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Effect of solid contaminants on ratcheting and crack nucleation in wheel-rail contact

A. Mazzù[1], D. Battini[1], and N. Zani[1]

**[1]Department of Mechanical and Industrial Engineering,
University of Brescia, Italy**

Abstract

Solid contamination is a key issue in recent studies on wheel-rail contact. In fact, these components are more and more called to resist to the severe damage due to the presence of sand at the contact interface, caused either by the intentional addition as friction modifier, or by operation in sandy environments, such as deserts.
In this work, a fast numerical method for studying ratcheting in solid contaminated contact is presented. It is based on an analytical plane strain model for determining pressure distributions in solid contaminated contact, coupled with the non-linear kinematic hardening model of Chaboche-Lemaitre for the material cyclic plasticity.
As a case study, the method was used for assessing the results, previously published, of experiments carried out by means of a bi-disc test bench, where three wheel steels were coupled with the same rail steel in sand contaminated contact. The steel constitutive laws were obtained by approximating with the Chaboche-Lemaitre model the previously published data. The pressure distributions were obtained considering round equally-spaced particles of solid contaminant, with three different sizes within a realistic range.
The calculations showed that, at a depth comparable with the particle size, the stresses are mainly influenced by the contact between the particles and the main body (disc), determining stress peaks much higher than the case of clean (non-contaminated) contact; furthermore, each load passage causes multiple stress cycles, due to the number of particles entrapped at the contact interface. As far as the depth increases, the role of the particles decreases and the stresses are similar to the case of clean

contact. Depending on the material cyclic yield stress, this stress field can determine ratcheting at a twofold level: at a surface layer, mainly driven by the local contact between the contaminant particles and the discs, and at a sub-surface layer, mainly driven by the global contact between the contacting discs. Ratcheting cannot practically be avoided at the surface level in contaminated contact; on the contrary, it can be limited at the sub-surface level by increasing the steel cyclic yield stress. Furthermore, the contaminant particle size appears very important in determining the severity of the damage: the smaller the particles, the thinner the highly damaged surface layer.
The calculated results were consistent with the experimental ones: softer material showed ratcheting involving both the surface and sub-surface layer, whereas in hard materials the damage was confined to the surface layer.

Keywords: Wheel-rail contact, Solid contaminant, Damage assessment, Ratcheting.

1 Introduction

Railways are a key factor in the development of industry, especially mining. Historically, the diffusion of railways was primarily driven by economic factors, but also by some hindering environmental factors, such as harsh orography or climate. However, things are rapidly changing in many areas, characterized by flourishing economies and unfavorable environmental conditions. Desertic areas have the greatest technical problems: sand causes severe damage when it enters the wheel-rail contact interface.

Researches on the effect of sand on wheels and rails have been carried out, especially aimed at studying damage when sand is used as adhesion enhancer in wet environments. Sand was found to increase wear, up to 30 times the wear in clean dry conditions [1-3]; third body abrasive wear usually occurs [2,4]. The subsurface region is characterized by huge plastic strain, formation of surface cracks and detachment of large material particles [2-4]. Therefore, understanding and modeling the interaction between the wheel, the rail, and the interposed solid contaminant is crucial for meeting the challenge of new railways in desertic environments.

In [5], the damage mechanisms related to sand contamination were assessed by experiments and simulated by Finite Elements (FE). Two plastic strain layers were identified. The shallower one, characterized by very high plastic flow, involves a depth of the size scale of the contact area between the wheel and the sand particles. The deeper one, characterized by moderate plastic strain, involves a depth of the size scale of the wheel-rail contact area. In relatively soft steels, ratcheting occurs in both layers, which can even merge causing deep damage. In hard steels, ratcheting occurs only in the surface layer. In [6], the effect of various wheel-rail steel couplings with solid contaminant were analyzed by FE, considering single-cycle wheel-rail contact events, and utilizing Ramberg-Osgood constitutive laws for the steels. The depth of the shallower high-ratcheting layer was quantified. In [7], an analytical method for determining the contact pressure distribution and the subsurface stresses in solid-contaminated contact was proposed.

In this paper, a fast numerical method for assessing ratcheting and wear in solid-contaminated wheel-rail contact is proposed. A simplified Chaboche-Lemaitre model was used for steel cyclic plasticity. Wear is introduced as material removal from the surface. Simulations of repeated solid-contaminated contact events were carried out, investigating the effect of steel properties, contaminant particle size and wear rate. The results were compared with the experimental results published in [5].

2 Methods

The pressure distribution on the contact surface with solid contaminant was obtained by the analytical method described in [7]. It allows determining the distribution of the forces transmitted by the contaminant particles between the wheel and the rail, under the hypotheses of plane strain, rigid particles, elastic wheel and rail material, constant particle radius and spacing. Once the force distribution is determined, the local pressure distribution at the interface between each particle and the main bodies is determined by the Hertz model. Distributions such as the one shown in Figure 1 are obtained, depending on the particle radius and spacing, the rail and wheel material and radii, and the contact load.

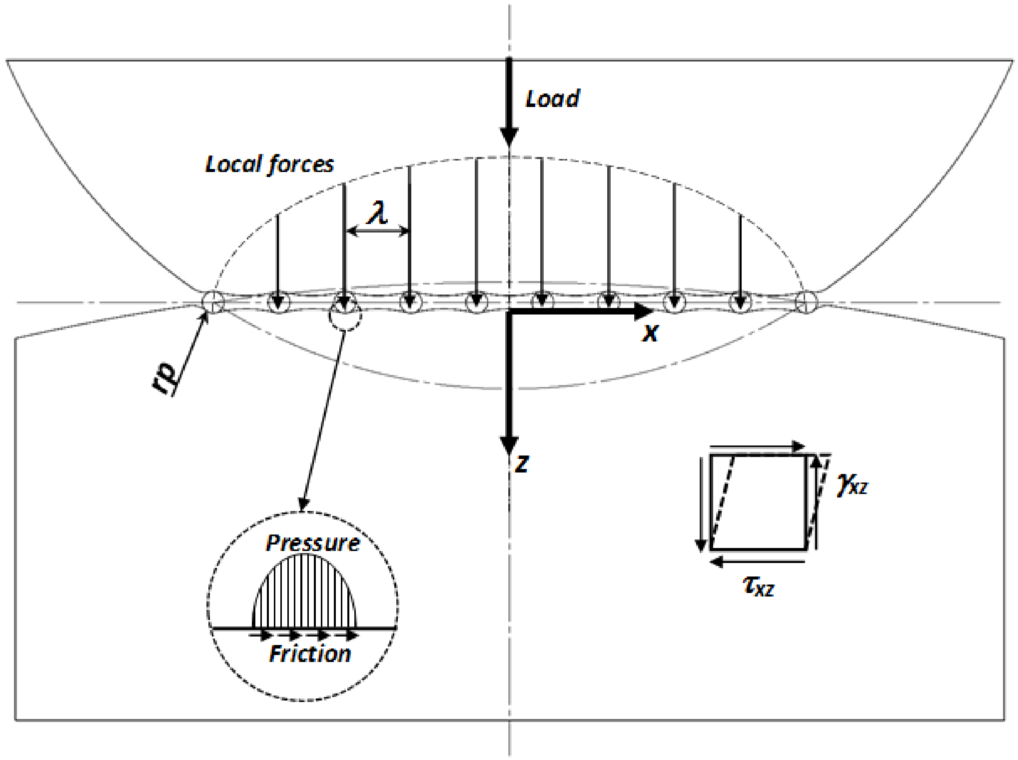

Figure 1: Schematic of solid contaminated cylindrical contact.

Although such distributions are based on the hypothesis of elastic material for the main bodies, they were used as external loads for calculating the plastic strain accumulated under the contact surface. This is justified by the results of [6], where finite element simulations of solid contaminated contact between plastic bodies were carried out: they show that pressure distributions obtained with elastic materials give an upper bound for the calculated plastic strain field, which is not far from the effective strain.

For the material constitutive law, the non-linear kinematic hardening model of Chaboche-Lemaitre was considered, in the simplified form of Mazzù [8,9]: it is limited to the plane strain case and considers the orthogonal shear strain γ_{xz} as the unique responsible of plastic flow (see Figure 1). This is based on the evidence that, under a shallow surface depth, γ_{xz} is the sole strain component that can accumulate indefinitely for high cycle number, as the other components, being always compressive during a load cycle, would cause volume collapse.
As a case study, the method was applied to the conditions of the experimental tests published in [5], where discs in wheel and rail steels were put in contact contaminated with sand. The working conditions of those tests are listed in Table 1, together with the material constants for the Chaboche-Lemaitre (C-L) model. In particular, the cyclic yield stress was taken from [7], and the constants were determined in such a way to obtain the best possible approximation of the Ramberg-Osgood (R-O) model given in [6]. In Figure 2, the used models, compared with the Ramberg-Osgood ones of [6], are shown. The effect of varying particle size, chosen in a realistic range [4], was investigated.

General contact conditions					
Wheel/rail disc diameter [mm]	Wheel/disc thickness [mm]	Contact load [N]	Nominal contact pressure (P_0) [MPa]	Contact half-width (a) [mm]	Coefficient of friction
60	15	7557	1100	0.29	0.3

Contaminant particles			
Size	Small	Medium	Large
Radius (rp) [µm]	30	45	60
Inter-particle spacing (λ) [µm]	90	135	180

Material constants for Chaboche-Lemaitre constitutive law			
Steel	EN ER8	AAR CLASS C	SANDLOS® H
Cyclic yield stress [MPa]	470	640	720
Cyclic shear yield stress (k) [MPa]	271	370	416
C [MPa]	1050	1450	1650
γ	0.5	0.5	0.5

Table 1: Geometry, working conditions and material properties in the solid-contaminated contact simulations.

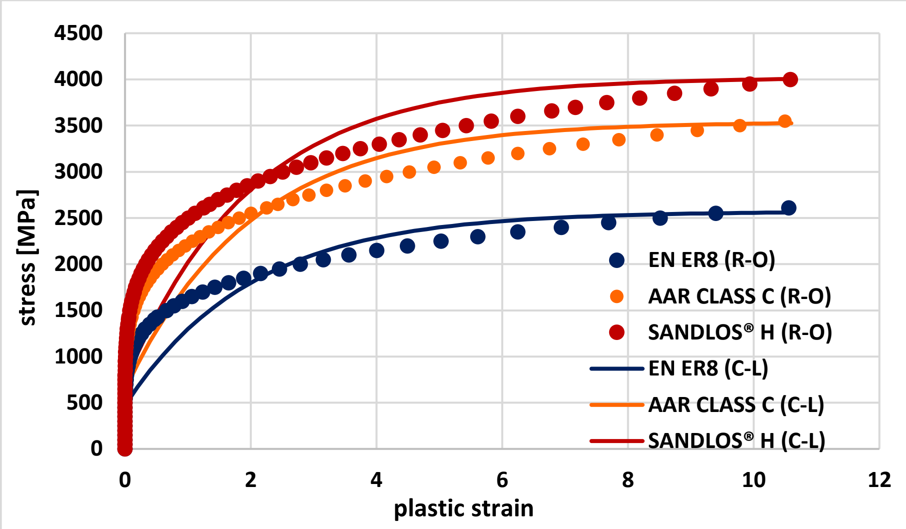

Figure 2: Constitutive laws of the simulated steels according to the Chaboche-Lemaitre (C-L) and Ramberg-Osgood (R-O) models.

3 Results

Figure 3*a* shows the normalized shear stress at a shallow depth, in clean and contaminated contact. The local stress field due to the particle-body contact is predominant, generating stress peaks up to more than 20 times the peak in clean contact. Furthermore, at each load passage the material is subjected to multiple stress cycles. Figure 3*b* shows the same quantities at a higher depth: the effect of the contaminant is negligible with the smaller particles, slightly more evident with the larger particles, but in all cases the predominant effect is due to the contact between the main bodies, with a single stress cycle per load passage.

Figure 4 shows the maximum shear stress range along the depth in clean and contaminated contact, compared with the elastic shakedown limits (given by $\Delta\tau_{xz}=2k$) for the three materials: where the limit is exceeded by the stress range, ratcheting is expected. In the case of clean contact, the limit is slightly exceeded only in the subsurface region for the EN ER8 steel. In the case of contaminated contact, a stress range peak is identified in the surface layer, corresponding to the region where the effect of the solid contaminant is maximum. With the SANDLOS® H steel, ratcheting is only due to the local body-particle contact, involving a depth of 0.2-0.3 times the clean-contact half-width *a*. With the EN ER8 steel, ratcheting can involve a depth higher than 0.7 *a*. With the AAR CLASS C steel, ratcheting can involve the transition layer between the local and global contact stress field.

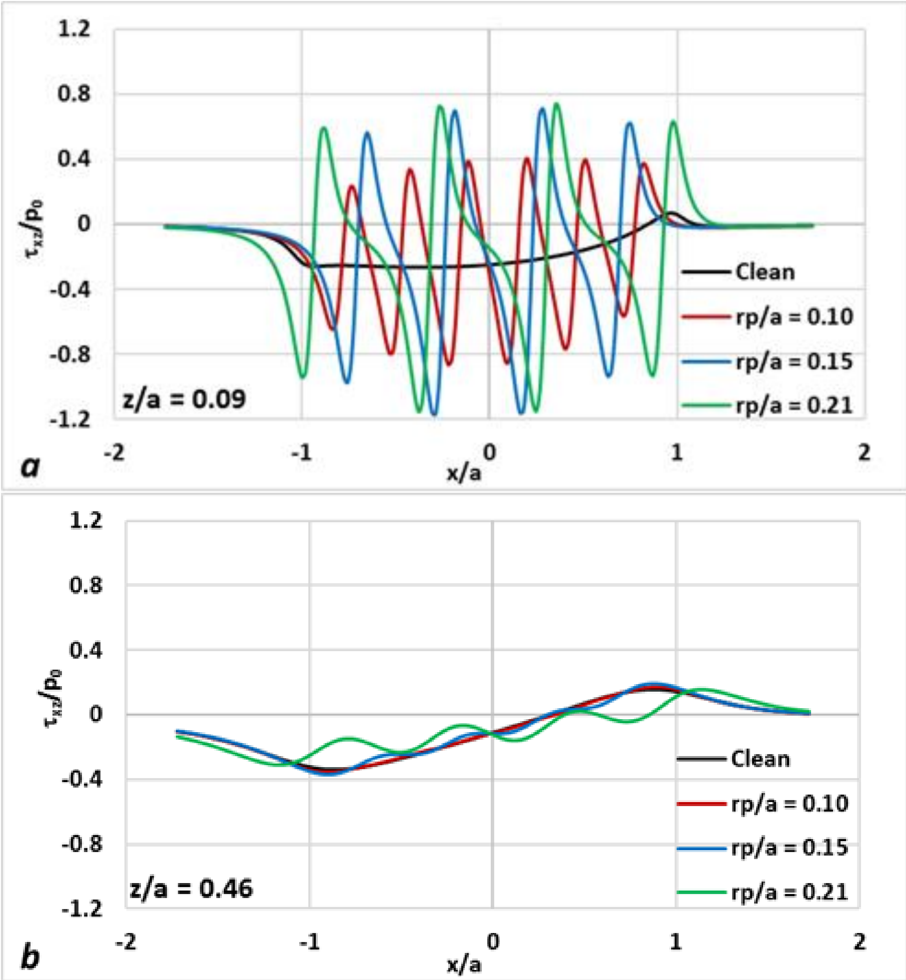

Figure 3: Normalized shear stress τ_{xz} in clean and solid contaminated contact, with various particle size at two different depths

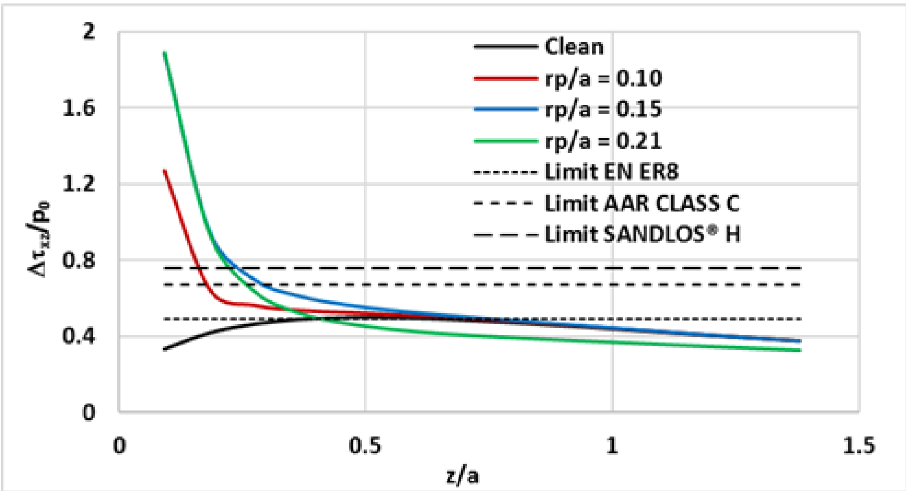

Figure 4: Normalized shear stress range $\Delta\tau_{xz}$ along the depth in clean and solid contaminated contact, with various particle size.

Figure 5 shows the stress-plastic strain curves during 3 load passages at two different depths, in the case of the EN ER8 steel with the smallest particles. At the lower depth each load passage causes 6 plasticization cycles with accumulation of huge strain; at the higher depth, each load passage causes a single plasticization cycle with moderate strain accumulation.

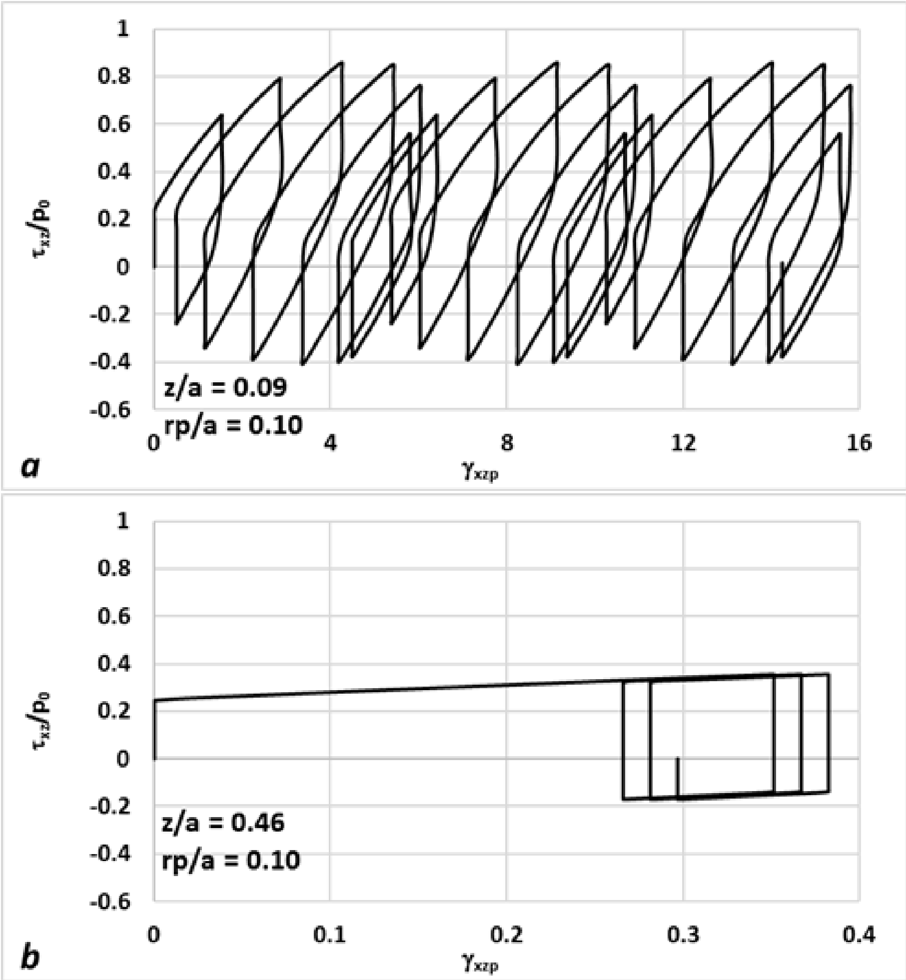

Figure 5: Stress-plastic strain curves in the EN ER8 steel with the smallest particle size at two different depths.

Figure 6 shows the plastic strain accumulated in 100 cycles by the three materials. For all, in the presence of solid contaminant, a surface layer with huge plastic strain is present. For the EN ER8 steel, even a subsurface layer with moderate plastic strain can be identified, due to ratcheting (for $z/a < 0.7$) and to the initial strain occurring before the elastic shakedown. For the other steels, with the elastic shakedown limit increasing, the plastic strain is confined to a more and more shallow depth.

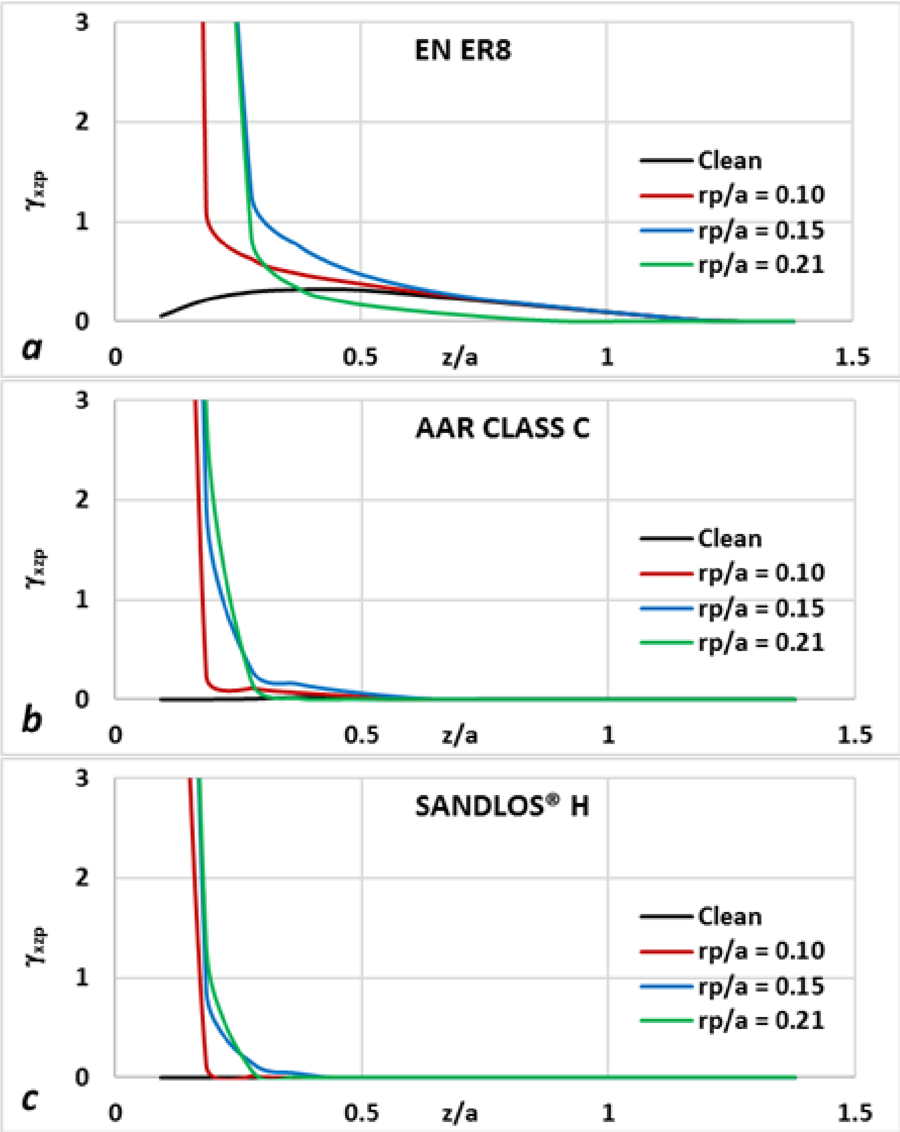

Figure 6: Accumulated plastic strain in the three simulated steels after 100 load passages in clean and solid contaminated contact, with varying particle size and depth.

4 Conclusions and Contributions

These results are consistent with the experimental ones of [5], despite the model simplifications in the particle properties and geometry, number of cycles and effect of wear. In those tests, the EN ER8 steel exhibited a layer of huge ratcheting, even leading to the incorporation of sand clusters into the metal. The thickness of such layer was comparable to the size of the global contact area between the two discs, meaning that ratcheting occurred at both the local and global contact scale. As far as the tested steel hardness increased, the thickness of the layer with high plastic flow decreased, remaining confined to a shallow depth. This means that ratcheting was limited to the depth related to the local particle-disc contact.

The following general conclusions can be drawn:

1. The presence of solid contaminant causes a surface layer characterized by very high stresses, related to the local contact between the contaminant particles and the main bodies. In this layer, not only the stress range during a load passage is higher with respect to the case of clean contact, but even the number of stress cycles is higher, due to multiple particles being entrapped between the main bodies. In this layer, ratcheting cannot be avoided in the practice.
2. As far as the depth increases, the effect of the solid contaminant decreases, becoming predominant the effect of the global contact between the two main bodies. In this layer, ratcheting can be prevented by increasing the material cyclic yield stress.
3. The particle size plays a key role in determining the depth of the surface layer affected by high ratcheting: the smaller the particles, the thinner this layer. This suggests that when sand is intentionally added as a friction modifier, finer sands should be preferred to coarser ones.

The main way to limit damage in solid contaminated environments (such as sandy deserts) is to increase the material hardness, which is usually correlated to the cyclic yield stress. Hard materials, while increasing the resistance to ratcheting and wear, sometimes have the drawback of decreasing the beneficial effect of wear, which removes surface layers with cracks and prevents their propagation. However, surface crack propagation is a concern especially in wet environments, being enhanced by fluid entrapped inside the cracks; furthermore, in sandy environments wear cannot be removed even in hard materials, therefore its beneficial effect is expected to be still present.

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