INFLUENCE OF STRESS RELIEVING AND STRAIGHTENING ON THE FATIGUE AND TOUGHNESS BEHAVIOUR OF RAILS

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ABSTRACT

The straightness of rails and their fatigue and toughness behaviour are a central concern for railroads. But straightness and "in service" behaviour are two conflicting characteristics of a rail, as a result of the internal stresses generally induced by straightening. This paper analyses the effect of different straightening processes on the fatigue and toughness behaviour of rails, using both standard specimens and rail coupons.

INTRODUCTION

The straightness of rails and their fatigue bahaviour have an important influence on track maintenance cost. Demands for improved straightness led to installation of new roller-straightener facilities. This led to problems with residual stresses, as the low-level internal stresses coming from the cooling bed were turned into high-level stresses coming from the roller straightener which could impair fatigue and fracture behaviour.

In fact, the pattern of heterogeneous plastic strains, wich makes rail straightening possible, is well know to develop high longitudinal internal stresses. These stresses are distributed in a particularly harmful way since the tensile stresses occur on the surface of the running table and in the center line of the base, the web being in compression. Railroads are very concerned with tensile residual stresses in the head because they add to the service stresses. They are very concerned, also, with tensile internal stresses located under the base which are considered as potentially damaging for heavy-haul tracks.

To avoid these problems, a new rail straightening means, the stretch-straightening process, has been developed (DEROCHE and others, 1982). This paper deals with the evaluation of the residual stress fields developed during straightening and the influence of different procedures on the fatigue and the relative toughness of the rails.

EXPERIMENTAL METHODS AND RESULTS

1 - Steel grades

Two grades of rail steel have been studied :

- UIC 60 90B grade
- 136 RE alloyed rail.

The mechanical properties are given in Table 1.

Rail type	σ_Y	UTS	Elongation	Reduction in area
	(MPa)		(%)	
UIC 60 136 E	485 695	940 1145	14,5	23

TABLE 1 - Mechanical properties of the rail steels.

2 - Evaluation of residual stress fields

Residual stess measurements have been made on rail surfaces by mean of the hole drilling method. Figures 1 and 2 show the longitudinal stresses obtained for the two rail types. In these figures the lower level of residual stresses induced by stretch-straightening, especially in the head and in the base, is shown clearly. Table 2 gives the levels of the residual stresses in the head and the base surface.

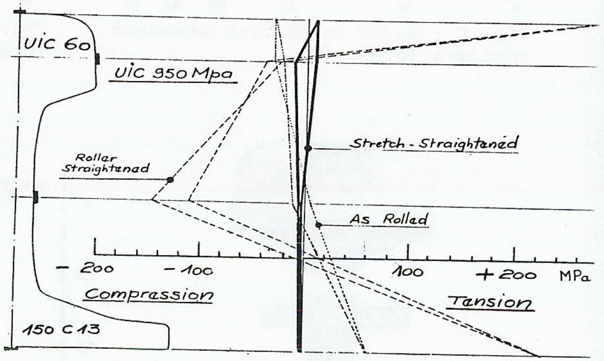


Fig. 1 : Comparative results of stresses in a UIC/950 MPa grade (hole method).

The transverse stresses were small (less than 40 MPa) for both processes.

3 - Fatigue behaviour

A four point fatigue bending test has been developed, comprising repeated bending (R = 0,1) of a rail specimen (1.40 meter long) prenotched in the head. Fatigue crack propagation is followed by means of a strain gauge extensometer and a potential drop method (MARANDET and others, 1978). Markings are made on the crack surface by changing the stresses amplitude. Crack depth "a" is measured as a function of number of cycles "N".

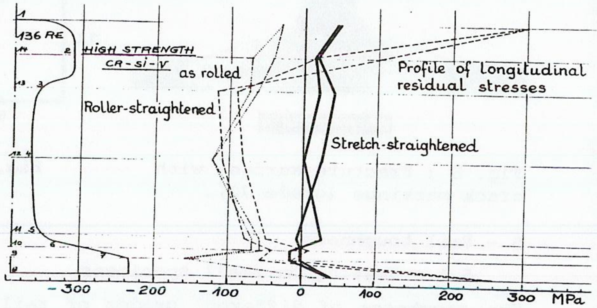


Fig. 2 - Comparative results of longitudinal residual stresses in a 136 RE alloyed premium rail.

	As rolled		Roller-Straightened		Stretch-straightened	
	UIC 60	136 RE	UNIC 60	136 RE	UIC 60	136 RE
Head (running table)	+ 37	- 30	+ 282	+ 300	+ 10	+ 45
Base (center)	+ 61	+ 20	+ 225	+ 260	0	+ 40

TABLE 2 - Longitudinal residual stresses (MPa).

This test was performed using the two rail steels mentioned above (figures 3, 4). For the same loading conditions, the roller-straightened rail, of UIC 60-90B grade (figure 3) displays a rather short fatigue crack area which is ponctuated by brittle pops, while the strech-straightened rail shows a wider pure fatigue area coming off far from the running table radii.

The ratio

$$\frac{\text{fatigue area (stretch)}}{\text{fatigue area (roller)}} = 1.55$$

For 136 RE grade, figure 4 shows that the stretching process again enhances fatigue properties.

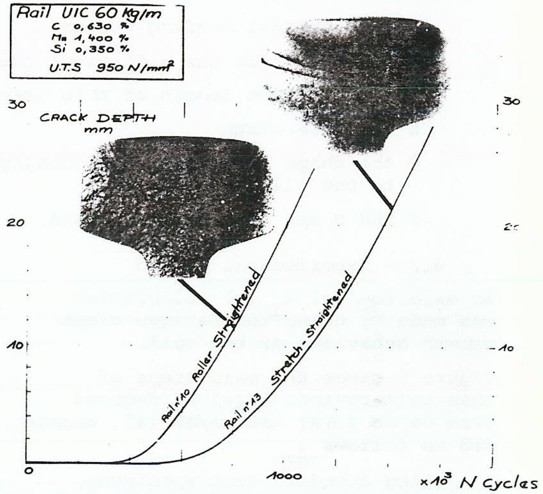


Fig. 3 : Comparison of crack initiation and propagation (UIC 60/rail 950 MPa grade)

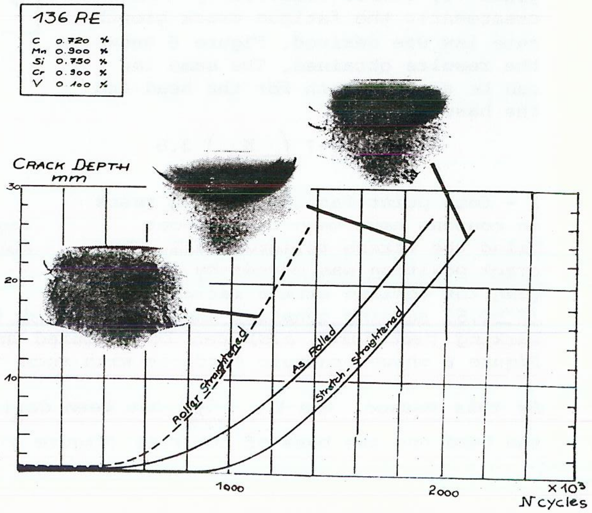


Fig. 4 : Comparison of crack initiation and propagation (136 RE alloyed premium rail)

4 - K-calibration

Two methods have been used to determine K_I (a) in the head and in the base of the rail, one analytical, and the other experimental.

4.1 - Analytical method

In the case of the rail base, the following equation developed by NEWMAN and RAJU (1978) was applied :

$$K_I = (\sigma_t + H\ \sigma_b) \cdot \frac{\pi . a}{Q} \cdot F\ (\frac{a}{c}, \frac{a}{t}, \frac{c}{b})$$

where σ_t is the nominal tensile stress

σ_b the nominal bending stress

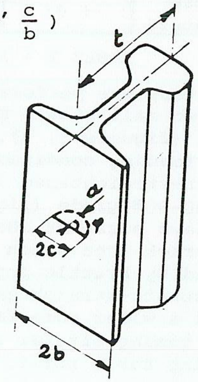
a the depth of the elliptical crack

2c the surface length of this crack

b the base width

Q the shape function corresponding to the elliptical crack

F and H are boundary functions.



4.2 - Experimental method

An experimental K_I (a) calibration was made by using the fatigue crack growth behaviour of the rail.

Figure 5 gives the main steps of this calibration. ΔK(a) is deduced from da/dN (ΔK) and da/dN (a), measured as follows :

1 - using standard test specimens, machined out of the head or the base of a stress relieved rail (UIC 60 grade 70, stress relieved by heat treatment), the fatigue crack growth rate law was derived. Figure 6 shows the results obtained. The same law can be adopted both for the head and the base :

$$\frac{da}{dN} = 10^{-7} \left(\frac{K}{25.8}\right)^{3.8}$$

2 - four point fatigue bending tests on coupons have been carried out using the stress relieved rail. The crack position was marked by changing the applied stress ratio, ($R \simeq 0,5$) keeping constant the maximum load (HUSSET and others, 1980). By this marking procedure, a(N) can be measured and da/dN (a) deduced (figure 7). Figure 8 shows fracture surfaces with such "beach markings".

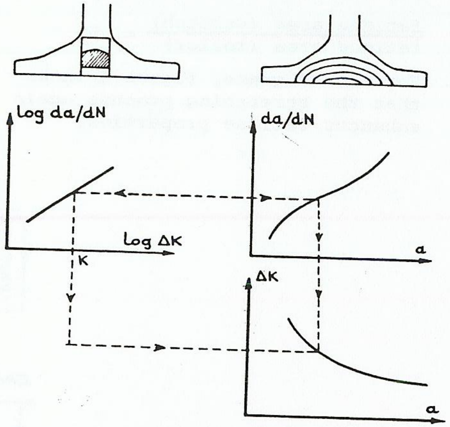


Fig. 5 : Procedure to derive ΔK (a) for the rail base

By this method, the $Y = (\frac{K}{\sigma\sqrt{a}})$ has been derived as a function of "a" for both the head and the base of the rail (figure 9).

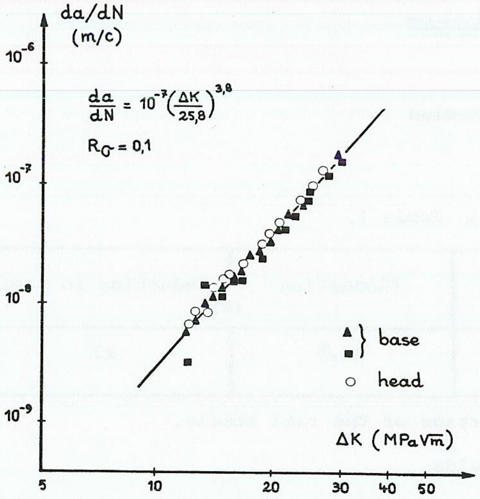


Fig. 6 : da/dN vs ΔK from standard specimen (grade 70)

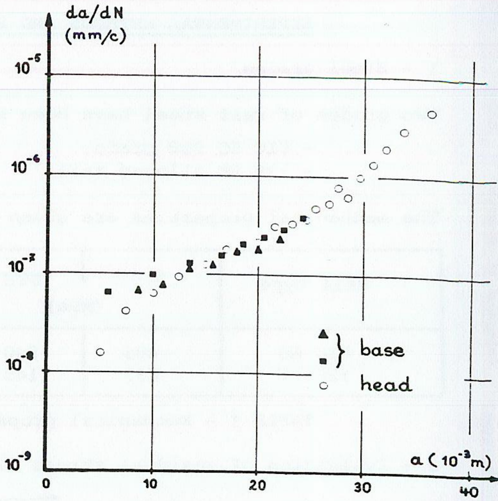


Fig. 7 : da/dN vs a in rail coupons (grade 70).

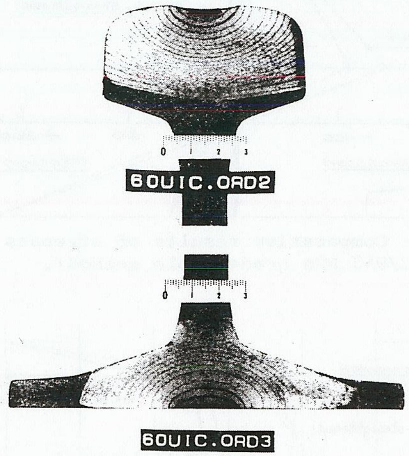


Fig. 8 : Fracture surface with crack markings (grade 70).

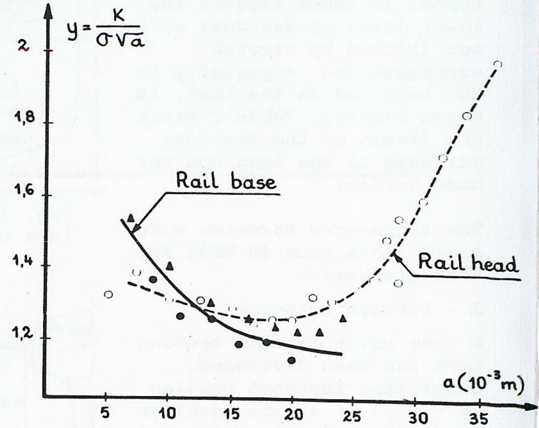


Fig. 9 : $Y \frac{K}{\sigma\sqrt{a}}$ vs a (grade 70).

5 - Rail toughness

5.1 - Testing on small specimens

The toughness of different grades of rail steel (UIC 60 : 70, 90A and 90B) has been evaluated using standard bend specimens machined out of the base of rail coupons. The K_{Ic} values are given in table 3.

Grade	Straightening	a_c (mm)	a/2c	σ_R (MPa)	K_{Ic} (1) (MPa $\sqrt{m}$)	K_Q	
						(2) (MPa $\sqrt{m}$)	(3) (MPa $\sqrt{m}$)
70	roller-	27.5	0.37	170	62.4	66	(76)
90A	roller-	5.9	0.24	152	44	41.6	43
90B	roller-	3.7	0.21	230	43.5	42.4	44
90-DG	roller-	8.5	0.37	165	45.6	43 } 42	48 } 46,6
90-ND	as rolled	18.6	0.43	115		44	49
90-DT	Stretch-	23	0.41	40		39	43

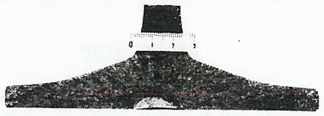
(1) from standard specimen
(2) from NEWMAN-RAJU (1982)
(3) Using calibration function Y (figure 9)

TABLE 3 - Critical crack depth to failure and toughness of the rail

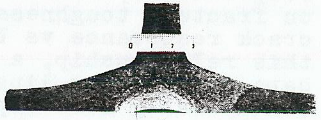
5.2 - Testing on rail coupons

Four point bending fatigue tests have been carried out on coupons (cf § 3). During the fatigue test, the maximum stress, σ_{max} = 200 MPa (R=0.1), was applied to coupons prenotched in the base. The critical dept to failure, a_c, was measured (figure 10). For this loading condition, a_c varies from 3.7 to 27.5 mm, depending on the steel grade (or toughness) and the straightening procedure (or residual stress gradient).

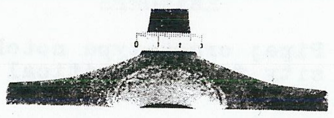
In addition, the longitudinal residual stress, σ_R, was measured on the base surface. Results are summarized in table 3. They show a rather good behaviour of the 90 DT coupons (stretch-straightened) corresponding to a_c = 23 mm and σ_R = 41 MPa in comparison with the 90 DG coupons (roller-straightened) corresponding to a_c = 8.5 mm and σ_R = 165 MPa. Also included are calculations of toughness, to be described below.



a) Roller straightened.



b) as rolled.



c) Stretch straightened.

Fig. 10 : Fracture surface depending on straightenin (grade 90).

The evolution of a/2c as a function of a is shown in figure 11. The results show some scatter but this scatter can also exist for the same rail grade (see 70D, stress relieved rail). Therefore we can consider that the residual stress field does not largely influence the shape of the semi-elliptical crack in the rail base.

In table 3, the K_{Ic} and K_Q values have been reported, where K_{Ic} is the toughness obtained on a standard specimen and K_Q the rail toughness derived using either equation (1), or the experimental calibration function Y (figure 9). In both cases the stress was calculated as the nominal bending stress, given by :

$$\sigma_b = \sigma_{max} + \sigma_R \qquad (3)$$

For the coupons tested, the difference between K_{Ic} and K_Q is less than 10%. The K_Q values calculated by either equation (1) or the function Y are very similar. Therefore, using (3) it becomes possible to explain the influence of the straightening procedure on the "in service" apparent toughness of a rail.

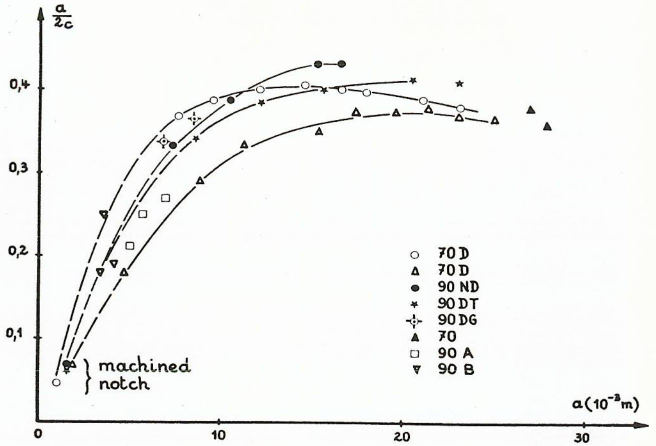


Fig. 11 : a/2c vs a for different steel grade grades and processes.

CONCLUSION

Increasing need both for accurate geometry and for improved properties of rail-either for high speed trains or heavy hauled railroads- has led to study of the influence of the straightening process used on the toughness and fatigue behaviour of rails.

The strong variation of the "in-service" apparent toughness of rails, has been explained, as a result of the residual stress field induced by the straightening, by using a calibration function $Y = \frac{K}{\sigma\sqrt{a}}$ derived experimentally and theoretically.

Stretch-straightening seems to be an attractive process, combining good straightness with very low residual stress levels, two requirements previously in conflict. This process increases the critical (failure) defect size and increases the fatigue life both in crack initiation and crack propagation stages.

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