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A re-examination of rolling contact fatigue experiments by Clayton and Su with suggestions for surface durability calculations

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Abstract

A re-interpretation of recent RCF experiments by Clayton and Su (C&S) [Wear 200 (1996) 63] under water lubricated rolling/sliding conditions, with careful measurements of ratchetting strains, and their comparisons with experimentally observed lives, seems to confirm the validity of ratchetting failure (RF) mechanism and Kapoor's "critical ratchet strain" as a material property. However, the complexity of modelling the ratchetting phenomenon and the uncertainties on the material's critical ratchet strain, suggests that perhaps a more realistic alternative is the use of empirical Wöhler-like life curves similarly to currently used for the contact fatigue evaluation in gears design and standards. In particular, it is found that the "pitting" fatigue limit at 10^7 cycles suggested by the gears standard is reasonably accurate also for the C&S experiments on various typical rail steels. Since the gears life factor suggested for gears turns out quite conservative at shorter lives, it seems a single new life factor could be suggested, at least for all pearlitic and bainitic steels tested by C&S under water lubrication.

Keywords: Rolling contact fatigue; Railways; Structural integrity

1. Introduction

The development of rail materials has slowly progressed, in parallel and perhaps separately from the improvements in the understanding of wear and fatigue occurring in the rail-wheel contact. Indeed, despite the critical nature of the components involved, there is lack of extensive prototypical testing with respect to, for example, car manufacturing and aeronautical industries where ultimately fatigue testing in service is conducted on a large number of vehicles [2]. The typical pearlitic rail steel has a high carbon content (0.5%), and progress has concentrated on lowering the level of phosphorus and other impurities at a reasonable cost. For switch and other crossing components under more severe operational conditions, Hadfield's manganese steel has become the standard proving high strength but has the drawback of low weldability. For this purpose, research continues to explore various alternatives, and particularly lower carbon bainitic steels.

Several experimental findings suggest that the shear strain ratchetting failure (RF) mechanism dominates wear and rolling contact fatigue (RCF) processes. Merwin [3] and Merwin and Johnson [4], see also Johnson's book [5], firstly showed the mechanics of shakedown and excess of shakedown in rolling contact. With a simple elastic-perfectly plastic material model, the shakedown limit in a plane contact for frictionless contact corresponds to $p_0/k_0 = 4$. For higher loads, Merwin solved the plasticity problem with a simplified approximate method; however, later refined FEM analysis [6] found much higher ratchet rates than Merwin's, which were also corrected by an improved elastic-perfectly plastic solution [7]. In a recent paper [8], another aspect of Merwin's experimental results was noticed, i.e. that in reporting his ratchetting results, he had used a yield limit corresponding to nearly 1% of plastic deformation in the monotonic curve for Dural and for his steel, but to *a much higher deformation* (25%!) for copper. Therefore, clearly the effect of cyclic hardening had been guessed by an educated "a posteriori" choice of the yield limit, in order to match (at least, approximately) the observed beginning of ratchetting with the nominal shakedown limit, $p_0/k_0 = 4$. However, even with an adapted yield limit, it is clear that the perfectly plastic prediction seems to largely over-predict the ratchet rate. This may appear quite obvious as the model is a crude simplification of the real behaviour of material, but unfortunately models of significant increased complexity do not lead to much better results. Indeed, the Armstrong

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Nomenclature

HB	Brinell hardness number
k_0	yield stress
N_f	number of cycles to failure
p_0	peak Hertzian pressure

Greek letters

γ	ratchetting shear strains
γ_c	critical ratchetting shear strain (ratchetting ductility)

and Frederick non-linear kinematic hardening as that used by Bower and Johnson [9] is the simplest model needed and was shown to correlate with some success copper ratchetting measured in biaxial tests with those of RCF tests. A lot more difficult appeared the following of the ratchet rate decay in rail steel, despite a modified non-linear kinematic term in the model. The disagreement was attributed partly to earlier fatigue failure in biaxial tests, with respect to RCF tests, but it is unclear how elaborate would a plasticity model need to be to predict sufficiently well the plastic process from the first hundreds of cycles to millions of cycles. It would be possible to fit the constitutive constants directly on the RCF tests to escape the problem of early failure in biaxial tests, trying to find the dependence on few material constants (material ratchetting constants) instead of the purely empirical fitting of measured ratchetting strain as done by [1].

Given it will be shown in this paper that failure (initiation) occurs when a "critical" amount of ratchet strain is reached (ratchetting ductility), then resistance to RCF would be dependent on the combined effect of material ratchetting constants and ductility. It would then be possible to explore how to decrease ratchetting rates or increase ductility. However, this seems very remote at present, and at the same time single constants such as hardness or yield limit, will be shown to characterise the RCF fatigue behaviour well enough. Indeed, as in the corresponding problem of wear (which is suspected to depend on ratchetting strains as well), "wear maps" and Archard's law are currently used as an essentially empirical approach, the corresponding RCF problem can be treated with an empirical Wöhler curve ($p_0^m N_f$ = const), and interpolating between static failure and an appropriately defined fatigue limit, as suggested for gears design [10,11]. After all, in fatigue in general many underlying mechanisms are not always clear, or are very different from one material to another, and it is not surprising if an engineering approach to RCF, which contains various unusual and challenging features, such as open multiaxial and non-proportional cycles of stress–strains, as well as severe stress concentrations, is the only realistic alternative. In fact, the empirical Wöhler curve approach opens also the route to the case of random fatigue loading and load spectra, as occurring in all rail-wheel applications, very remote from laboratory experiments.

Table 1
Yield shear stress and Brinell hardness for some rail steels as obtained from [1,12]

Material	Yield shear stress, *k* (MPa)	Brinell hardness (HB)
J1	673	342
J6	579	367
CrMo	442	317
HH1	483	337
STD	311	277
BS11	289	253

2. RCF fatigue tests in [1]

Extensive experimental investigations on various rail steels were conducted by Clayton and Su [1]. The materials are various commercial rail steels (STD—AREA standard carbon steel, HH—Si–Cr head hardened, STD hear hardened HH1, BS11, UICA, UICB, 1% Cr, CrMo), various experimental bainitic heats steels (J1, J2, J4, J6). As shown in Table 1, the hardness values vary from HB 253 for BS11, to 367 for J6, while the yield stress in shear, *k*, is lowest for BS11 at 289 MPa but is not highest for J6, indicating that the ratio between hardness and yield stress is not constant. The criterion for end of life was either loss of material due to spalling or collapse of the fatigue damaged surface—in either cases, it was detected by increase of vibrations.

Three log–log plots of RCF life are reported in Fig. 1 as adapted from the data in [1], confirming, as suggested already in [1], that the best correlation is obtained when the factor (p_0/k_0) is used as load parameter, and not when p_0 alone or p_0/HB (compare Fig. 1A with 1B and 1C). However, the difference between p_0/k_0 and p_0/HB in terms of correlation is not very large ($R^2 = 0.80$ instead of $R^2 = 0.71$) while it is considerable with respect to p_0 alone ($R^2 = 0.37$).

Fatigue limit (at 2 millions cycles) seems to be just above $p_0/k_0 = 2$ in the range where the stresses are well within the nominal shakedown limit, and indeed the elastic limit. This could be attributed partly to cyclic hardening (which increases the effective yield limit), and partly to the fact that the tests were *not* run under pure rolling conditions (rather, a 10% creep ratio was used in most tests) and this may decrease significantly the nominal shakedown limit (see Johnson's book [5]). No clear change of slope in the Wöhler curve can be distinguished, although it is known that under RCF no real fatigue limit is expected, and a ultra-long fatigue curve should appear. Since hardness takes necessarily into account only monotonic components of strain hardening (corresponding to around 8% in the Brinell tests), this may explain why it is not more significant than yield limit.

Another general trend which emerges from Fig. 1 is that while softer materials like BS11 or STD in absolute terms correctly show lower fatigue characteristics, in relative terms of p_0/k_0 they perform much better than the average, while the situation is reversed again in terms of p_0/HB. However,

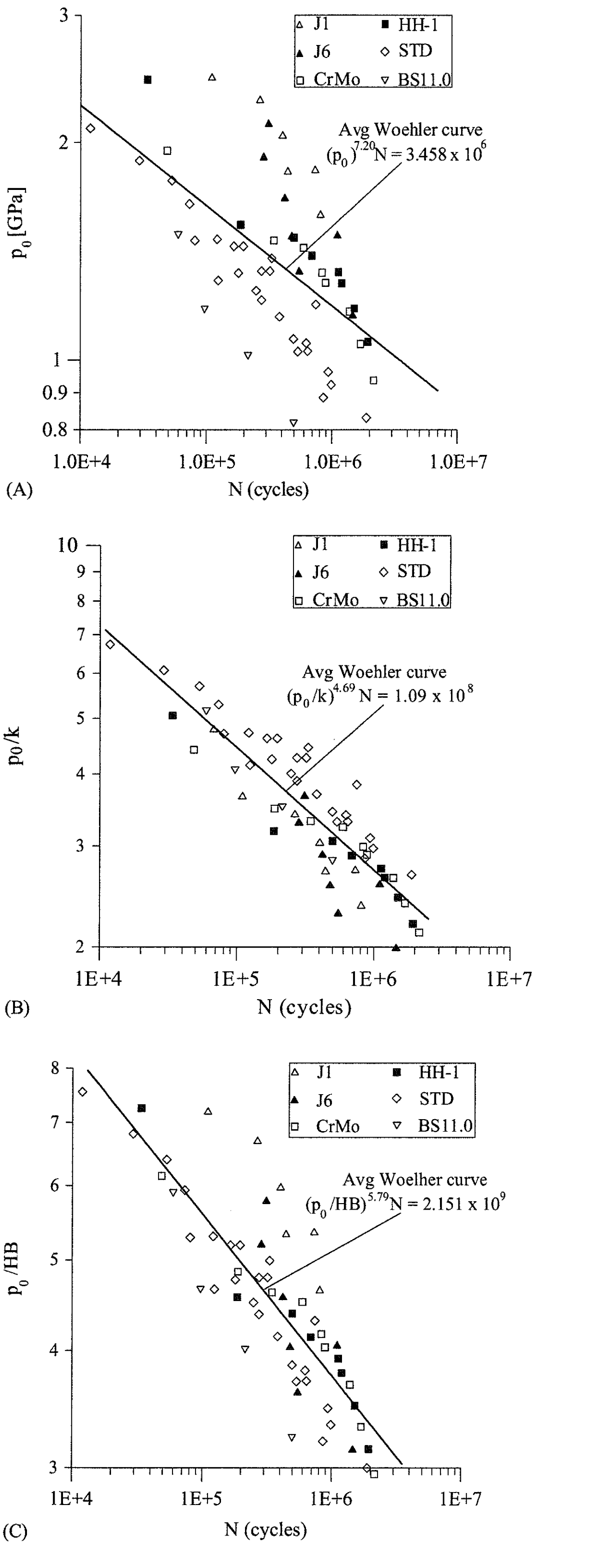

Fig. 1. Surface RCF life at 10% slide/roll ratio under water lubrication (adapted from [1]) versus: (A) the maximum contact pressure; (B) p_0/k_0 and (C) p_0/HB.

this is again due to the fact that harder materials (such as the experimental bainitic steels Jx) increase their yield strength more than their hardness. This is a peculiar characteristic of bainitic steels, as in general the gain of fatigue resistance with respect of hardness is known to be less than proportional particularly at high hardness.

3. Kapoor's RF hypothesis

A relevant feature of the RCF experiments of [1,12], is that they contain extensive measurements of ratchetting strains, although limited to the STD steel case. This permits to check the RF hypothesis, i.e., as suggested in particular by Kapoor [13], the critical condition is essentially exhaustion of ductility. Empirical fitting of ratchetting strain suggested for their rail steel a power-law dependence on N

$$\gamma = \gamma_0 N^b \tag{1}$$

where $b = 0.5$–0.6 was found a function of the pressure itself, a decreasing function such as

$$b = 1.1023 - \frac{0.093 p_0}{k_0} \tag{2}$$

and the initial ratchet rate[1] was given approximately by:

$$\gamma_0 = 8.3275 \times 10^{-8} \exp\left(\frac{1.812 p_0}{k_0}\right) \tag{3}$$

Notice that this equation has been derived for $p_0/k_0 = 5$–6.7 and $N = 10^3$ to 10^5. Instead of the Merwin power-law curves, this empirical equation suggest an exponential increase with pressure. If we adopt Kapoor's idea of "critical strain", it follows:

$$\gamma_c = \gamma_0 N_f^b = \text{const} \tag{4}$$

As we expect that under RCF condition the ductility of the material is higher than in standard tensile conditions, and assume the value at the largest measured strain in [1,12], i.e. around $\gamma_c = 1.5 = 150\%$, we could write the Kapoor's critical condition (4) by taking logarithms from (4) and using ((1), (2) and (3))

$$16.71 - \frac{1.812 p_0}{k_0} = \left(1.1023 - \frac{0.093 p_0}{k_0}\right) \ln N_f \tag{5}$$

which is *not* exactly a power-law Wöhler form. However, in Fig. 2 the data of STD steel only are plotted in terms of p_0/k_0 and Eq. (5) is shown with dotted line to fit quite well the trend even outside the range ($p_0/k_0 = 5$–6.7 and $N = 10^3$ to 10^5) for which it was obtained, and in particular up to nearly $N = 10^6$ and is probably expected to work well in the very low number of cycles range as extrapolating, it

[1] We removed here the apparent dependence on friction coefficient which was assumed $f = 0.235$, making clear that this formula is only valid under the particular conditions of the tests and for the ranges for which it was obtained.

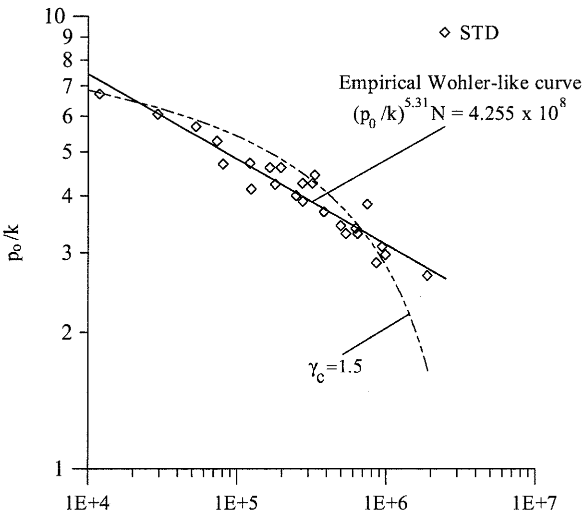

Fig. 2. Surface RCF life at 10% slide/roll ratio under water lubrication (adapted from [1]) for STD steel. Comparison of Kapoor's critical ratchet strain hypothesis at $\gamma_c = 1.5 = 150\%$, with the best-fit Wöhler curve.

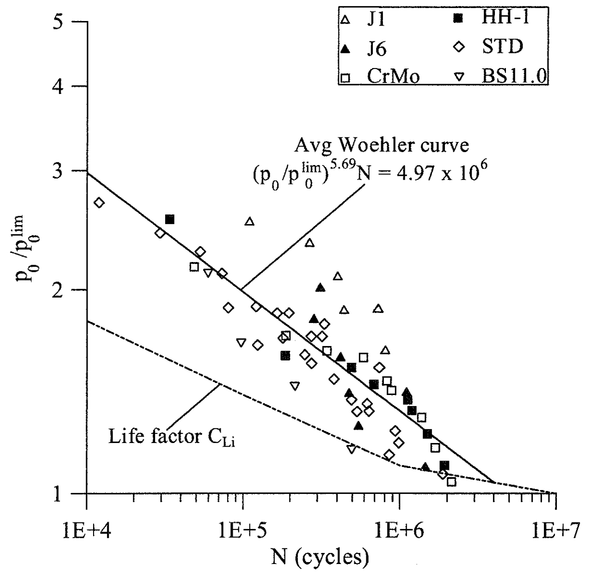

Fig. 3. Surface RCF life at 10% slide/roll ratio under water lubrication (adapted from [1]) versus $p_0/p_0^{\lim}$, where $p_0^{\lim}$ (MPa) $= 2.8\text{HB} - 69$. Also included the life factor curve C_{Li}.

would give static failure at $p_0/k_0 = 9.3$. However, at the long lives, the best-fit Wöhler curve which is also plotted in Fig. 2, seems to be more stable, as the decrease of the RF curve is to rapid. Being an extrapolation, it is likely that this trend is due to overprediction of the ratchetting strain in this range. However, notice that at the low number of cycles, it is the best-fit Wöhler curve to give wrong extrapolation, as static failure would be predicted at an unrealistically high value of $p_0/k_0 = 42$. Clearly, a Wöhler curve approach would need to change slope at various regimes.

4. Fatigue Wöhler curve approach

When a power-law Wöhler slope is used such as

$$p_0^m N_f = \text{const} \tag{6}$$

in RCF conditions, m is sometimes said to be much smaller than usual, and for example, is reported to be in the range 0.5–1.5 by various authors and for various conditions (see [12]). It is clear that these slopes depend strongly on the range of cycles where they obtained, but this indication seems contradicted by the results in [1,11], as presented in Figs. 1 and 2, where for various non-dimensional parameters, we obtained $m = 4$–7.

Turning back to the original Merwin's experiments on copper, they had suggested a constant ratchet rate ($b = 1$ in Eqs. (1) and (4)) and

$$\gamma_0 \propto \left(\frac{p_0}{k}\right)^c \tag{7}$$

with $c = 4$. If a Wöhler curve is used in conjunction with the Kapoor's hypothesis of critical ratchet strain, copper would follow a power-law with $m = 4$ (at least within the range of measured ratchet strains, i.e. few thousand cycles). Generalising this reasoning for a ratchet strain showing a power-law decaying rate with $b < 1$, and a pressure dependence of the ratchet rate is also of the power-law type with exponent c, the Wöhler curve turns out of exponent

$$m = \frac{c}{b} \tag{8}$$

Also, contact fatigue results have been collected for design rule and standard in gears. For example, Juvinall and Marshek [10], collecting and simplifying various standards for gears design (such as AGMA 2001 or BS-ISO 6336 [11]) reports a table for various materials, and for steel a fatigue limit at 10^7 cycles of[2]

$$p_0^{\lim}\ (\text{MPa}) = 2.8\text{HB} - 69 \tag{9}$$

and for the entire life curve, a factor C_{Li} is used. For example, $C_{\text{Li}} = 1.7$ at 10^4 cycles, and $C_{\text{Li}} = 0.65$ at 10^{11} cycles. In Fig. 3, the data in [1] are reported again, normalised by the fatigue limit at 10^7 cycles (9), and the factor C_{Li} is also plotted, showing a good accuracy in the region around the fatigue limit, and otherwise a quite conservative estimate at the shorter lives.

Given that permanent static damage (which we must consider as a "definition" of failure here) can be expected at values around Brinell hardness itself, which in the correct dimensions could be written as $p_0 = 10\text{HB}$ (MPa), nothing surprising occurs for the engineering point of view, a typical

[2] Since Brinell hardness has (kgf/mm^2) units, the notation 3HB really indicates roughly 0.3 the pressure in the hardness test, and the notation 10HB roughly the hardness pressure itself.

fatigue curve, with the largest differences at the long lives, where fatigue limit seems to be suppressed. Even if we ignore most details of the fatigue mechanisms, interpolating between static collapse and fatigue limit is still a valid procedure for preliminary calculations.

5. Discussion

It would seem quite surprising that, in the best of the authors' knowledge, no previous attempt was made to relate the RCF strength for rail steels according to the gears standard approach. In fact, despite gears materials and surface or other conditions may be different, the gears standards, based on the classical suggestions of Buckingham (see [10]) who in turn had tested a large variety of materials, seems the most practical approach in engineering terms. Obviously, there is no pretence to cover the mechanisms of wear, friction and fatigue initiation and propagation of cracks, but the complications of RCF seem large enough to motivate an empirically based but practically successful approach, as that used in the gears industry worldwide with success. RCF in fact seems an area where fundamental aspects of fatigue, tribology and fracture mechanics will be of interest for a long time. Also, consider that the conditions found in practise in railways are various and sometimes unclear, and for example, not much is known of load spectra in service. It is generally desired to have larger friction than in gears, as high friction is needed for traction or braking of the vehicles, whereas in gears it is pure loss, but this should not induce the assumption that this is always the case, and indeed very low friction coefficients can be found, especially at low temperatures where ice is formed, where transmitting of torque becomes a major concern than RCF! For the conditions of C&S's experiments discussed in the paper with water lubrication, we have implicitly neglected wear. Under dry friction, although the stress field induced is potentially more severe (simply because the friction coefficient may be larger), wear is usually so high that proper crack initiation and propagation cannot occur. This is what emerged in the classical experiments by Way [14] who suggested, however, an alternative explanation, stating lubricant is needed for pressurising the crack. Kapoor and co-workers [15,16] have recently further developed the ratchetting-based models, to include potentially the competing effects of wear and crack initiation, which would presumably dictate if cracks are initiated fast enough to then follow a propagation phase with some fracture mechanics model. These models approximate the solid with "layers" or "bricks", and apply a very simple equation for the ratchetting strain rate, which is in turn obtained from interpolation of a *limited* number of experimental results in [17]. The critical ratchet strain is much larger than what found here for C&S's experiments ($\gamma_c = 11.5$ instead of 1.5), and the use of the elastic stress field to predict strain values up to these extremely large values in essentially discrete models is certainly fascinating but ambitious, so that further assessments are required to judge if the models can be made of quantitative interest. In the meanwhile, it would be interesting to use the empirical Wohler-based approach for realistic conditions, such as service load-spectra, perhaps applying Miner's rule to assess the effect of varying load.

6. Conclusions

In the present note, a re-interpretation of recent ratchetting measurements by Clayton and Su [1] shows evidence of ratchetting as the mechanism dominating in RCF fatigue. In particular, Kapoor's "critical ratchet strain" hypothesis has been shown to be reasonable, directly from RCF life ratchetting measurements although limited to only one steel (STD) a under specific set of RCF conditions, and although a quantitative comparison should be made to understand if the values suggested by Kapoor are so much higher than those found in C&S (critical strain of the order of $\gamma_c = 11.5$ instead of 1.5). It remains difficult to predict accurately the ratchet strain for large number of cycles from "exact" plasticity constitutive equations (and certainly, a finite strain analysis would be also needed), but the ratchetting-based models have the advantage of giving insight into possible failure modes and interaction with wear, which also is governed mainly by similar deformation processes.

However, ratchetting-based equations seem at present not particularly useful for practical design procedures, whereas it is probably more efficient to follow the approach of pitting contact fatigue Wöhler curves, which indeed seem conservative in the present form, and could be modified if a sufficiently large experimental database could be added for rail-wheel steels and conditions. However, the results of C&S tests, suggest that a single fatigue limit equation based on hardness, and a single Wohler curve would be a very reasonable initial approach, for most rail materials (at least under water lubrication conditions).

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