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Rail machining – current practices and potential for optimisation

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Current practices on rail machining show large variations in strategies and amount of grinding and milling. To identify reasons for this and suggest strategies to further optimise rail machining, objectives of machining are scrutinised and consequences of not fulfilling objectives are investigated. This leads to a discussion on potentially detrimental effects of rail machining and how to minimise these. With this background, general aspects of rail machining optimisation are discussed. The study shows several means to improve rail machining, but also how the potential is restricted by the current lack of knowledge and predictive models. This prevents quantifying benefits of innovative solutions, and complicates transfer of knowledge between different operational conditions and translations of (scaled and controlled) test results to (full-scale, uncontrolled) operational conditions.

1 Introduction

Rail machining in the form of grinding and milling is employed to remove rail surface damage, and modify/restore surface profiles. This enhances railhead integrity and decreases contact stress levels, which extends rail life, and decreases risks of severe failures.

Grinding uses rotating abrasive stones. Each grinding stone produces a (plane) facet. Several stones with varying inclination are used to obtain the correct rail head profile – more stones improve profile accuracy and allow more material removal even though removal depth is limited to parts of millimetres.

Conventional grinding can be performed at speeds, of up to some 20 km/h. As grinding speed increases, machining depth decreases and there is a need for high rotational speeds of the stones to ensure a good surface quality. At higher speeds, reprofiling depth is so shallow that profile

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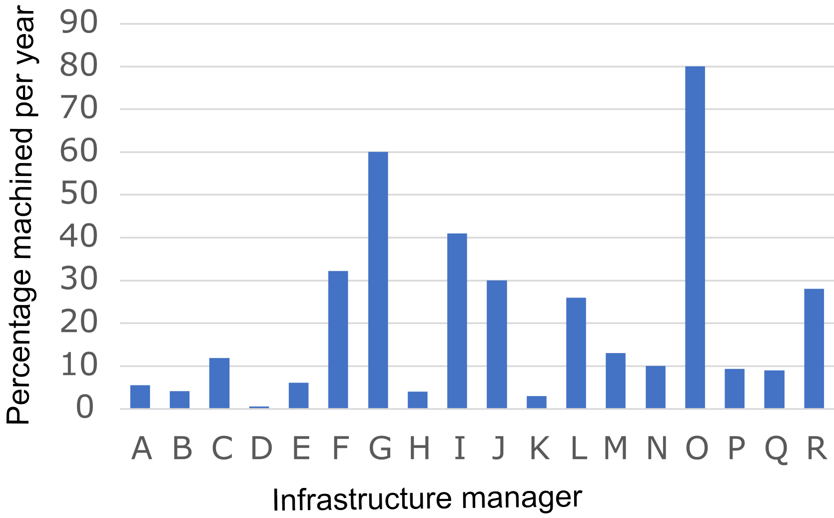

Figure 1: Estimation of the part of the network ground/milled per year.

geometry cannot easily be restored. On the other hand incipient cracks can be removed, and the speed is sufficiently high to limit disruptions in time-tabling. This is the philosophy behind high-speed grinding.

Milling allows for deeper (more than one millimetre) machining, results in less thermal loading, and provides a smoother rail surface. It is however slower (at best speeds of some km/h) and has a limit in how shallow machining can be. Milling is therefore commonly used for corrective maintenance with deep machining required over limited distances. Another common use is in tunnels and on bridges since milling chips can be easily captured. In addition, milling produces less sparks than grinding.

2 Current practices of rail machining

To evaluate operational rail machining practices, a questionnaire was distributed to infrastructure managers (IMs) through the UIC Track Expert Group. Sixteen responses, mainly from European railways were obtained in 2020. They were followed up by individual contacts where further information was needed.

The IM's rough estimation of the amount of rail machined annually showed a surprisingly large variation that could not be explained by operational differences, see Figure 1

The railways answering the questionnaire predominantly focused their maintenance strategies towards preventive maintenance with an aim to minimise corrective maintenance. To this end, there are a number of possible transition strategies.

To detect rail cracks, ultrasonic and/or eddy-current are the most common techniques. Photographic or video records are used only by a few railways. Planning horizons vary between seven months to three years. The variation seems to be related to the traffic situation.

2.1 Grinding

All railways employed grinding as the main technology for preventive machining, although one was shifting to exclusive use of milling. Grinding is usually reimbursed per shift, and performed in dedicated maintenance slots. Limited maintenance slots are indicated as a major challenge.

Most railways employ target profiles, and prescribe different grinding intervals for curves and straight tracks. About 50% of railways relate grinding intervals to mega gross tonnes (MGT) – in curves between 15 to 25 MGT, and in straight track between 45 to 60 MGT. No railway considered the rail grade in establishing rail grinding intervals.

Approaches on how to adjust to missed grinding cycles vary. Some railways aim to carry out the missed surface treatment immediately, while others postpone the grinding.

Most railways follow EN 13231-3 (now superseded by [5] see section 5) or internal rules based on this standard. Many railways use additional restrictions on grinding speed and/or depth.

2.2 Milling

About 70% of the railways do milling. It is mainly used for corrective rail machining mainly of deep rolling contact fatigue (RCF) cracks. It is unclear whether there is a best practice as for when milling should be preferred.

The price for milling is considered to be about 40% higher than for grinding, but this depends on depth of material removal and operational factors such as track availability, available machining equipment *etc*.

2.3 General aspects of rail machining

Grinding and milling is usually performed by external contractors with contracts running for 2 to 5 years. In general, the contractors have large responsibilities and freedom in how the work is performed – few railways have in-depth control of the execution of rail machining. Documentation and follow-up of quality and efficiency of machining show large differences between railways. This scattered response indicates a potential to gain better control over work performed.

Many IMs have the opinion that grinding and milling should be complementary, and technology selected based on required removal rates and operational speeds. With current knowledge this approach seems to be the best practice.

Identified drawbacks include risk of fire during grinding, material transformations especially during grinding, too low efficiency especially in relation to available maintenance slots, potential influences of grinding marks, slag left on track. The risk of too much surface treatment causing more problems than it solves was also highlighted.

Despite these potential detrimental effects, all but one railways are convinced that surface treatment is beneficial to the network in that it controls rail head geometry and surface defects and thereby increases rail life. There is however very scarce information on how large these benefits are. This is a key issue further addressed in the current report.

3 Rail machining objectives and consequences of not achieving these

The main objectives of rail reprofiling are rail head geometry restoration and surface defect removal. In practice, these objectives will not always be fully achieved as discussed below.

3.1 Maintenance of railhead geometry

To limit contact stresses, rail head profiles should feature a ‘sufficient’ match towards wheel profiles considering both allowed rail profile deviations before grinding and grinding tolerances. In practice ‘sufficient’ matching is a compromise considering all different wheel profiles passing the rail section. This also relates to lateral positions of the wheels, which depend on characteristics of running gear and track.

The transverse profile has significant influence on deterioration: In [15] a mismatching (within grinding tolerances) profile shifted wheel damage peaks from winter/spring to autumn on a heavy haul line. In addition to this ‘global’ profile match, there is a need for a ‘local’ profile match since the machined profile will not perfectly follow the (theoretical) rail head profile. In milling, this is normally less of an issue, whereas ground rail head profiles feature facets. Using more grinding stones narrows facets, but increases costs. Corners between facets are subjected to locally increased contact stresses that may plastically deform and/or wear down the peaks. If this is a fast process, detrimental consequences are limited. If not, RCF cracks may initiate. The border between ‘benign profile adaption’ and cracking is affected by operational loads and tribological conditions. As low-strength steels are subjected to larger plastic deformations and higher wear rates, the profile will adapt faster. However, wear and crack growth rates are generally lower in high strength rails, see e.g., [22]. Thus, tolerances should preferably be tighter for high strength rails, whereas grinding intervals can be longer.

Faults related to the longitudinal profile may arise from different reprofiling depths at different sections, or from transitions between machined and connecting rail sections. There may also be periodical (corrugation) faults caused by vibrations in milling and grinding vehicles especially at increased operating speeds. In addition, shorter faults may be caused by material fall-out or result from indentations or machining operations. It can be noted that removal of longer irregularities by grinding is restricted by the stone diameter (less of an issue for milling). Shorter irregularities are better from that perspective but may, if they are deep, require machining over a long distance to provide a smooth transition.

Longitudinal profile faults increase load and noise levels. The influence of corrugation can be assessed using simulations and measurements [20] if the large influence of high frequency vibrations is accounted for. Acceptable corrugation levels can be defined based on noise levels and risks of wheel and rail failures [43, 16]. Also influences of local faults can be assessed although results may be harder to interpret, cf. section 3.2. Transverse profile deviations cause less high frequency vibrations but affect both lateral and vertical vehicle–track dynamic interaction. The effects are thus more vehicle dependent.

The load situation is indicated in figure 2. As the (idealised) wheel comes into contact with the rough surface, the high local stresses may plastically deform asperities (indicated by the red asperity) and waviness, or wear them off (indicated by yellow), which alters contact stresses. A

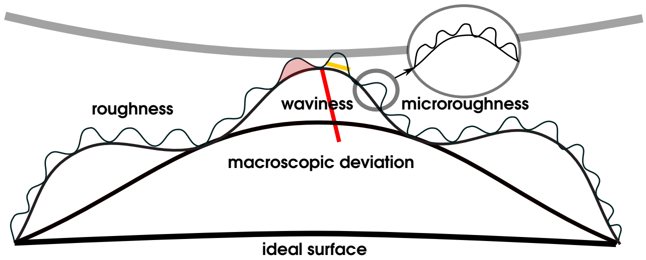

Figure 2: Idealisation of rail surface roughness at different levels in contact with ideal wheel surface (thick grey line). In the current context, 'waviness' corresponds e.g., to grinding grooves and 'macroscopic deviation' e.g., to corrugation (in the longitudinal cross-section).

crack may then form (red line). As it propagates, it exits the highly stressed zone and may arrest. This causes complexity and uncertainties to increase along the chain of predicting contact forces – contact stresses – plastic deformation – wear – crack formation. Here uncertainties relate to current knowledge, means to analyse the phenomena, and sensitivity to local conditions.

3.2 Removal of surface defects

With the exception of high speed grinding, the aim of grinding and milling is to completely remove surface defects. Ideally, rail machining and natural wear should then match crack growth rates at a 'magic wear rate' [36]. Incomplete removal may be due to an inability to detect deep cracks e.g., due to poor surface conditions and/or shielding [37, 9], failure to detect the full extent of the crack, cf. [26], or due to lack of maintenance time or grinding budget to remove all surface defects from all rail.

3.2.1 Influence of remaining surface cracks

Remaining surface cracks and grinding scratches decrease the fatigue resistance. To estimate consequences in plain (uniaxial) fatigue, the methodology in [38] is employed. The Murakami criterion [41] estimates the reduced fatigue limit σ_{erM} [MPa] due to a small surface crack as

$$\sigma_{\mathrm{erM}} = \frac{1.43\,(H_{\mathrm{v}}+120)}{\sqrt{area}^{(1/6)}} \tag{1}$$

Here H_{v} is the Vickers hardness [kgf/mm^2], $\sqrt{area}$ is projected defect area [μm]. The criterion is valid when σ_{er} is below the unreduced fatigue limit, σ_{e}, estimated as [41]

$$\sigma_{\mathrm{e}} \approx 1.6 H_{\mathrm{v}} \tag{2}$$

and σ_{er} is below threshold stress amplitude for crack growth according to linear elastic fracture mechanics

$$\sigma_{\mathrm{lefm}} = \frac{\Delta K_{\mathrm{th}}}{2F\sqrt{\pi a}} \tag{3}$$

where ΔK_{th} is threshold stress intensity for crack growth.

For a semi-circular surface defect of depth a [m] $F \approx 0.73$ [12], which gives

$$\sigma_{\mathrm{lefm}} = \frac{\Delta K_{\mathrm{th}}}{1.46\sqrt{\pi a}} \tag{4}$$

and

$$\sigma_{\mathrm{erM}} = 0.138\,(H_{\mathrm{v}} + 120)\,a^{-(1/6)} \tag{5}$$

This can be compared to the El Haddad criterion, [17], which defines a reduced fatigue limit

$$\sigma_{\mathrm{erEH}} = \frac{\Delta K_{\mathrm{th}}}{2\sqrt{\pi\,(a + l_0)}} \tag{6}$$

Presume (as in [17]) that l_0 is the length of a crack that will not propagate at the fatigue limit, which implies that the threshold stress intensity range at the fatigue limit is

$$\Delta K_{\mathrm{th}} = 2\sigma_{\mathrm{e}} F\sqrt{\pi l_0} \tag{7}$$

For fatigue limit testing, we presume a small crack in a test specimen with $F = 1$. Combining (7) and (6) gives

$$\sigma_{\mathrm{erEH}} = \frac{\sqrt{l_0}}{\sqrt{(a + l_0)}}\sigma_{\mathrm{e}} \tag{8}$$

Employing $F = 0.73$, $\Delta K_{\mathrm{th}} \approx 7\,[\mathrm{MPa}\sqrt{\mathrm{m}}]$ [12] and (2) in (7) gives

$$l_0 = \frac{1}{\pi}\left(\frac{\Delta K_{\mathrm{th}}}{1.46\sigma_{\mathrm{e}}}\right)^2 \approx \frac{2.86}{H_{\mathrm{v}}^2} \tag{9}$$

and

$$\sigma_{\mathrm{erEH}} = \frac{2.7}{\sqrt{\left(a + \frac{2.86}{H_{\mathrm{v}}^2}\right)}} \tag{10}$$

Equations 5 and 10 are compared in figure 3, which indicates that a 0.1 mm surface crack would reduce the fatigue strength with some 30% to 45% (Murakami) or 30% to 60% (El Haddad). The highest reductions are for high strength steels.

Short crack growth accounts for some 50% to 90% of plain fatigue life with a lower portion for short lives. Remaining cracks should thus be more severe for rails with longer operational lives, e.g., rails in shallow curves (or tangent track) and rails of premium grade steels.

In RCF the situation is more complex due to contact loading that promotes shear crack growth *etc*. Tests on the influence of surface roughness on RCF lives (see section 4.5) are inconclusive and should be taken with caution. Field investigations [50] indicate that residual cracks are more detrimental in shallow curves, but have less effect than in plain fatigue although there are uncertainties (e.g., crack sizes are quantified by surface length). There is also a large scatter, which may partly be due to altered wheel/rail contact loading of remaining cracks caused by the

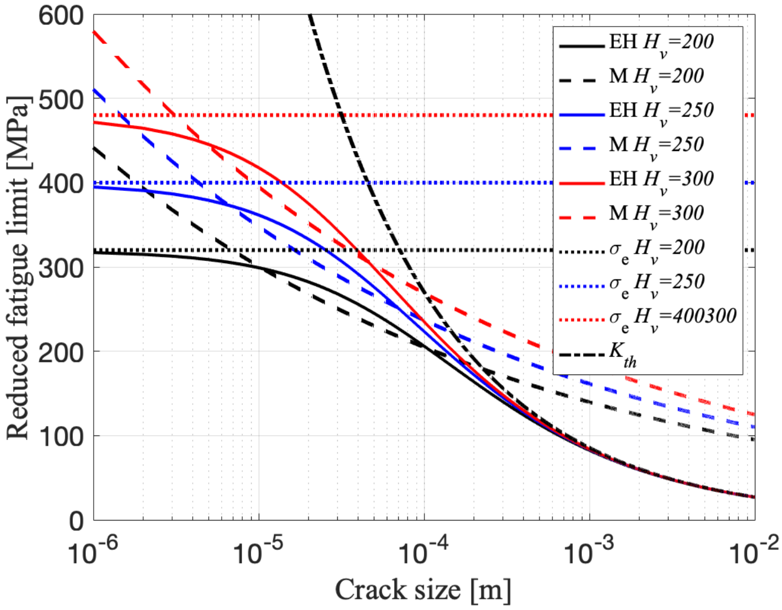

Figure 3: Comparison of El Haddad (EH) and Murakami (M) theory for small cracks and varying hardness levels (H).

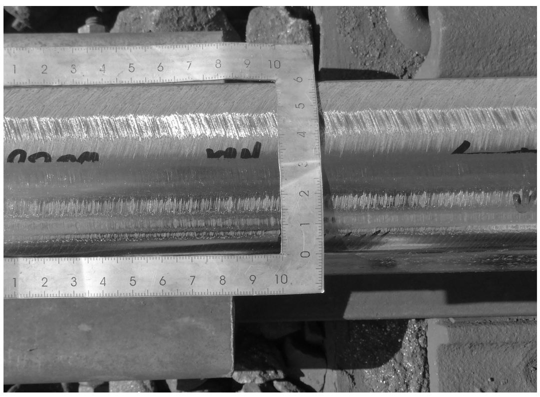

Figure 4: Rail with about a week of heavy haul traffic after grinding. Remaining gauge corner cracks indicated by inclined marks partially worn off by a passing train.

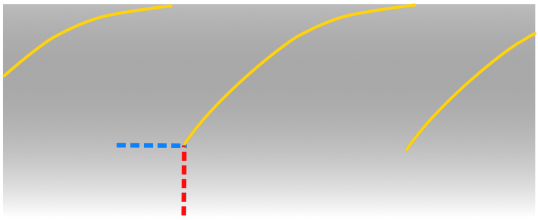

Figure 5: Schematic morphology of railhead cracks with initial growth along the deformed microstructure (yellow) and branching/deviation along the surface (blue), or towards transverse failure (red).

grinding, cf. figure 4. For a better understanding, more experimental and field studies combined with predictive analyses on growth rates of small RCF cracks is needed. This is a very complex topic where much research is still required, cf. [18, 42, 44].

To further understand the influence of remaining cracks after grinding, note that RCF cracks tend to initially propagate in a shallow angle to the surface, which deviates to a steeper angle that may be interrupted by a transition or branching to growth perpendicular and/or parallel to the surface, see figure 5. When the upper part of the crack is ground off, remaining cracks will have an orientation different from the 'preferred' growth direction. Consequently, growth rates should be lower than for a 'naturally oriented' crack.

Remaining local surface dents will have a significant effect on crack formation and growth even if they are shallow (tenths of millimetres) provide their width is sufficiently large [3, 4]. Plastic deformation and wear will gradually smooth out the defects. Some defects will thus wear off without adverse effects, whereas other will cause crack initiation and growth. In [33] the limit size was evaluated as a surface diameter of 7 mm. This is likely dependent on operational conditions.

4 Limiting detrimental effects of rail machining

4.1 Minimising rail material consumption

Minimising rail material consumption relates to risks of remaining profile deviations and/or surface defects. Since rail head cracks deviate towards transverse growth (see figure 5) which increases required reprofiling depth, it would seem that more frequent surface machining would limit rail consumption. There is however a minimum depth that has to be machined. Further, propagating rates of RCF cracks depend on the crack length. Numerical simulations of cracks at surface 'dimples', [3], indicated that close to surface dimples (that induce higher stress gradients than nominal wheel/rail contact) the propagation rate was actually less for larger (i.e., deeper) cracks than for more shallow cracks.

Operational experiences from five countries [14] indicate that at a depth of around 4–5 mm there is a sharp deviation to transverse growth for cracks causing rail breaks. Note that these cracks are likely subjected to higher tensile and bending stresses than non-fractured cracks. Still, not removing cracks before this depth would significantly increase maintenance costs and will induce a safety risk as crack growth rates increase towards transverse failure.

In summary, it is clear that (fairly) early surface machining is beneficial. However current knowledge is far from precise enough to allow for an optimisation.

4.2 Minimising traffic disruptions by improving machining efficiency

Rail machining includes transportation to work site, preparation work (e.g., measurements), reprofiling, finishing work (e.g., validations, disposal of grinding stones). An obvious benefit is obtained if more machine deployment time is devoted to actual machining. In [24] it is stated that internationally, some 60% of machine deployment time is devoted to production, including grinding, reversing, measuring and cleaning. Improvements can be obtained by more efficient transportation to work site, less need for multiple grinding passes, use of longer uninterrupted shifts *etc*. Also obtaining knowledge of pre-machining rail condition to improve planning e.g., through opportunistic maintenance planning [21] will be beneficial. The opposite – to wait with maintenance until rail machining is carried out at nearby sites – is possible but requires considerations regarding safety and progress of deterioration if maintenance is delayed.

Machining processes with higher material removal rates and/or higher operational speeds would increase efficiency. In grinding, this would require more aggressive abrasion with higher thermal input which may increase surface damage. Instead more frequent grinding at higher speeds (i.e. high-speed grinding) can be used. This would however require decreased reprofiling depths to limit heat input and risks of dynamic instability in grinding stones.

In milling, increasing the removal rate by deeper machining has limited influence on rail heating. On the other hand, the potential to increase operational speed is much more limited than for grinding.

4.3 Removal of the surface layer

Removing surface cracks and defects is positive and a core objective. However, this may leave remaining damaged surface material with microscopic cracks. Measurements indicate an affected layer up to some five millimetre deep with significant variation depending on rail hardness [23]. In this layer there have been plastic deformations with irreversible deformations causing material damage. The surface layer also features compressive residual stresses and material hardening which limit subsequent plastic deformations. Surface machining removes (part of) this layer and may heat the rail surface causing tensile residual stresses. At resumed rolling contact loading, material hardening [1] and compressive residual stresses [29] are restored.

The surface layer is also severely anisotropic due to rail material roll-out, see [40]. The influence of this anisotropy on RCF is complex, and it is currently difficult to give general statements regarding its effects on crack initiation and propagation, see [19].

Machining will move any subsurface defects closer to the surface and thereby increase their loading. This becomes less important as rail steels become cleaner. It is, however, still relevant especially for heavy haul rail with loads high enough to trigger subsurface initiated RCF also from small defects, and/or for welds were material defects are more common.

Figure 6: Thermal facets with local crack formation on a railway wheel. Note the different orientations of the thermal cracks and the RCF cracks.

Rail grinding removes any existing (natural, or artificial) interfacial layer that may decrease friction, and so can increase wear and RCF initiation [13]. As operations continue, the surface layer is restored. However, where artificial lubrication is used, it is recommended to lubricate directly after grinding to restore friction levels since low viscosity lubrication after dry operations may decrease RCF life significantly, see [48].

4.4 Thermal loading of the rail

Grinding (and to some extent milling) locally heats the rail head, which decreases the yield limit. This is of less importance since the heated rail only is loaded by grinding stones / milling wheels, and by work vehicle wheels. The localised heating may however increase susceptibility for crack formation due to residual stress formation, cf. figure 6 and [11]. In addition, if the temperature locally gets very high and cooling is rapid, martensite may form which further promotes crack formation, see e.g., [2].

The influence of grinding parameters on rail temperature is investigated in several studies. In [34] laboratory tests caused temperature increases with increases in rotational speed, grinding pressure, and grinding stone grain size. Colour shifted from yellow to blue as temperature increased to 735°C (the austenitizing temperatur). Grinding burns and white etching layers (WEL) appeared at temperatures over 600°C. At 800°C visible grinding and quenching cracks appeared. Martensite formed at temperatures above some 750°C.

In [51] analyses of thermal loading are performed and compared to experiments. Increased temperatures were found at higher grinding pressures and rotational speeds. WEL started to appear at 400°C, and yellow burning at 528°C, which can be compared to some 600°C in [34].

Heating due to grinding may result in tensile residual stresses. In [32] a grinding coefficient is derived as

$$B = P/(b_{\mathrm{d}} v_{\mathrm{w}}) \tag{11}$$

Here P is total grinding power, b_{d} grinding width, and v_{w} working speed of the grinder. The relation between B and maximum residual stress was found to be linear and not affected by studied grinding conditions.

In [49] a test case featuring a tram rail is presented. Case hardening depth increased and max Barkhausen noise (indicating material damage) decreased with increased cut depth and decreased feed speed.

Laboratory studies in [39] featured ground twin disc test samples with developed WEL. This caused decreased wear for the first 2500 cycles, but afterwards resulted in larger (but not more frequent) cracks than in non-ground discs.

The studies above indicate temperature limits for the formation of WEL, burning, and martensite formation, and how these temperatures are influenced by process parameters. However, exact limits and relations are still uncertain. which may be exacerbated by the high sensitivity in temperature measurements. It is also unclear how transferable results are between different materials and test/operational conditions.

4.5 Grinding induced surface roughness

Surface roughness influences wheel/rail interaction and resulting deterioration in a complex manner where phenomena interact. It is usually quantified as surface deviation, $z(x)$ averaged over length (R_{a}) or width (S_{a})

$$R_{\mathrm{a}} = \frac{1}{l}\int_0^l |z(x)|\,\mathrm{d}x \tag{12}$$

$$S_{\mathrm{a}} = \frac{1}{lw}\int_0^l \int_0^w |z(x)|\,\mathrm{d}x\mathrm{d}y \tag{13}$$

where l and w are length and width of the measured area.

Grinding causes surface roughness that increases with cut depth and feed speed, but decreases with increased rotational speed of grinding stones and decreased stone grain size [49, 34]. Increased pressure resulted in an unclear trend in [34] with initially increasing roughness, which decreased as pressure increased, stated to be an effect of martensite formation causing a more shallow grinding.

4.5.1 Influence on contact friction

Surface roughness influences the interfacial wheel/rail friction. Quantification of the influence of roughness in scaled tests under wet conditions [8] showed peak adhesion at a roughness of around $R_{\mathrm{q,eq}} = 1$ to 3 μm where $R_{\mathrm{q,eq}} = \sqrt{R_{\mathrm{q,w}}^2 + R_{\mathrm{q,r}}^2}$ with R_{q} being the root mean square average roughness and indices w and r indicating wheel and rail specimen. Increasing roughness beyond peak adhesion did not affect friction, or caused a slight decrease.

In [39] twin-disc tests of ground rail specimens featuring a WEL showed that the initial roughness caused a high coefficient of friction that initially dropped together with the roughness after which roughness and friction increased at the onset of macroscopic wear and then stabilised.

In [35] twin disc tests were carried out with wheels and rails featuring smooth ($S_a = 0.5$ and 2 μm for rail and wheel, respectively) and rough ($S_a = 2$ and 14 μm) surfaces. The lowest coefficient of friction after run-in was found for a rough wheel surface on a smooth rail surface.

From these examples, it is clear that no simple conclusions on how post-grinding surface roughness influences friction levels can be drawn. A large number of interacting parameters influence frictional characteristics in a complex manner, cf. [7]. Further, friction characteristics evolve over time, and are influenced by environmental factors such as precipitation, temperature, debris *etc*.

4.5.2 Contact stress distribution

Wheel/rail contact stresses are affected by surface roughness which transfers contact load to asperities. Elastic 2D analyses [30] indicate that this influences the elastic stress field in wheel and rail to a depth of about 0.1 mm with maximum subsurface von Mises stress essentially not affected [25]. In practice plasticity (and wear) further limits the effect as asperities are deformed, see figure 2.

There will also be stress/strain concentration effects in the troughs of the grooves, see figure 2. This may cause surface cracks to initiate and grow. The compressive loading however makes the effect limited. Cracks initiated at asperities will be shallow unless bulk contact stresses are sufficiently high to drive growth since local stress magnitudes at asperities decrease rapidly with depth.

4.5.3 Influence on rolling contact fatigue (RCF) life

The influence of grinding on subsequent RCF is studied in [45] where the influence of grinding on standard carbon (R260Mn) rail in a curve was compared to that of a heat-treated rail (R370crHT/MHH) in a curve. A complication with studies of RCF formation under operational conditions, as in [45], is the difficulty in distinguishing effects of grinding from the influence of other (operational) parameters. To this end laboratory experiments are useful even though they are limited by test equipment capabilities and typically introduce scale effects. In [10], an increased surface roughness caused an increased life in water lubricated twin-disc tests with $p_0 = 1.5$ GPa, but the effect saturated at a roughness level of about $R_a \geq 0.2$ μm. In [27] RCF life increased with decreased surface roughness for twin-disc tests of hard turned bearing steels in oil-lubricated contact with $p_0 = 3.8$ GPa. Experimental results from [10] and [27] are compared in figure 7. It should here be noted that rail grinding provides a roughness of around $R_a \approx 10$ μm [28]. This poses the question of whether the apparent saturation level in [10] is valid also for ten times higher roughness levels.

Run-in of ground surfaces is studied for twin-disc tests in [6] with $p_0 = 0.75$ GPa, slip ratios of 0 and 0.2%, and maximum roughness $R_z = 10$ to $R_z = 40$ μm (not comparable to R_a). After some 80 000 cycles, surface roughness decreased to the same values irrespective of the initial

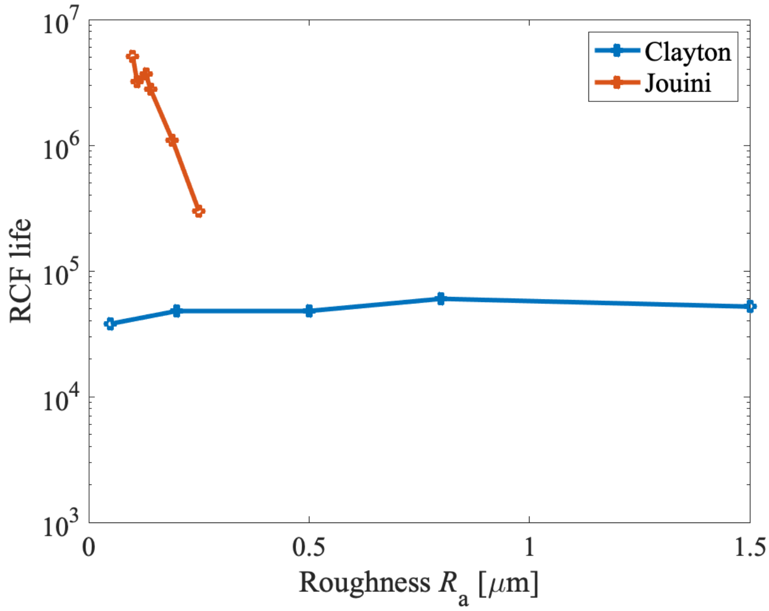

Figure 7: Influence of surface roughness (R_a) on RCF life, estimated from reported graphs in [10] and [27].

roughness. It was concluded that detrimental effects caused by high grinding surface roughness must be induced during this phase.

5 Optimising rail machining

The standard EN 13231-2 [5] specifies demands on, and verifications of rail reprofiling procedures. Two longitudinal profile tolerance classes and four transverse profile classes are defined. In summary, the classes specify percentage of measurements that may exceed prescribed limits. The standard specifies maximum facet widths and their maximum variation at different positions on the rail head and prescribes a 'smooth' transition to the parent (unground) rail.

The standard defines three surface quality classes based on an index combining low-pass filtered vertical profiles for three lateral coordinates. It is noted in the standard that the quality index relates to noise emissions.

The demand on thermal power is limited to a demand of no continuous blueing in the reprofiling zone.

It may further be noted that

- Class 2 has no restrictions for isolated defects with a wavelength below 30 mm.
- There is only one class for facet width limitations.
- No demand on RCF crack removal is defined.

There is significant room for more detailed specifications, which several IMs also impose. However, as the current study shows, current knowledge and predictive abilities essentially only provides an understanding of detrimental factors (such as facet width), but few means to quantify the influence under different operational conditions. Consequently, cost–benefit analyses of altered specifications (and procedures) become uncertain.

In addition to technical specifications, other factors related to maintenance planning that influence an 'optimum' reprofiling strategy include

- Reprofiling intervals – should be based on overall maintenance strategies, but also include operational considerations (time-tabling, machine availability *etc*)
- Reprofiling depth – influenced by intervals and deterioration rates, but also relies on decisions on full removal (or not) of existing cracks, and full restoration (or not) of rail profile.
- Number of reprofiling passes – relates to depth of reprofiling, available equipment and maintenance slots.

Maintenance planning requires means to predict needs for reprofiling. This requires prediction of wear and crack growth. Such predictions can be data driven (under steady-state conditions), or simulation based. In addition to the geometry and status of the track, the deterioration phenomena are influenced by operational factors such as

- Progressive deterioration of track that increases operational loads.
- Characteristics of trains and their operational parameters (speed, braking, acceleration *etc*).
- Rail material – a harder rail reduces crack development and wear rates [22], but has a slower profile adaption.

An optimum strategy further needs to consider overall costs, reliability, traffic disruptions, environmental issues *etc*. Consequently, machining strategies should be adapted to local operational conditions. However, this needs to be balanced by the need for (fairly) uniform and practical strategies across the network.

Follow-up of grinding efficiency requires data. At a first level, the amount of grinding and the interval combined with failure statistics provides a rough estimation of whether needs (and safety levels) are increasing or decreasing. In addition, information on curve radii intervals *etc* allows a comparison between track sections.

For improved assessment, more information is required on grinding geometry in relation to target profiles, rail gauge and track geometry deviations *etc*. Here profile quality indicators are useful, see [31]. Also repeated measurements of surface roughness, friction levels, and crack depth are useful in assessing post-grinding evolution.

5.1 Influence of traffic

Optimisation of rail machining relate to operational conditions. Mixed traffic complicates optimisation since the different types of traffic pose conflicting demands, which calls for compromises. In contrast, one type of train dominates heavy haul operations. This allows for a high level of optimisation where a 'mother nature strategy' that employs the profile worn in by the existing uniform traffic is used by some heavy haul operators.

New passenger trains are optimised for acceleration and deceleration that promotes new forms of rail damage (especially squats/studs). These tend to require more corrective measures since the formation is a relatively rapid process and prevention strategies are not tailored for these types of faults. In general, higher tractive (and braking) forces will increase RCF formation rates, se e.g., [13].

Metros and trams have special challenges (sharp curves, often placed in tunnels and on bridges, located in urban areas etc.) where milling often is a good option due to environmental aspects and simplicity in starting and finishing the work (getting on and off track).

For bidirectional traffic, twin disc tests [46, 47] show that rolling direction reversal has a beneficial effect on the RCF life of pearlitic rail steel. A reversal of direction at intervals of some 5% caused a 30% increase in RCF life. In the questionnaire (see section 2), only one responding railway considered traffic on single versus double tracks. Here single (two-way) tracks had 15–20 MGT more traffic before grinding. Heavy haul railways, which are often two-way, typically show high MGT values per rail life. How much of this that is due to bidirectional traffic and how much that is related to factors such as the ability to optimise grinding profiles (see above) needs to be studied more in detail.

6 Concluding remarks

As productivity demands on grinding increase, thermal power is becoming a key bottleneck that limits material removal rate. How that limit relates to machining parameters is today not fully understood. A key question is how transferrable the relatively few tests in the literature are to other operational conditions. To this end, current simulation abilities need to be enhanced and supported by well designed (physical and laboratory) tests. This can also improve the currently very vague directives in [5] e.g., on allowed thermal input.

Remaining surface cracks and other defects will decrease the operational life of rails. In general rails with the longest expected lives should experience the largest relative reductions in lives, but the current level of knowledge and predictive abilities only allow for a qualitative analysis of the decrease in RCF life.

The influence of removing the upper part of the surface layer is likely to be minor but beneficial. There is however limited research on mechanisms and magnitudes of this influence. Where artificial lubrication is used, lubrication directly after grinding is recommended to restore friction levels and prevent RCF crack initiation.

For rail grinding related roughness there is a significant lack of knowledge regarding how different parameters influence time for run-in (and induced damage during this time), saturation levels regarding friction, influence on RCF life *etc*. Two interesting questions are how interrelated a decrease in RCF life is to an increase in friction, and how the influence of scale effects are when twin-disc test results are transferred to full-scale wheel/rail contacts – roughness doesn't scale, but curvatures of contacting surfaces do. In addition transfer of knowledge (from experiments, tests and field experiences) is hindered by an inability to describe and account for variations in tribological conditions between investigations. To better standardise tests and quantification of test conditions, and to relate them to wheel–rail conditions is a field with a major potential for improvements.

Finally note that the current lack of knowledge and predictive models limits possibilities to estimate effects of altered rail machining. This restrains development and limits transfer of empirical knowledge between different operational scenarios and translation of (scaled) experimental tests to (full-scale) operations. The restricted ability to optimise rail machining is also likely to be a major reason as to why the amount of grinding and milling currently varies significantly between infrastructure managers: As long as it is not possible to quantify benefits of altered machining strategies, it is difficult to motivate modifications and avoid cuts in budget and track access.

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