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# A new test to study the cyclic hardening behaviour of a range of high strength rail materials

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ABSTRACT

Plastic ratcheting plays a key role in wear and rolling contact fatigue crack formation at the wheel–rail interface. Tests to examine the wear and rolling contact fatigue behaviour of rail materials over a wide range of service conditions are expensive and can be impractical. A physical simulation of the deformation behaviour associated with ratcheting is an attractive replacement for such tests. In this work, the Plane Stress Local Torsion (PSLT) test is proposed as a novel mechanical testing method to physically simulate near-surface deformation in rails and to characterize the cyclic deformation behaviour of rail materials. Contrary to the orthodox mechanical tests, the proposed method is capable of producing a nonlinear strain gradient in test samples which resembles the real gradient in the rail–wheel system. The PSLT testing was performed on specimens of the nominated rail steels in a strain-controlled fashion to simulate the unidirectional as well as the fully reversing strain cycles. The test was used to examine the cyclic hardening behaviour and ratcheting characteristics of a range of high strength rail materials under cyclic loading at room temperature. The effect of the cyclic strain amplitude under symmetrical strain cycling on the cyclic hardening behaviour was investigated. Experimental torque–twist data were used to compare the plastic flow behaviour of commonly used rail materials in heavy haul applications under cyclic loading. The cyclic and ratcheting strain accumulation behaviour in the test samples was characterized based on the torque–twist data to allow a comparative study of the mechanical properties. Optical microscopy of the tested samples was also performed to compare the microstructures at the flow localization zone for different materials subjected to cyclic strain accumulation.



## 1. Introduction

Flow localization can be studied in two extreme contexts; as a useful process or as a damage precursor. As an example of the former, localized grain refinement processes have been considered recently to improve material strength at critical zones of a part or structure (e.g. Surface Mechanical Attrition Treatment (SMAT) [1] and the plane stress local torsion (PLST) process [2]). The latter has been proposed and studied recently to enhance the mechanical properties of materials locally. The PSLT process offers a zero shape change treatment to accumulate localized shear strain and localized grain refinement at a critical zone (e.g. a fastener hole edge). The flow localization can be devised deliberately as it develops a gradient of microstructure in the metallic parts and results in their local reinforcement. The process is characterized by variations in the structure and mechanical properties of the material similar to functionally graded materials [3] or those obtained by a method called "OPTICA" to improve wear resistance of ductile iron by locally optimizing the microstructure [4]. A large number of studies have shown that the gradient contributes as a strengthening mechanism developed by the severe plastic deformation [5,6], compressive residual stress [7] or laser peening [8].

In contrast, there are situations in which the flow localization is harmful and has to be prevented. This is the case when due to a severe loading condition (such as contact loading) a significant amount of local plastic strain develops by time. For example, the cyclic loading in the presence of a mean compressive stress can lead to wear in rails caused by ratcheting that eventually results in component failure [9,10].

At the wheel–rail interface, both rolling and sliding occur in the contact zone. Wheel–rail systems are inherently subject to damage due to sliding that typically manifests itself as plastic deformation,

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wear or rolling contact fatigue (Fig. 1). The key factors that influence the rate of damage are "material behaviour" and "the severity of loading", i.e. normal load or contact pressure in addition to the sliding velocity or creepage. Plastic ratcheting in rails, accumulation of small increments of plastic deformation with each pass of the wheel, occurs when the loading conditions are above the plastic shakedown limit [13]. The localized deformation usually develops a large and nonlinear strain gradient in the direction of friction at the contact surface. The gradient is necessary for a continuous and smooth transition between the plastic zone and its underlying undeformed zone. Experimental observations on the microstructures developed by a twin-disk test such as those reported in [14] have confirmed the non-linear nature of the strain.

The "incremental plastic strain" and "microstructure degradation" immediately below the rail surface affect the wear and fatigue behaviour of the rail system subjected to cyclic loading or adverse service environments.

The features of cyclic deformation in rails have been modelled using "two-surface plasticity" [15], "revised two-surface model" [16], and "unified visco-plastic model" [17]. For rail steels, some results of uniaxial and multi-axial strain cycling and ratcheting have been reported [18,19]. However, analytical calculations are not practical due to the "incremental" and "hysteresis" nature of the near surface deformation; some history-related parameters are needed to quantify the damage. A significant number of multi-faceted "transient" and "history related" phenomena are actively interacting during formation of the damage, including microstructure degradation. The deformation response of the rail to the cyclic loading and un-loading depends not only on the current loading but also on its past status. This dependence arises because a lower stress is required to reverse the direction of slip on a certain slip plane of the polycrystalline metal than to continue slip in the original direction. Actual tests on the operating rail–wheel system are impractical. It is therefore desirable to develop a "physical test" that can be fully controlled under laboratory conditions during which the instantaneous damage is measured and correlated to the in-field damage using a combination of modelling and simple measurements.

Two commonly-used physical tests for simulation of ratcheting in the rail–wheel system are the compression-torsion and the twin-disc tests. The torsion test or its variants (e.g. torsion–tension) have been frequently used to simulate complex paths of deformation (e.g. [18,20–25]) and the flow localization in situations where shear is the prominent deformation mechanism. However, the tests suffer from serious limitations. They are limited in their ability to reproduce the exact deformation mode corresponding to actual service conditions. The torsion test produces heterogeneous deformation but its deformation gradient, even for large plastic deformations, remains linear in the radial direction. Based on some symmetry considerations, Canova et al. [25] have explained the conditions which are responsible for the linear gradient. In many cases such as the running surface in rails, the gradient is highly nonlinear and cannot be adequately represented by a torsion/tension test. Another physical simulation, twin disk test [14], requires relatively large samples and therefore could be unsuitable when the rail has a non-uniform structure such as in rail welds. High pressure torsion test has been frequently used as a grain refinement process (see for example [26]) or as a physical test [27]. The test requires small test samples, however its gradient of deformation in the radial direction and the longitudinal direction are not fully known yet; several researchers have assumed a linear gradient.

A physical simulation of the deformation behaviour with a small sample can offer a higher resolution for the non-uniform material cases and therefore is an attractive replacement for twin-disk tests or tests under actual service conditions. The test could also provide initial screening data to rank the behaviour of a range of rail material grades.

A new physical test, the Plane Stress Local Torsion, is proposed and performed in this work to avoid the limitations with the orthodox physical tests. The test is used to produce a nonlinear strain gradient in its samples and to study and compare their strain cyclic behaviours.

## 2. Plane stress local torsion (PSLT)

### 2.1. Description of PSLT

The plane stress local torsion test is an axi-symmetric (one-dimensional) test that allows the physical simulation of the flow localization. The test involves twisting the material in a constrained manner to produce a localized plastic deformation via torsional loading and measuring the torque–twist response. It creates a plastic zone adjacent to a rigid zone with a nonlinear distribution of the shear deformation in the plastic zone which is similar to the deformation of rail materials after a certain number of rolling cycles. As a result, the microstructure developed in the sample can be used for a better understanding of strain distribution during ratcheting and the requirements for controlling the strain accumulation.

The Plain Stress Local Torsion (PSLT) [2,28], is a novel mechanical test that can produce hysteresis plastic deformation and a non-linear strain gradient in its sample. These are in accordance with the observations of near surface damage in rails (produced by the twin disk test [14]). The PSLT test has been used recently to simulate localized deformation in rails and to generate relevant data in a fully laboratory controlled condition.

This axisymmetric (one-dimensional) test (Fig. 2a), physically simulates the flow localization by twisting a disk shape specimen (Fig. 2b) via torsional (shear) loading and measures the torque–twist hysteresis response. For a physical simulation of the near surface damage in rails using the PSLT, we assume that point 3 in

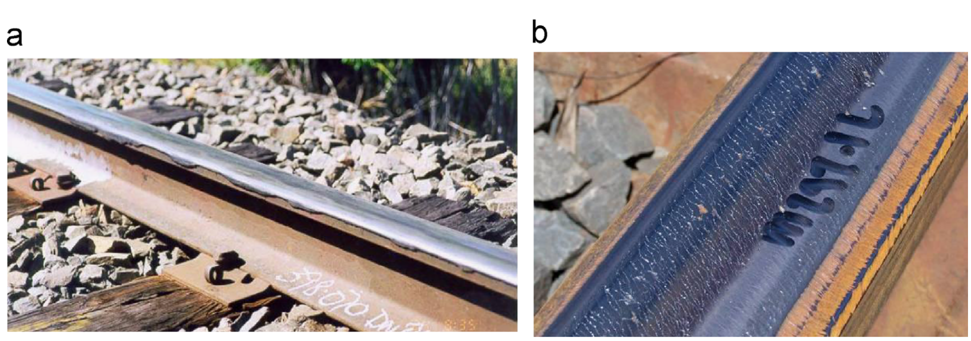


**Fig. 1.** (a) Typical rail plastic flow [11] and (b) rolling contact fatigue profiles of a rail in service [12].