LEROS has proved capable of testing under these severe conditions with a good degree of control. Tests under similar conditions to those seen on the Amsler gave a similar patterns of wear results.

11.3 Disc surface undulations and test machine vibrations.

Periodic undulations of both Amsler and LEROS disc surfaces were generated during some mid-range tests. Results indicated that, for each material and machine, these occurred within a limited range of test conditions that were related to the mechanical properties of the respective materials. These undulations increased machine vibrations.

Undulations took two forms on the Amsler machine; highly visual, 0.3mm wavelength small undulations of a few microns amplitude, termed *corrugations*, and long wavelength, variable amplitude large undulations, termed *facets*. Amsler disc facets were visually obscured by corrugations and were detected by Talyrond profilometry. Only facets formed on LEROS discs. These were highly visible and similar in both appearance and microstructural features to the 40-80mm wavelength, axial undulations that form on British Rail track, known as *short wavelength rail corrugations*.

The fine 0.3mm wavelength Amsler undulations, which formed at both machine speeds, were thought to be connected to a form of "stick-slip" contact and differential wear/deformation generated by the fixed gearing, although no direct linkage to gear impact frequencies was shown. The range of corrugation frequencies was close to the natural resonance of loaded discs at the higher speed setting only.

Limited comparative tests indicated that Amsler disc facet frequencies remained constant at both machine speeds, whereas LEROS disc facet frequencies varied with speed, i.e. wavelengths remained constant. On both machines, facet amplitudes were greatly reduced at the lower speeds. Machine vibration *accelerations* and *velocities* could not be directly linked to facet frequencies, although later work on this Amsler has linked facet formation to the frequency of vibration *displacement* generated by a harmonic of the natural machine frequency. Increasing the rigidity of the Amsler loading system did not affect corrugation and facet formation.

As found on rails, the differential wear/deformation implied by undulation formation did not have a major effect on overall wear rates. The growth, or clearance, of undulations during testing did not significantly affect wear rates compared with small changes in set test condition.

11.4 Wear rate analysis.

Wear rate has been expressed either as mass lost per unit contact area per mean distance rolled, Y_r, or mass loss per unit contact area per mean distance slid, Y_s. These expressions are connected by creepage, $\gamma = Y_r / Y_s$. The sliding expression facilitates comparisons with pure sliding wear tests. The rolling wear rates given by other workers, usually related to the distance rolled of one one disc only, contain an implicit creepage term, which can be either negative or positive for driven or driving discs, respectively.

With the present work, limited comparisons could be made between wear rates of the respective materials and the product of the test conditions, maximum contact stress, p_o, and creepage, γ. Slightly better comparisons could be made against $T\gamma/A$ $[=0.25(\pi\mu p_o\gamma)]$, a description of work done, where T is tractive force, A is contact area and μ is the traction coefficient. For the majority of the test results, this produced wear resistance rankings for the top rail driven discs of B52 > R52 > B20 > B04 and for the bottom W64 driving wheel discs of W64/R52 > W64/B52 > W64/B04 > W64/B20. Under these conditions the carbide free bainitic steels, B04 and B20, performed badly compared with conventional pearlitic rail steel. Although the carbide containing bainitic steel, B52, performed slightly better than the conventional pearlitic rail steel of equivalent carbon content, R52, it sharply increased wear of the pearlitic counterface wheel steel.

However, these generalised results, based on the product of test conditions, hide distinct changes in wear behaviour that can occur within one value of that product, i.e. at high creepage and low contact stress, or vice versa. For example, wear of the W64 driving discs, irrespective of counterface material, was sharply increased at the highest maximum contact stress examined (1800 MPa), with material failure by a different wear mechanism.

The present results have indicated that use of low carbon bainitic rails will not give longer service lives under the contact conditions seen on rail curves installed in high speed, passenger rail networks. Their greater resistance to plastic deformation at the gauge face will be offset by higher wear rates. However, under the severe loading conditions seen on heavy haul rail networks, high carbon, conventional (upper and lower) bainitic steels may offer both high wear and high deformation resistance. Also, under heavy haul conditions, the performance of some carbide free bainitic steels may match that of pearlitic rail steels with the bonus of the good weldability of such bainites. Published work on heavy haul usage of such rails has not mentioned wheel wear. The present results indicated that use of bainitic rails may significantly increase wear of pearlitic rail wheels.

11.5 Wear mechanism.

Under most test conditions, tractive forces were higher than the respective shakedown limits of the steels, with maximum shear at the disc surfaces. These surfaces were deformed by incremental strain, "ratchetting", with surface initiation of angled cracks resulting in flake formation. Even under mild test conditions, shakedown can be exceeded with asperity contacts.

Flake widths were observed ranging from sub-micron to complete 10mm track widths. Material above flake cracks was highly strained and removed by all four wear mechanisms; adhesion, abrasion, micro-fatigue and tribo-oxidation. Even for severe tests, where much large flake debris was produced, the majority of debris (by weight analysis) was on a very fine scale and had passed through the 0.4mm square grid filter.

Only under high contact stress conditions was the competitive wear mechanism of low cycle fatigue observed. This was for driving pearlitic wheel steel (W64) discs. At the highest value of contact stress tested, all W64 wear rates were grouped in a range which was five times the magnitude of the grouped pearlitic and bainitic driven disc wear rates. This behaviour was partly associated with driving disc surfaces being under tension approaching the contact, whereas driven disc surfaces are under compression.

11.6 Wear resistance and microstructure.

The present work has not shown that bainitic steels have poor rolling-sliding wear resistance, given their mechanical properties, rather that pearlitic steels have exceptionally high wear resistance. This was observed to be due to the re-alignment of lamella carbide in pearlite under steady incremental strain. This results in an area fraction of hard carbide being presented at the wear surface which is larger than the volume fraction of carbide. Thus work-hardening of pearlite, in the plane of the wear surface, appears greater than that of initially harder bainitic structures. Such performance can be optimised by refining the pearlitic interlamellar spacing and by reducing the manganese sulphide inclusion content; flattened ductile inclusions provided planes of weakness which facilitate flake crack propagation. Large MnS inclusions were not present in the bainites.

There were indications that inter-lath carbide in upper bainite could, to a far lesser degree, similarly align. Hard lower bainite, and martensite-austenite areas in carbide free bainites, did not readily deform under ratchetting strains.

Where the alignment of pearlite carbide lamellae is disrupted, its wear performance rapidly deteriorates, as seen with severe rolling-sliding wear, impact wear and, to a far lesser degree, where the counterface material contains blocks of hard phase. Surface disruption can also occur where loading is such that surface material fails by low cycle fatigue as observed on the driving discs at the highest level of contact stress tested.

11.7 Suggestions for further work.

1. The dry rolling-sliding wear performance of bainitic structures should be examined at higher value combinations of contact stress and creepage, which would be more applicable to heavy haul rail networks. The present work has indicated that standard pearlitic rail or wheel steel will fail by low cycle contact fatigue at such high contact stresses, when used as the driving disc. The performance of different bainitic steels, and higher grade pearlitic steels, should be assessed as both driven and driving discs, both mixed and against each other. This will be of interest as rail networks have started to use low carbon bainitic steel wheels.

2. The dry rolling-sliding wear performance of low carbon, carbide-free bainitic steels should be compared with that of conventional higher carbon bainites, with 100% upper bainite and 100% lower bainite structures. It would be of interest to link the strain alignment of hard phases in such steels with wear performance and to compare performance ranking with the respective mechanical properties.

3. The directional alignment of lamellae carbide in pearlitic steels, induced by rolling-sliding contact, and also by wire drawing, indicates that lamella structured composite materials may similarly have unexpectedly good wear properties, with respect to their mechanical performance, if structures can be similarly aligned. This should be explored.

4. Further controlled tests, comparing results from installed test rails with those obtained from air-cooled tests on laboratory twin disc rolling-sliding wear machines, should be carried out. Both wear and plastic deformation could be examined at test conditions representative of European and Japanese passenger rail networks and the more arduous heavy haul rail networks.

5. The effect on rail wear and fatigue of the size and distribution of manganese sulphide inclusion stringers should be further examined. These stringers are aligned normal to the high transverse creepage experienced by upper rails in curves. It may prove cost effective to have the premium rails which are installed in curves manufactured from cleaner steels.

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