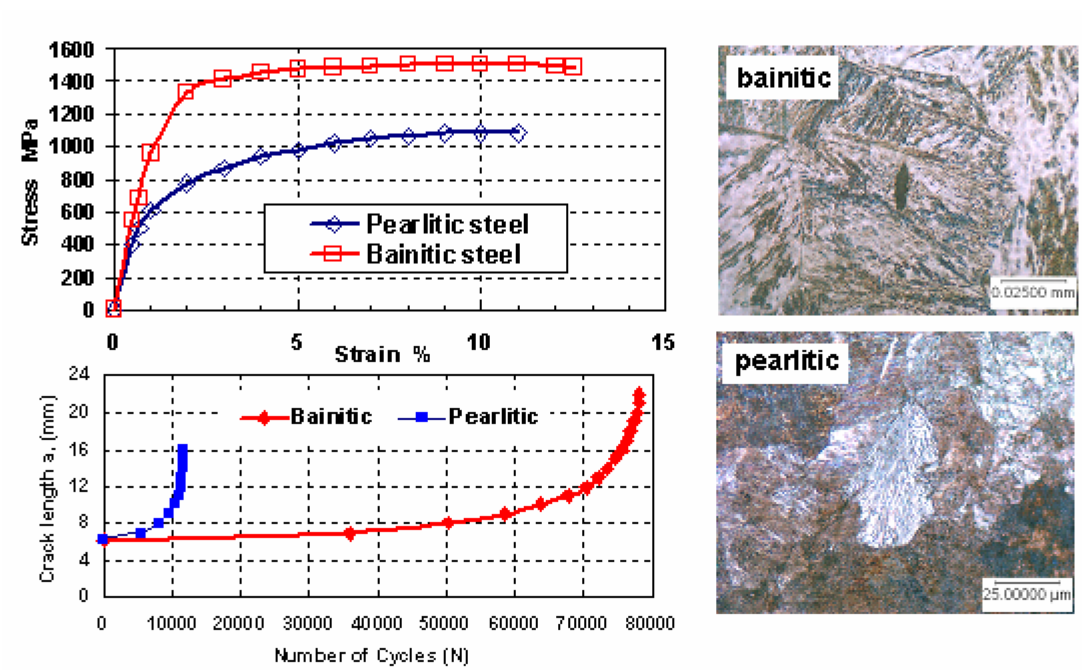

Figure 1. Microstructure - Mechanical properties and fatigue relationships of Bainitic and pearlitic rail steels.

BACKGROUND

Pearlitic steels obtain their strength from the fine grains of pearlite. However, there is a limit in the production of very fine grains in manufacturing and post-heat treatment processes. In contrast, bainitic steels derive their strength from ultra-fine structure with many dislocations that are harmless and confer high strength *(1)*. The microstructure of bainitic steel is a metastable aggregate of ferrite and cementite produced from the transformation of austenite at temperatures below the pearlite range and above the martensite starting temperature. Failure analysis of rails has demonstrated that fatigue crack propagation and fracture is one of the major reasons of broken rail derailment and other severe accidents. For example, Orringer et al. *(2)* studied the fatigue crack propagation life of detail fracture in rails. Glowacki and Kuziak *(3)* have investigated the effect of coupled thermal-mechanical processes on the evolution of microstructure in rails. Fracture toughness and fatigue strength have been applied as criteria for characterizing the fatigue damage resistance of railway rails *(4)*. The limitations of fracture toughness and fatigue strength criteria are obvious due to the diversified composition of rails and the complicated live bending stress, shear stress and residual stress conditions.

The microstructure-properties relationships, plane strain fracture toughness, and fatigue crack growth of a J6 bainitic and a premium pearlitic rail steel were studied to gain fundamental understanding of the underlying mechanisms between these performance-related properties and the microstructure of the materials.

REPRESENTIVE RESULTS

Fracture Toughness Evaluation

The general expression of the plane strain fracture toughness for a compact tension specimen used to compare the two rail steels is:

$$K_1 = \frac{P}{B\sqrt{W}} f(\frac{a}{W}) \quad (1)$$

Where P is the load, B is the thickness, W is the distance from the center of the loading holes to the edge of the specimen, *a* is the total crack length (initial plus fatigue pre-crack) and f (a/W) is a geometrical correction factor. The geometrical correction factor, f(a/W), in Equation (1) can be expressed as:

$$f(\frac{a}{W}) = \frac{(2+(\frac{a}{W}))[0.886+4.64(\frac{a}{W})-13.32(\frac{a}{W})^2+14.72(\frac{a}{W})^3-5.6(\frac{a}{W})^4]}{(1-(\frac{a}{W}))^{3/2}} \quad (2)$$

The bainitic steel demonstrated elastic behavior and cleavage fracture; therefore ASTM Standard E 399 was used for the analysis. The data for all three samples tested along with their calculated values of K_{Ic} based on Equation (1) are presented in Table 1.

Table 1. Compact tension specimen geometry and test results for bainitic and pearlitic steels

Sample	a (mm)	f(a/W)	P_m (kN)	B (mm)	K_{Ic} MPa $\sqrt{m}$
Bainitic Rail Steel					
#1	**11.89**	**10.66**	**6.6**	**9.14**	**51.43**
#2	**12.39**	**11.48**	**6.3**	**9.14**	**52.87**
#3	**12.29**	**11.13**	**6.4**	**9.14**	**51.44**
				Average value of K_{Ic}	**52**
Pearlitic Rail Steel					
#1	**12.09**	**10.98**	**5.7**	**9.14**	**45.75**
#2	**12.19**	**11.25**	**4.7**	**9.14**	**38.74**
#3	**12.19**	**11.85**	**4.3**	**9.14**	**37.25**
				Average value of K_{Ic}	**41**
W = 22.4 mm. a = total crack length P_m = maximum load P_q = load at which K_q is calculated B = thickness K_q = stress intensity factor calculated from Equation 1 K_{Ic} = mode I fracture toughness					

In order to validate the calculated value of K as a true K_{Ic} fracture toughness, the following conditions must be met:

$$a \text{ and } B \geq 2.5\,(K_Q/\sigma_y)^2 \quad (3)$$

$$P_{max}/P_Q < 1.1 \quad (4)$$

For the bainitic steel, the value of 2.5 $(K_Q/\sigma_y)^2$ = 2.5 $(52/1100)^2$ *1000 = 2.24 mm. This value is less than B, which is 9.14 mm and less than *a,* which is about 12 mm; therefore the condition of Equation 3 is met. In addition P_{max} equals P_Q so the condition of Equation 4 is met. Therefore these fracture tests for the bainitic steel yield a valid value of K_{Ic} according to ASTM E399. The average value of K_{Ic} for the bainitic steel was found to be 52 MPa √m.

The pearlitic steel also demonstrated elastic behavior and cleavage fracture. Similarly ASTM Standard E 399 was used for the analysis of the plane strain fracture toughness, K_{Ic}. The data for all three premium pearlitic steel samples tested along with their calculated values of $K_{Ic,}$ based on Equation 1, are also presented in Table 1. For the pearlitic steel, the value of 2.5 $(K_Q/\sigma_y)^2$ = 2.5 $(41/700)^2$ *1000 = 8.6 mm. This value is less than B, which is 9.14 mm, and less than *a* which is about 12 mm, therefore the condition of Equation 3 is met. In addition P_{max} equals $P_{Q,}$ so the condition of Equation 4 is met. Therefore these fracture tests for the pearlitic steel yield a valid value of K_{Ic} according to ASTM E399. The average value of K_{Ic} was found to be 41 MPa √m for the premium pearlitic steel.

Based on the plane strain fracture toughness analysis using compact tension specimens, the fracture toughness of the bainitic steel was found to be about 27% higher than that of the premium pearlitic steel.

Fatigue Crack Growth Analysis

The average crack length, *a*, versus the number of cycles, N, for both bainitic and pearlitic rail steel is shown in Figure 1. It can be seen from Figure 1 that the total fatigue lifetime of the bainitic steel is much higher than that of the pearlitic steel. This is based on the average of three macroscopically identical specimens from each material. The total average fatigue lifetime for the bainitic steel is about 78,000 cycles, while that for pearlitic is about 11,000. It is also shown that both initiation lifetime and propagation lifetime for the bainitic steel is higher than that for the pearlitic. The slopes of the curves in Figure 1 are taken as the average crack speed at each crack length.

Energy Release Rate

The potential energy, P, was calculated from the hysteresis loops recorded at intervals of number of cycles. It is the area above the unloading curve at each crack length. On this basis, the relationship between the potential energy and the fatigue crack length, *a*, was established. The energy release rate J* was evaluated from the potential energy curve based on the following equation:

$$J^* = \frac{1}{B}\frac{\partial P}{\partial a} \quad \text{............... (5)}$$

Where P is the potential energy, *a* is the crack length and B is the specimen thickness. Figure 2 illustrates the average energy release rate, J*, as a function of the crack length, *a*, for the bainitic and pearlitic rail steels. The value of J* increases with the increase of the crack length, *a*. The critical value of J* for the bainitic steel is about 40 kJ/m^2, while that for the pearlitic steel is about 13 kJ/m^2. This is the point where the onset of rapid crack growth is observed. The ratio between the critical crack length, $a_{c,}$ and specimen width ($\frac{a_c}{W}$) is higher for bainitic steel than that for pearlitic steel. The value of $\frac{a_c}{W}$ is 0.8 and 0.63 for bainitic and pearlitic steels respectively.

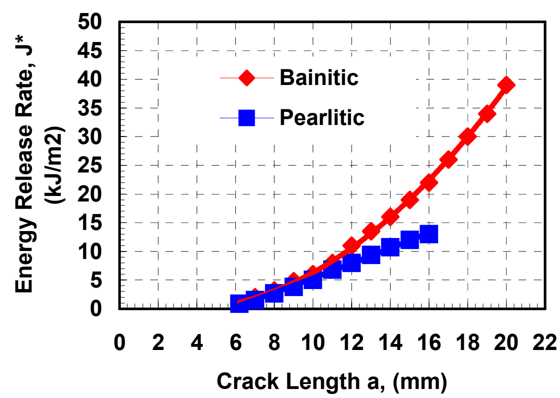

Figure 2: Energy release rate, J*, versus the fatigue crack length, a.

Fatigue Crack Growth Kinetics

The crack speed versus the energy release rate J* for both the bainitic and pearlitic rail steel are shown in Figure 3. The crack deceleration in the case of the bainitic steel started after a J* value of about 10 kJ/m^2. This is indicative of material damage ahead of the crack tip. It can also be seen from Figure 4 that the first stage, or initiation stage, of fatigue crack propagation (FCP) kinetics is well developed in the bainitic steel, while that for the pearlitic is less pronounced. Under the same J*, the crack growth rate of pearlitic steel is higher than that of bainitic steel, which means that bainitic rail steel has higher resistance to FCP.

In order to analyze the fatigue crack growth behavior of the two materials the Paris Law was used, as defined in the following equation:

$$\log\left(\frac{da}{dN}\right) = \log A + m\log(J^*) \qquad (6)$$

In this equation, da/dN is the crack speed and J* is the energy release rate, both obtained from Figure 3. The empirical constants, *A* and *m* are parameters that depend on the material properties, obtained from Figure 3. The average values of A and m for the bainitic steel are 1.0 x 10^{-8} and 1.13 respectively, while those for the premium pearlitic steel are 3.04 x 10^{-12} and 5.44. The influence of the value of m in the above equation is much greater than the influence of the constant A due to its role as an exponent rather than as a multiplicative factor. The lower value of m reflects the considerably lower crack speeds at the same value of J* for the bainitic steel, even with the much higher value of A.

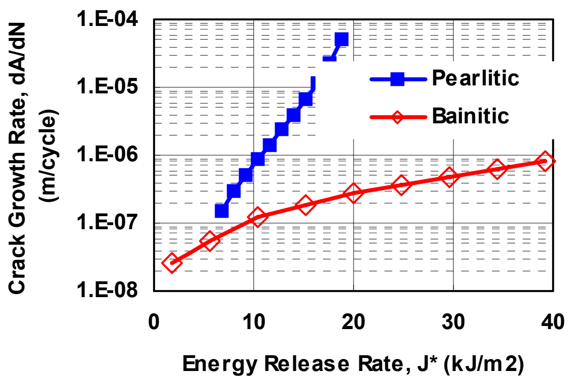

Figure 3 Crack growth rate, da/dN, versus energy release rate, J*.

CONCLUSIONS

Fracture toughness evaluation was conducted on bainitic and pearlitic rail steels using (½ T) compact tension specimens according to ASTM standard E399. It was found that the average K_{Ic} for the bainitic rail steel is 52 MPa √m, while that of the premium pearlitic steel is 41 MPa √m.

It was also found that the crack speed for the bainitic steel is lower than that for the pearlitic steel over the entire range of the energy release rate. The bainitic steel exhibits a higher rate of crack deceleration in the second stage, as indicated by the lower slope of the FCP curve in comparison with the pearlitic steel. This indicates the superior resistance of bainitic rail steel to FCP, i.e. higher fatigue damage tolerance. Also, ductile tearing and extensive ridge formation are associated with the stable crack propagation region of the bainitic steel. Pulled-up pearlite lamella, limited microcracks and micro-void coalescence can be found in the pearlitic steel. In general, the more ductile features of the bainitic steel reflect the crack deceleration and indicate a considerably high energy consuming process giving it its superior fracture and fatigue damage tolerance.

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