Rail Grinding and its impact on the wear of Wheels and Rails

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Preface

The work presented in this thesis has been carried out at the Division of Machine Elements, Department of Applied Physics and Mechanical Engineering at Luleå University of Technology in Luleå, Sweden. The project has been financially supported by Banverket, LKAB/MTAB and Speno International AS. Banverket in Luleå, Sweden, has been the main industrial partner during the work.

A special thanks to my supervisors at the division, Professor Braham Prakash and Professor Erik Höglund, for their support and guidance during the project. All present and former colleagues at the division and the people at JvtC, are also due my gratitude. I would especially like to express gratitude to the persons from the industrial partners that have been involved in this project: Dr. Per-Olof Larsson-Kràik, Anders Frick, Thomas Nordmark and Dr. Wolfgang Schöch.

Finally, I would like to thank my family and friends, especially Elisabet Kassfeldt and my office mate Jens Carlevi, for always making time for discussions. Last but certainly not least, I thank my girlfriend Elin for her encouragement and patience throughout the cause of the project.

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Jonas Lundmark
Abstract

Rail grinding has been employed since the 1980s in maintaining optimal rail profile as well as in the elimination of surface defects such as corrugations and head-checks. Likewise, the wheel sets also require re-turning to remove surface defects and restore the desired profile. The influence of surface roughness in the wheel/rail contact has been a concern for railway owners since the introduction of rail grinding as a maintenance strategy. Presently, there are no scientifically derived guidelines regarding the surface topographies of ground rails and re-turned wheels. There is thus a need to establish well defined guidelines regarding the surface topographies for new surfaces on the rails and wheels in order to minimize grinding cost/time and improve wheel/rail performance.

This thesis concerns the influence of surface roughness of wheel/rail surfaces on running-in behaviour, wear, friction and resultant surface damage. The results presented in this thesis are based on both field measurements and experimental simulations in the laboratory. A two-disc rolling/sliding test machine has been used in the experimental work to simulate the wheel/rail contact. The test specimens were manufactured from actual wheel/rail parts. The machining/finishing parameters were chosen in such a way as to obtain different surface roughness on the test specimens. A Design of Experiment approach (DOE) has been used to conduct experiments and to analyse the results.

Results obtained from the field measurements show that the surface roughness of a newly ground rail changes rapidly during the initial stages following grinding. It was also concluded that there is a considerable variation of the surface roughness of re-turned wheels depending on which workshop performed the turning operation. Experimental results show that the surface roughness of the test specimens in certain material pairs do influence wear, friction and resultant surface damage. There is also a significant difference in the tribological behaviour of tests run in dry conditions and those run with water lubrication.
Thesis

This thesis consists of the following papers;

Paper A

Paper B

Paper C
J. Lundmark, B. Prakash, The influence of surface topography and water lubrication on the wheel/rail interface during rolling/sliding conditions, to be submitted for journal publication
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1 Introduction

1.1 Tribology

Tribology is the science and technology of friction, lubrication and wear, derived from the Greek “tribo” meaning “I rub” and defined as the science of interacting surfaces in relative motion. In any situation where one surface rolls or slides over another, whether lubricated or not, it is affected by complex tribological interactions. Sometimes it is desirable to have low friction, to save energy, or high friction, as in the case of brakes or in the running band of a wheel/rail contact. There are many parameters influencing the performance of a tribological system, either dry or lubricated. This is the reason why designing realistic simulation tests and creating models of surfaces in contact is a complex task.

1.1.1 Friction

The friction force is the resulting resistance when a solid object in contact with another is moved tangentially with respect to the surface of the other. The ratio of the friction force (F) to the normal load (W) is called the coefficient of friction (μ). Usually, low friction is desirable as high friction results in energy losses. On the other hand, high friction is crucial in some applications such as brakes, tyres and shoes. Depending on the contact conditions, the friction can be divided into two main categories: rolling friction and sliding friction. Within each main category there are further classifications depending on whether the interface between the surfaces is dry or lubricated. To be able to determine the friction coefficient for two surfaces in contact, a large number of variables need to be known as friction is a system response and not decided by material parameters only. Owing to the difficulties of determining all parameters, it is therefore in many cases only possible to give rough estimation for the friction coefficient.
1.1.2 Wear

Wear is the process leading to loss of material from one or more solid surfaces in a sliding, rolling or impact motion relative to one another. As with friction, wear is not a material property, it is a system response. It is common in the railway community to divide the wear seen in the field into three regimes: mild; severe; and catastrophic. The different regimes were introduced by Bolton and Clayton [1], and refer to the severity of the wear. When describing the mechanism of how material is lost, there are six major types of wear including: abrasive; adhesive; impact by erosion and percussion; fatigue; chemical (or corrosive); and electrical-arc-induced wear [2]. In many cases the wear process is a combination of these mechanisms adding to the complexity. Theoretical prediction of wear is therefore difficult and wear coefficients are often calculated from experiments to get accurate results. The most commonly used wear equation when dry sliding contacts are investigated is Archard’s wear equation (1). The wear volume \( V \) per unit sliding distance \( S \) equals the non-dimensional wear coefficient \( K \) multiplied by the applied load \( F_N \) divided by the hardness of the worn material.

\[
\frac{V}{S} = K \frac{F_N}{H}
\]  

(1)

Wear calculations using Archard’s wear equation are usually only an approximation since there are a number of assumptions made when applying it. The best results are given when the hardness of the two bodies differ significantly, for example a chalk and a blackboard. One problem with using Archard’s wear equation arises when some metals work harden as the surfaces deform.
2 The wheel/rail contact

As the outer rail in a curve is situated higher in a curve due to canting, it is called the “high rail”. The inner rail is lower than the outer rail and is therefore called the “low rail”. The inside of the rail head facing the other rail is called the “gauge face” and the outside of the rail head is, for obvious reasons, called the “field face”. In the wheel/rail contact both rolling and sliding motion occurs. Sliding motion can be found in sharp curves where the wheel flange is in contact with the rail head at the gauge corner. In the wheel/rail interface, there must be low friction to permit moving heavy loads with little resistance as well as sufficient friction to provide tractive effort, braking effort, and steering of the train. Generally there is a desire to keep the friction between the wheel flange and the gauge face of the rail as low as possible to reduce wear in this area and decrease the rolling/sliding resistance in curves. This can be attained by lubricating the gauge face of the rail with either trackside lubricators or onboard lubricating systems. The influence of lubricants on wear in sharp rail curves has been studied by Waara [3]. Rail lubrication is one of the environmental parameters of the wheel/rail contact that can be controlled. Other parameters, like weather conditions, are not possible to control although they strongly influence the tribological environment in the contact between the rail and the wheel. This difference in operating conditions will lead to differences in wear and frictional behaviour for both wheel and rail. It has been seen by other researchers [4] that precipitation has a significant influence on rail wear. In this study, field measurements revealed that rail wear decreased with increased daily precipitation and lower temperatures. It was concluded that precipitation creates a natural lubricating layer of water in the wheel/rail contact and may also absorb energy when transformed from solid or liquid phase to gaseous phase.
A wheel/rail contact can be divided into three regions as can be seen in figure 1.

- **Region 1**: Contact between the field side of both rail and wheel is taking place on the low rail in sharp curves. Contact stresses can be high due to “hollow” worn wheels.
- **Region 2**: Contact between the central region of the rail crown and wheel tread is where contact is made most often when vehicles are running on straight sections of track or in mild curves. Contact stresses in this region are the lowest found between the rail and the wheel due to the relatively large contact area.
- **Region 3**: Contact between the gauge corner of the rail and the wheel flange is found in sharp curves.

*Figure 1. Regions in the wheel/rail contact.*
2.1 Rolling resistance

Pure rolling ideally occurs between two bodies which have the same elastic properties, are geometrically identical and experience little deformation in the contact region. Rolling resistance is mainly a combination of hysteresis loss and micro-slip. Micro-slip occurs due to differences in diameter in the elliptical contact created between the rail and the wheel. Micro-slip also occurs as the materials deform elastically. The arc length a-b in figure 2, representing the contact length, is reduced in length for the rolling wheel, while it has increased in length for the rail. This will result in micro-slip, sometimes also referred to as Reynolds slip.

![Figure 2. Micro-slip in wheel/rail contact.](image)

In tractive rolling, as in the contact between the locomotive wheel and the rail, the friction force must be less than or equal to $\mu W$ where $\mu$ is the coefficient of friction and $W$ the normal load. If the friction force attains a value greater than $\mu W$, local sliding (micro-slip) or gross sliding (in the entire contact) occurs. The heaviest wear in the rail/wheel contact will be located where the most sliding occurs. From an energy point of view, the smallest energy losses are therefore found where there is pure rolling.
3 Rail grinding

One of the important aspects in wheel/rail interface management is the introduction of rail grinding. Rail grinding has been used since the 1980s in maintaining optimal rail profile as well as the elimination of surface defects such as corrugations and headchecks. The rail grinding process has progressed from a technique for removing corrugations to a high-tech multi-purpose maintenance technique. Rail profile correction, noise reduction and removal of contact fatigue induced head-checks are some of the main reasons for grinding the rails. The Swedish railway network, owned by Banverket, covered about 17 000 kilometres in the year 2003. The yearly grinding, referred to as maintenance grinding by Banverket, involves about 1000 kilometres at a cost of approximately 50 MSEK. In addition to maintenance grinding, preventive grinding and grinding of switches is also performed at an annual cost of 15-20 MSEK. Rail grinding in Sweden is currently performed by grinding train equipped with rotating grinding stones driven by electric motors. Each motor can be pivoted with motion controlled by a hydraulic system. The grinding stones in contact with the rail will produce grinding facets on the newly ground rail surface. The number of facets depends on the number of grinding stones in contact and how they are located. By adding grinding train units, the productivity of the grinding train can be increased.

3.1 Grinding modes

When grinding is used to correct rail surface conditions there are three different types of grinding modes as specified by Cooper [5]:

1. Preparative: cleaning mill scale and construction damage from newly-laid rail to assure optimal initial conditions for commercial service

2. Preventive: removing fatigued metal before micro-cracking leads to more serious damage

3. Curative/corrective: recovering rail that has been damaged by ballast imprints or other foreign bodies pressed into wheels etc
The relative merits and demerits of corrective grinding compared to preventive grinding are well known and have been reported by several researchers [6, 7, 8, 9, 10, 11]. By adopting preventive grinding, the overall volume of removed material can be reduced and rail life prolonged. A corrective grinding mode removes the work-hardened layer leaving behind a surface with soft steel and with some residual cracks still present due to the fact that the deepest cracks could not be removed. If, on the other hand, a preventive grinding mode is used, a surface free of cracks with fresh, work-hardened material is left behind. The preventive grinding mode has the advantage to be well planed as rail breaks will not be as frequent as before. The rail can be replaced when worn beyond a specific value which will be relatively easy to foresee, instead of being replaced when fatigue or other types of deterioration that are more unforeseeable, have occurred. Unplanned activities tend to be very costly for railway owners as it hinders traffic during maintenance. A rail break on a heavily trafficked line will at the best hinder traffic during the time for replacement of the broken rail, but could also lead to derailment or even loss of life. Another advantage with preventive grinding is that it requires machines with fewer grinding stones as less material is to be removed. The cost for the grinder can therefore be reduced. Tests on a heavy-haul system [5] showed that a preventive grinding strategy could increase the rail life by up to three times compared to that of a corrective ground rail. The costs for each kilometre of grinding were reduced and the railway company can grind more track miles for the grinding budget.
The statement “magic wear rate” has been used to indicate the optimum amount of metal to be removed both by natural wear and through material artificially removed by grinding to optimise the service life of rails. Rails with a wear rate higher than the optimum wear rate will have a shorter service life. Insufficient wear will lead to fatigue while cracks will have propagated deeper than the worn surface of the material. To be able to achieve the magic wear rate, both adequate lubrication and a preventive grinding strategy are usually required. As all track sites are specific in terms of axel loads, speeds, annual tonnage, lubrication, rail/wheel material, boggie types etc. the magic wear rate has to be determined for each rail system. Other factors that will play an important role are environmental aspects such as temperature, humidity and precipitation which also can change drastically during the year and differ from one rail system to another. By monitoring the status of the rail system, the magic wear rate can be found and the grinding intervals and metal removal rate can be decided, see figure 3 [10, 11].

![Figure 3. “Magic” wear rate.](image-url)
Table 1. Rail surface roughness after grinding.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Grit #16</th>
<th>Grit #20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 km/h</td>
<td>11 km/h</td>
</tr>
<tr>
<td>$R_a$ ($\mu$m)</td>
<td>10,7</td>
<td>11</td>
</tr>
<tr>
<td>$R_{max}$ ($\mu$m)</td>
<td>61,8</td>
<td>73,5</td>
</tr>
<tr>
<td>$R_{tm}$ ($\mu$m)</td>
<td>53,3</td>
<td>54,5</td>
</tr>
</tbody>
</table>

Where:
$R_a$ - “Centre line average”, arithmetic mean of the departures of the profile from the mean line.
$R_{max}$ - maximum measured peak-to-valley height for the area sampled.
$R_{tm}$ - mean peak-to-valley height between the adjacent peaks and valleys.

Metal removal is dependent upon the characteristics and condition of the abrasive stones and the applied pressure as well as the speed and angle between the grinding stones and the rail. Tests with grinding stones containing different grit size [7] have shown that a rougher stone leaves behind a rougher surface and increasing speed also increases the roughness, see Table 1. The average particle size of abrasive grains are 1,66 mm and 1,34 mm for grit size 16 and 20 respectively. For the railway owners, it is extremely important that rail grinding is carried out in the shortest possible time as it hinders the regular traffic. The desire to adopt the preventive grinding mode and spend as little time as possible on the rail with grinding trains creates a dilemma, as grinding has to be carried out more often. But as preventive grinding requires less time at every occasion, it is easier to squeeze into the timetable. Single pass grinding instead of multi-pass grinding is preferable in terms of rail access time but it requires a more effective grinder. This has raised demands on the rail grinding contractors to improve the productivity of their grinders. Productivity can be achieved by using grinding trains at higher speeds, using rougher grinding stones and/or higher grinding pressures. All these factors may result in greater relative surface roughness of ground rails. An increase of the grinding speed will reduce metal removal if all other parameters are kept constant [6].
3.2 Rail profiles

The shape of the mating surfaces in a wheel/rail contact has been the subject of interest for railway researchers for a long time. It is through this tiny contact that the load from the train will be supported and also given its steering capability in curves. The use of engineered rail profiles is a well known way to improve the wheel rail contact [7, 9, and 10]. Choosing the rail profile will most often be a compromise for the railway administrator. Most tracks are used as mixed traffic tracks and both car types and train weights can vary a lot. By grinding the rail profile to a similar shape to that of a worn rail, contact stresses as well as curving performance can be improved [12]. On straight track, rail grinding can be used to move the running band towards the gauge or field side of the rail from one grinding campaign to another. The reason for moving the running band is to distribute the wear on the rail head and minimize the number of wheel passes that leads to fatigue.

3.3 Surface roughness

Surfaces may look smooth, but on a microscopic scale they are rough. When two surfaces are pressed together, contact is made at the peaks of the roughness or asperities. The real area of contact can be much less than the apparent or nominal area. At the points of intimate contact, adhesion, or even local welding, can take place. To create a sliding motion of one surface over the other, a force has to be applied to break those junctions. Surface roughness is the component of surface texture given by the production process but excluding waviness and deviation of form. The influence of surface roughness on the performance of wheel/rail interface has not been well researched and the consequences of ground rails having a coarse surface are not yet known. In Europe today it is common to specify a maximum surface roughness, $R_a$-value, of 10 μm. This value has also been implemented in the draft specifications for CEN-standard prEN 13231-3 and is considered to be a good compromise between surface roughness and metal removal, but no scientific investigation of the influence of roughness has been done.
The $R_a$-value is the one most commonly used and is defined according to equation (2) and figure 4.

$$ R_a = \frac{1}{l_r} \int_{x=0}^{x=l_r} |z(x)| \, dx $$  \hspace{1cm} (2) 

Figure 4. Schematic of a surface profile.

The evaluation length for assessing roughness, $l_n$ in figure 4, is standardized in ISO4288. For every roughness measurement, roughness values are calculated over five adjacent sampling lengths, $l_r$ in figure 4, and than averaged. The $R_a$-value alone is not enough to completely describe a roughness profile of a surface as it, for example, does not state anything about the shape and number of asperities. Nevertheless, given the manufacturing process of the surface, it is extensively used for comparative measurements of surfaces. It is common to use a capital letter “S” (for Surface) to identify 3D parameters as opposed to “R” for 2D parameters. More on 3D surface topography measurements can be found in [13, 14].

If a rough surface is ground so that the ratio of the pitch to the depth of the grinding marks is small, the asperities could fold over each other when deformed during service causing cracks to grow. The presence of water/moisture or lubricant in the contact after grinding could also have an accelerating effect on wear and surface defects. Previous work [15] in a twin-disc test machine showed that oil is more effective in reducing crack face friction while water is able to penetrate the crack tip more easily. It is well known that heat introduced by the grinding stones is absorbed by the uppermost layer of the rail, transforming it to hard martensite [7]. When the martensite peaks are worn away by traffic, wear debris from the surface with a hardness of 1000 HV100 could be embedded in the wheel causing accelerated wear of the rails. A rail ground with a rough stone...
would then experience more wear due to the larger debris embedded in the wheel. If block brakes are used on the trains trafficking the newly ground line, the wear of wheels could be accelerated if wear particles from grinding are embedded in the braking pads. The role of resultant surface roughness of ground rails and its influence on wear in the wheel/rail contact has been indicated but this aspect has not yet been thoroughly investigated [9, 16, 17]. The role of rail surface roughness on noise and vibration has been investigated and proven by several researchers [18, 19, 20]. With lighter axle loads, a rougher surface will cause more problems with noise and vibration than a smoother surface. The rougher surface after grinding has a longer running-in time and therefore produces noise for a longer time. This is the reason why some grinding companies polish the rail after it has been ground. Problems with noise and vibration are mostly found in urban areas with frequent traffic. On heavy haul lines the roughness is smoothed out after some days due to the higher axle loads and the demands on noise levels are also not as strict as for the urban lines. Kapoor et al. have shown that surface roughness plays an important role in subjecting a thin layer to severe contact stresses [21]. The pressures at asperity contacts in some cases exceeded the limiting values by an order of magnitude. Similar results have also been reported by other researchers [8, 22]. From these results it was therefore expected that surface roughness will adversely affect the fatigue life of rails. The role of rail surface roughness is likely to be much more significant in view of the trend towards the use of harder and two-material rails. Field tests on Malmbanan in Sweden with two-material rails have shown that grinding marks were still visible after the tests conducted from 27 September 2001 to 2 May 2002, or 6,7 MGT (Million Gross Tonnes) [23]. If the roughness after grinding does not influence the wear of wheels or deterioration of rail, it would be possible to use coarser grinding stones with higher stone pressure to increase the productivity of the grinders. By being able to increase the productivity, time on the track for the grinders could be lowered by using single pass grinding instead of multi-pass grinding or by increasing the speed of the grinding train.
4 Objectives

The overall aim of this thesis has been to get a better understanding of the influence of surface roughness on traction, wear and fatigue life of rails and wheels in the presence of air and moisture/water. The running-in of new wheel and rail surfaces has been studied to investigate the variation in the produced surface roughness and how long the initially produced surfaces are present and how it affects the future tribological performance. The ultimate goal is to identify appropriate surface roughness specifications that can be employed during rail grinding and manufacturing of wheels. If needed, a strategy for running-in of new rail and wheel surfaces will be presented.

The work is limited to small scale surface roughness, typically in the micro scale, produced within the same grinding facet on the rail. Waviness, wheel flats and other irregularities on wheels and rail have not been covered in this study.
5 Experimental methods

This chapter gives a brief overview of the experimental techniques and equipment used in the present study.

5.1 Design of experiments

Experimental design is a method used to plan and conduct experiments in order to extract the maximum amount of information from the collected data in the fewest number of experimental runs. By varying the chosen factors simultaneously over a set of planned experiments, the factors and the response can be connected by means of a mathematical model. This model is then used for interpretation, predictions and optimization. In most cases, the influencing parameters are not known and therefore a screening test could be performed where many parameters are used as factors and the results reveal which parameters are significant for the response. During an investigation one needs answers to the following questions: Which factors have a real influence on the responses? What are the best settings of the factors to achieve optimal conditions for best performance of a process, a system or a product? What are the predicted values of the responses for given settings of the factors? An experimental design can be set up to answer all of these questions.

Perhaps the simplest and most commonly used technique used to define the set of experiments is the two-level full-factorial design which forms the basis for many other techniques. The investigated design space is defined by assigning each variable to be investigated with a high and a low level. The meaning of full-factorial design is that experiments are performed for every possible combination of factors and factor levels. For a design with \( k \) variables the number of experiments performed for a two-level full factorial design is \( 2^k \). Geometrically, the created experimental design may be interpreted as a cube if three variables \( X_1, X_2 \) and \( X_3 \) are investigated. With three variables and each variable assigned with two different levels the number of performed experiments becomes \( 2^3 = 8 \). Normally, replicated runs are carried out in the centre of the investigated design space if the factors are qualitative. Repetition of the experiments is done to determine the size of experimental variation known as the replicate error. More on Design of Experiments can be found in [24, 25].
5.2 Two-disc machine

The test rig used in the experimental work in this thesis is the Wazau UTM 2000 two-disc machine, see figure 5.

In the UTM 2000, both specimens are arranged in a horizontal position next to each other and loaded against each other by means of a dead weight system. The cylindrical disc specimens are mounted on separate shafts, each driven by a servo drive. The drives can be individually controlled which enables testing under conditions from pure sliding to pure rolling and also continuous or oscillating motion. When slip is desired at the disc contact, one of the servo drives will acts as a “brake” and the other as a “motor”. The specimens are secured with a conical clamp unit on the end of the shaft. The clamping unit will automatically centre the specimen on the shaft. The applied load is measured with a force sensor on the load lever and the maximum load that can be applied is 2000 N. One of the two servo drives is mounted on a slider which enables disc specimens from 45 mm to 80 mm in diameter to be used. The speed of the drives can be adjusted separately and step-less from 0,1 rpm to 3000 rpm. Direction of rotation can also be chosen for each of the drives. The friction force is calculated by measuring the traction force between the disc specimens with a torque sensor mounted between one of the servo motors and the shaft where the specimen is mounted.
The coefficient of friction is specified as:

\[ \mu = \frac{M \cdot 1000}{F_N \cdot \frac{d}{2}} \quad (3) \]

with \( \mu \) = friction coefficient [-]
\( M \) = torque [Nm]
\( F_N \) = normal force [N]
\( d \) = diameter [mm]

The slip can be controlled in the range 0.5\% to 20\% with an accuracy of 0.5\% by adjusting the rotational speed and is defined as:

\[ S = \frac{(n_1 - n_2)}{n_1} \quad (\text{if } n_1 > n_2) \quad (4) \]

with \( n_1 \) = rotary speed of drive 1 [min\(^{-1}\)]
\( n_2 \) = rotary speed of drive 2 [min\(^{-1}\)]

The test specimens were machined from actual rail and wheel components to simulate the actual conditions as accurately as possible. Hardness profiles of the supplied wheel and rail material have been performed to ensure that there was a uniform hardness through the profile.
The maximum contact pressure $p_0$ (MPa) is calculated by the formula suggested by Timoshenko and Goodier [26].

$$p_0 = 0.418 \left( \frac{WE}{TR} \right)^{\frac{1}{2}}$$

(5)

Where $W$ is the contact load (N), $T$ is the line contact length (mm), $E$ is the modulus of elasticity of steel (MPa) and $R$ is calculated by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

(6)

Where $R_1$ (mm) and $R_2$ (mm) are the radii of the disc specimen.

### 5.3 Miniprof

To be able to follow the wear and profile change of the rail, a Miniprof rail profile measuring device has been used, see figure 6. A description of the device can be found in Esveld and Gronskov [27]. By taking repeated profile measurements at the same location on the rail, the difference between the profiles can be calculated using the Miniprof software. The rail wear can then be calculated as the difference between the reference profile and the latest measurement.

![Miniprof rail profile measurement equipment](image_url)

*Figure 6. The Miniprof rail profile measurement equipment.*
6 Results and discussion

The results obtained from field measurements in paper A on the newly ground rails and during the initial running-in stage are presented as pictures and 3D images in Figure 7. It can be seen that the topography of the ground rail in the running band changes quite rapidly due to the passage of traffic. In approximately 35 hours, or 26 800 tonnes, the roughness of the surface was reduced from $S_a \sim 10 \mu m$ to $S_a \sim 1 \mu m$. These results indicate that the running-in of a newly ground rail on the Malmbanan essentially takes place during the first day of traffic. The change in roughness after the first day’s traffic is almost negligible.

![Figure 7. Running-in process of newly ground rail (Paper A)](image)
Results from the measurements on plastic replicas taken from the wheel surfaces are summarised in Figure 8. It can clearly be seen from these results that surface roughness values for the new wheels and those for the wheels re-turned at the two workshops differ significantly. The wheel surface produced at Duroc is the roughest ($R_z \sim 92 \, \mu m$) and it is three times rougher when compared to that re-turned by MTAB.

![Graph of initial wheel surface roughness](image)

*Figure 8. Initial wheel surface roughness (Paper A)*
From simulation tests in the two-disc machine presented in paper B, it was seen that wear of the driving wheel disc was generally higher than that for the driven rail disc. If the 1100 rail material is used, both wheel material and wheel roughnesses seem to be of importance. In all experiments with the Blue Light wheel material, the rougher wheel specimen resulted in lower wear than with a smooth wheel specimen. It was also obvious that there was a larger variation in the results in tests with the 1100 rail material as compared to that with boron rail material. It appears that the 1100 rail material is more sensitive to changes in operating conditions. From Fig. 9 it can also be seen that the wear rate of the wheel discs is less dependent on changes in counter-face material and surface roughness than the rail disc.

![Figure 9. Specific wear (Paper B)](image-url)
Simulation tests in the two-disc machine were run in dry and water lubricated conditions. Results from tests run in dry conditions (Paper C) are shown in figure 10. In both wheel material combinations, a rougher wheel has resulted in lower wear in all cases but one. The difference in total wear is mainly due to the changes in wear of the rail specimens. Using bainitic wheel material has resulted in more wear on both wheel and rail specimens.

It was also found that the wear of rail specimens increased significantly in the presence of water, see figure 11. Conversely, wear of all the wheel specimens decreased in the presence of water with most significant reduction occurring in smooth wheel specimens. The effect of the surface roughness of the rail specimens was not as clear as that for the wheels. This can be due to the differences in orientation of the surface roughness on rail and wheel specimens. The wear rate of the rail specimens has increased in all cases in the presence of water with the smallest increase being found in cases involving Blue Light wheel material and rough rail surfaces. As in the dry tests, the bainitic wheel material has demonstrated more wear compared to that for the Blue Light material. Rough rail specimens have resulted in higher wear in all combinations. Rough wheel specimens have resulted in lower wear in all tests except one.
The friction characteristics of different pairs from the dry tests are given in figure 12. These results show relatively stable friction behaviour following the running-in period. Irrespective of the wheel materials, the combinations with smooth wheel surfaces have resulted in higher friction than those with rough wheel surfaces despite the fact that their resultant surface roughness have similar values. In dry tests with Blue Light wheel material, the friction coefficients have generally been lower than those with bainitic wheel material. Smooth wheel specimens have however resulted in initial friction peaks during the running-in period.

Figure 11. Specific wear from water lubricated tests (Paper C)

Figure 12. Left: Friction plot of bainitic – 1100 dry tests, right: Friction plot of Blue Light – 1100 dry tests
The friction coefficients in the presence of water are lower compared to those run in dry conditions, see figure 13, although some instability in frictional behaviour has been observed. As seen earlier in the case of dry conditions, the initially rough wheel surfaces have resulted in lower and more stable frictional behaviour, especially in tests with Blue Light wheel material.

*Figure 13. Left: Friction plot of bainitic – 1100 water lubricated tests, right: Friction plot of Blue Light – 1100 water lubricated tests*
7 Summary of appended papers

7.1 Paper A
The work includes a field study of the running-in behaviour of new rail and wheel surfaces by using a plastic replica material to record the change of surface roughness due to traffic. Rail profile measurements were taken simultaneously to monitor the change in rail profile during the running-in period. A 3D optical surface profiler was used to analyse the surface of the plastic replicas taken of the rail and wheel surfaces. The surface roughness of re-turned wheels was also investigated as they were suspected to differ depending on which workshop carried out the turning operation. The field measurements were conducted on the iron ore line, Malmbanan, between Gällivare and Luleå and on wheels from an ore wagon. The results obtained indicate that new wheel/rail surfaces run-in rapidly. The $S_a$-values of the newly ground rail decreased from 10 $\mu$m to 1 $\mu$m after one and a half days of traffic or 260 800 tonnes. It was seen that the profile change (or wear) was relatively large in comparison with the change in surface roughness. Nevertheless the grinding marks were still visible which indicates that the profile is plastically deformed during the running-in period. It was also seen that the roughness of newly turned wheels differed significantly depending on where the wheels were turned.

7.2 Paper B
The aim of this study was to investigate the influence of initial surface roughness on running-in behaviour, wear, friction and resultant surface damage for different wheel/rail materials in dry conditions. This work was conducted as a screening test and covered both commercially available materials as well as new materials. A design of experiments approach was used to plan the experiments and analyse results from tests run in a two-disc rolling/sliding test machine in the laboratory. The test specimens were machined from actual wheel/rail materials and the operating conditions of the test rig were chosen to simulate the real conditions as closely as possible. Two different surface roughness values were produced on both the wheel and rail specimens. The results show that the surface roughnesses in some material pairs do influence wear, friction and resultant surface damage.
7.3 Paper C

The influence of surface roughness on wear, friction, work hardening and resultant surface damage has been investigated in a two-disc machine under dry and water lubricated conditions. As in paper B, the work includes a two-level full-factorial DOE approach for determining the relation between the investigated factors and the responses. In contrast to paper B, this detailed study focused on rail materials that are commercially available and presently in use. Advanced analytical instruments including a 3D optical surface profiler, micro hardness indenter, light microscope and SEM/EDS were used to analyse the test specimens. It is shown that the mechanism seen in dry tests clearly differs from the mechanism seen when the contact was lubricated with water.
8 Conclusions and future work

In this work the influence of surface topography of new wheel/rail surfaces on running-in behaviour, wear, friction and resultant surface damage has been investigated. The results presented in the thesis are based upon both field measurements on wheels and rails and systematic experimental studies in the two-disc machine. It has been shown that the surface roughness of wheels re-turned at different workshops differs significantly. The experiments have not shown a uniform result as to whether the difference in roughness would have a positive or negative influence on wear of the test specimens. In contrast to the wear, a clear relationship can be seen between the roughness of the wheel specimens and the coefficient of friction, independent of material combination and lubricating conditions. Even though the initial surface roughness produced on the surfaces is worn down during the test, the friction coefficient stays constant during the whole test. The lower coefficient of friction seen when rough wheel disc surfaces are used has also influenced the amount of work hardening. This indicates that the surface roughness on the new surface does not only influence the tribological behaviour during the initial running-in phase but also after the surfaces have been run in. This implies that even though the running-in of rail and wheel surfaces seen in the field measurements are rapid, it could influence the friction coefficient resulting in higher surface stresses and therefore also affect the degree of work hardening.

Future areas for investigation include other operating conditions such as slip, duration, contact pressure and lubrication. There is also a need to investigate the influence of sub-zero temperatures on tribological performance at the wheel/rail interface. This is an area of special interest for railway owners in cold climates.
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Paper A
RUNNING-IN BEHAVIOUR OF RAIL AND WHEEL CONTACTING SURFACES
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ABSTRACT
Rail grinding has been used since the 1980s in maintaining optimal rail profile as well as for elimination of surface defects such as corrugations and head-checks. Likewise, the wheel sets also require re-turning to remove surface defects and restore the desired profile. However, at present there are no well defined guidelines regarding the surface topographies of the ground rails and repaired wheel sets. The present study focuses on investigating the running-in behaviour of new rail and wheel surfaces of different initial roughness values. Field measurements have been carried out with a view to investigating the influence of traffic on both surface roughness and rail profile after grinding or re-turning of wheels. The results obtained from a 3D optical surface profiler show that the surface roughness of a newly ground rail changes rather rapidly during the initial stages. During the first one and a half days of traffic or 26 800 tonnes, the $S_a$-value of the newly ground surface in the running band changed from ~10 μm to ~1 μm. Further investigations are being carried out in the laboratory in an effort to understand the influence of initial surface topography on the roughness of run-in surfaces, running-in period, wear and traction behaviour by the use of a two disc machine.

KEYWORDS Rail grinding, surface roughness, wear, running-in.

1 INTRODUCTION
Finding the optimal surface roughness is an important step in finding the most cost effective way of grinding rails and turning wheels. Establishing guidelines regarding the optimal surface topographies of the rails and wheels will thus go a long way to reducing maintenance costs as well as enhancing the performance of rails and wheels. Producing too smooth a surface will have a negative influence on the productivity of the maintenance operation as the time for removing the specified amount of metal will increase. It will lead to prolonged interference with the time schedules on the part of grinding the contractor and significantly higher total costs for the railway company. Likewise, the reduced productivity in the turning operation will lead to
non-availability of wheels and/or the necessity for having larger stocks of wheels. On the other hand, rougher wheel/rail surfaces may result in deterioration of performance and service life owing to premature crack initiation and high wear rates. This will lead to shorter maintenance intervals and increased overall operating costs. As illustrated in Figure 1, establishing guidelines for optimal wheel/rail surface topographies from performance and service life points of view will enable reductions in maintenance costs and improvement of the overall operating economy.

Figure 1: Total cost as a function of surface roughness.

Presently there are no scientifically derived “standard” grinding specifications for heavy haul conditions. The maximum permissible surface roughness (Rₐ) on rails after grinding acceptable to the Swedish National Rail Administration is 10 μm. Different railway companies have their own guidelines mainly based on their experience and rules of thumb [1]. The wheels from the ore trains are re-turned at different workshops when the tolerances on the wheel profile and wear are reached. However, their surface roughness is rarely measured.

In the past, several studies pertaining to wheel/rail surface topographies have been conducted but most of these have focussed only on the noise and vibration aspects [2, 3]. The role of resultant surface roughness of ground rails and its influence on wear in the rail-wheel contact has been indicated but it has not yet been thoroughly investigated [4, 5, 6]. The role of rail surface roughness is also likely to be much more significant in view of trends towards the use of harder and two-material rails. Field tests on the Malmhanan in Sweden with two-material rails have shown that grinding marks were still visible after tests conducted between 27 September 2001 and 2 May 2002, (or 6.7 MGT equivalent [7]). The presence of water/moisture or lubricant in the wheel/rail contact after grinding can also have an adverse effect on their wear and surface damage. An earlier study by using a two disc test machine showed that oil is more effective in reducing crack face friction while water penetrates the crack tip more easily [8]. In studies on the Malmhanan, it was found that the roughness of the running band changed rapidly following the passage of 43,500 tonnes equivalent about one day’s traffic [6].

The maintenance of the ore car wheels running on the Malmhanan is performed at two different workshops: Duroc in Luleå and MTAB in Kiruna. In the absence of any roughness measurement after re-turning the wheels, their surface topographies may be assumed to differ.

The present study is thus aimed at investigating the changes in surface topography of the re-turned wheels and the ground rails through actual field measurements during the initial running-in stage.
Field measurements on rails have been performed on the Malmbanan, which runs from the
mines in Gällivare and Kiruna down to Luleå in the east and to Narvik in Norway. The iron ore
line is some 500 km long and carries ore trains, passenger trains and goods trains. The southern
segment (Luleå-Boden-Gällivare-Kiruna), where the tests have been performed, carries 7
million net tonnes per year. The iron ore line is being upgraded presently to carry trains with a
30-tonne axle load.

After the analysis of the results of the measurements on rail surfaces on the Malmbanan,
additional measurements were performed on the newly ground rails during the initial running-in
stage. These were carried out in order to investigate the influence of the traffic on topographical
changes at the wheel and rail surfaces. For these measurements, a new location on the
Malmbanan called Malmryggen was chosen as the test site. Malmryggen is a side track at
Boden train station and was built to avoid hindrance to the ore trains by the passenger trains. As
such, the traffic on Malmryggen is only that of ore trains and it is well suited for the running-in
measurements. Visual examination of the wheel/rail surfaces was done and replicas prepared for
subsequent analysis by 3D optical surface profiler with a view to investigating the changes in
surface topography, presence of wear debris or embedded particles etc. These results will enable
a realistic choice of surface topographies for experimental simulation of wheel/rail contacts in
the laboratory by using a two disc rolling/sliding test machine.

2 METHOD

In all field measurements, plastic replica moulds, Master Exact\(^1\) were prepared from the
wheel/rail surfaces. The surfaces were thoroughly cleaned by n-heptane and wiped with a cloth
before the replica material was applied. A blow torch was used to remove any residual solvent
from the surfaces and also to heat the surfaces in cases where the prevailing temperatures were
low. The replicas provide negative images of the surfaces. These replicas were then used for the
measurement and analysis of surface topographies in a 3D optical surface profiler (Wyko NT-
1100). The change of eight surface roughness parameters were monitored in all field tests.
These were: \(R_k\); \(R_{pk}\); \(R_{vk}\); \(S_a\); \(S_{ku}\); \(S_{sk}\); \(S_c\); and \(S_{dq}\). Changes in all these surface roughness
parameters showed similar trends. As such, only the \(S_a\)-values have been presented here. The
surface of a new wheel from Lucchini was used as a reference for the wheel tests. Rail profile
measurements using Miniprof were also performed initially on the Malmbanan. However, due
to extremely cold conditions, no data for the profile change could be recorded during the last
measurement.

2.1 Measurements on the Malmbanan

A rail track having a 655 metre radius curve on the Malmbanan was selected as the test site.
The first measurement was done directly after the rail was ground to get the initial roughness.
Both high and low rails have been monitored at three different locations, called 37, 38 and 39,
with 50 metres spacing in between them. The rails were marked on the sides of the rail heads to
ensure that the measurements were done at the same position every time. All measurements on
replicas were performed on the same grinding facet in the running band where the largest
change in roughness occurred.

\(^1\) Oriola Dental AB, www.oriola.se
Measurement schedule on the Malmbanan:
1. 8 September, newly ground rail
2. 9 September, approximately 26 800 ton of traffic
3. 15 September, approximately 259 000 ton of traffic
4. 16 November, approximately 2 070 000 ton of traffic

The initial profile after grinding was recorded and used as the reference profile when compared with measurements taken after 259 000 tonnes, or 1.5 weeks, after the rail was ground. Wear was calculated through the changes in profile by using the Miniprof software. The changes in profile are measured at three different locations on the rail head; vertical (W1); horizontal (W2) and 45° (W3) wear, see Figure 2. The wear is calculated as the difference between the measured profile and the reference profile, in this case the profile produced directly after grinding.

![Figure 2: Wear calculations in Miniprof software](image)

2.2 Measurements on Malmryggen

During field measurements on Malmryggen, only one of the rails was investigated due to limitations of time since both the grinding and preparation of the replica had to be undertaken between the passage of two trains. The high rail was chosen for the investigations. As the test site had only ore train traffic, it was specially suited for running-in tests since precise information regarding train weights and number of axels was available. A smaller grinding machine, usually used in grinding switches was used due to the grinding campaign of the contracted grinding entrepreneur having expired. This smaller grinding machine operates with a finer grinding stone, at lower grinding speed, lower stone pressure and produces a relatively smoother surface than that produced by the grinding train operating on the Malmbanan (owned by Speno International). The initial $S_a$-value from the smaller grinder was ~ 2 μm as compared to that of ~ 10 μm produced by the grinding train.

Surface replicas were prepared after the rail was ground and subsequently after passage of each of the first three trains sets. The first train set passing the test site after grinding was loaded, the second empty and the third was again loaded, see Table 1. To get the roughness of the run-in surface, a measurement was made approximately one month later, after the passage of 270 train sets.
<table>
<thead>
<tr>
<th>Train type</th>
<th>Number of axis</th>
<th>Total weight [tonnes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loaded</td>
<td>220</td>
<td>5479</td>
</tr>
<tr>
<td>Empty</td>
<td>220</td>
<td>1400</td>
</tr>
<tr>
<td>Loaded</td>
<td>220</td>
<td>5498</td>
</tr>
</tbody>
</table>

Table 1: Configuration of the first three train sets

2.3 Measurements of wheels

A randomly selected ore car was chosen and equipped with pairs of newly turned wheels from each of the two workshops. An axle of this car was also mounted with a new pair of wheels from Lucchini. Plastic replicas from the wheel surfaces were prepared before the ore car was first used. New replicas were than taken after each of the three first journeys between Malmberget and Luleå, a distance of approximately 200 km, as can be seen from Table 2. The last replica was made after 27 journeys or 5400 km when the change in surface roughness had reached a steady state. On the journey from Malmberget to Luleå, the ore cars were loaded and the maximum axle load was 30 tonnes. The axle load of the empty ore car on the return journey was 5.4 tonnes.

<table>
<thead>
<tr>
<th>Number of Journeys</th>
<th>From</th>
<th>To</th>
<th>Axle load (tonnes)</th>
<th>Total length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Malmberget</td>
<td>Luleå</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Luleå</td>
<td>Malmberget</td>
<td>5.4</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>Malmberget</td>
<td>Luleå</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>27</td>
<td>Malmberget</td>
<td>Luleå</td>
<td>30</td>
<td>5400</td>
</tr>
</tbody>
</table>

Table 2: Operating conditions for wheel surface run-in tests

Due to the tight time schedule, replicas could only be taken when the ore train had reached its final destination during loading and unloading. The plastic replicas were examined in a 3D optical surface profiler. Each replica was measured at two different locations: on the running band (high pressure) and on the outer side of the rim (low pressure), see Figure 3.

![Figure 3: Low and high pressure locations](image-url)
3 RESULTS AND DISCUSSION

3.1 Malmbanan

The results obtained from field measurements on the newly ground rails and during the initial running-in stage are presented as 3D images in Figure 4 and in terms of roughness parameter $S_a$ in Figure 5. These results are based on three measurements on each replica and the results shown in Figure 5 indicate an average of three measurements. It can be seen that the topography of the ground rail in the running band changes quite rapidly due to the passage of traffic. In approximately 35 hours, or 26 800 ton, the roughness of the surface was reduced from $S_a \sim 10 \mu m$ to $S_a \sim 1 \mu m$. These results indicate that the run-in of a newly ground rail on the Malmbanan essentially takes place during the first day of traffic. The change in roughness after the first day’s traffic is almost negligible. Further, it can also be seen from Figure 5 that the spread in the results is rather small after the rail surface has been run in.

![Figure 4: Running-in process of newly ground rail](image)
The results from the Miniprof measurements in Figure 6 show that the largest change of the profile, after 259,000 tonnes of traffic, can be seen in location 39 which is closest to the centre of the curve. The negative change of the profile in location 39 is due to the plastic flow of material.
The vertical profile wear, $W_1$, is calculated at the same position on the rail head where surface roughness measurements from Figure 5 are made. The profile wear, $W_1$, is relatively large in comparison to the roughness change shown in Figure 5, although the grinding marks can clearly be seen in Figure 4. This indicates that the rail profile has been plastically deformed during the first day of traffic, see Figure 7.

![Profile wear W1 vs Location](image)

**Figure 7**: Vertical rail wear, $W_1$, from 8th September to 9th September and to 15th September. Both high rail (H) and low rail (L) are displayed for each of the three locations.

The visual inspection of the rail directly after grinding revealed that surface fatigue cracks were still present, especially on the high rail. It was also found that an accelerated rate of flaking occurred after the rail was ground due to the presence of surface fatigue cracks, see Figure 8.

![Surface fatigue cracks](image)

**Figure 8**: Surface fatigue cracks on high rail on the Malmbanan, 9th September and 15th September and worn-off flakes, (scale in millimetres).

Samples of the flaked-off material were collected for hardness measurements. The micro-hardness measurements on these samples showed signs of work hardening. Six measurements were made on each of the four collected wear flakes and the mean hardness of all wear flakes was $\sim 502$ HV at 300g load, which is substantially higher than the original hardness of the UIC 1100 rail (340-380HV).
3.2 Malmryggen

The change of surface roughness due to traffic on Malmryggen is shown in Figure 9 for both the curved and the straight track. Results from the Malmbanan measurements have shown a large change of roughness following the first day of traffic and the same behaviour has been confirmed by measurements on Malmryggen. These results also show a rapid change in roughness during the initial stages on the newly ground surface. The most rapid change can be seen in the curve where the $S_a$-value has changed from 2,1 μm to 0,7 μm after the passage of three trains sets. The same $S_a$ -value was recorded after a month of traffic, or 270 trains sets later. The running-in of the surface on the straight track took more than three passages as can be seen from Figure 9.

From the first four measurements on Malmryggen, the running-in of a grinding facet in the running band was closely followed. The grinding facets are subjected to the highest contact pressures and therefore run-in quickly. The distance between the ridge and the surface 2,5 mm away from the ridge was measured as can be seen in Figure 10. The height of the ridge directly after grinding was 104 μm. After the passage of only one ore train, this height was reduced to 52,2 μm.
3.2 Wheels

Results from the wheel replica measurements are summarised in Figure 11. It can be clearly seen from these results that the surface roughness values of the new wheels and the re-turned wheels at the two workshops differ quite significantly. The wheel surface produced at Duroc is the roughest ($R_z \approx 92 \, \mu m$) and it is three times rougher when compared to that re-turned by MTAB.
On both the high and low pressure sites on the wheels, three measurements were made. The results displayed are the mean values. In the running band on the wheels, the initial surface roughness has very little influence on the running-in time as can be seen from Figure 12. The Duroc and Lucchini wheels run-in after the first journey (200 km) whereas the MTAB wheel run-in after two journeys (400 km).

The running-in results obtained in this work are in line with those reported by Grassie [6] where field measurements were made on the same ore line. Grassie did not however closely follow the running-in of wheel/rail surfaces since his work focussed more on transverse railhead profiles. Field measurements are quite tedious but useful in studying the running in behaviour as these results have shown. However, these field measurements are useful only in revealing the surface topographical changes during the running-in of wheels and rails. Experimental studies will have to be conducted with a view to investigating the influence of surface roughness on wear, traction and contact fatigue damage.

4 CONCLUDING REMARKS

Detailed field measurements on wheel/rail surfaces have been carried out. The results obtained from these measurements indicate that the wheel/rail surfaces run-in rather rapidly. In the case of a newly ground rail, \( S_a \)-values decreased from 10 \( \mu m \) to 1 \( \mu m \) after one and a half days of traffic or 260 800 tonnes. The roughness values of the re-turned wheels from different workshops differ significantly.

The initial wheel/rail surface roughness has almost negligible influence on the running-in behaviour as all the surfaces run-in rapidly to almost the same roughness value (\( S_a \sim 1 \mu m \)) irrespective of their initial roughness values. The effect of initial wheel/rail roughness on traction, wear, and contact fatigue damage is unclear and further studies are required to investigate these aspects.
Acknowledgements

The financial support for this work from Banverket, LKAB/MTAB and Speno International is gratefully acknowledged. The authors also wish to acknowledge the help and support from Tord Karlsson (MTAB) and Timo Hiltunen (Banverket).

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Influence of initial surface topography on tribological performance of the wheel/rail interface during rolling/sliding conditions

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SUMMARY

The influence of surface roughness in a rail/wheel contact has been a concern for railway owners since the introduction of ‘rail grinding’ as a maintenance strategy. Presently, there are no well defined guidelines regarding the surface topographies of ground rails and re-turned wheels. There is thus a need to establish scientific guidelines regarding the surface topographies for the rails and wheels in order to minimize grinding costs/time and improve rail/wheel performance. This study is thus aimed at investigating the influence of surface topographies of wheels and rails on running-in behaviour, wear, friction and the resultant surface damage through experimental simulation in the laboratory. A two-disc rolling/sliding test machine has been used in this experimental work. Two different roughness values were produced on both the rail and wheel test specimens. A Design of Experiment approach (DOE) has been used to conduct experiments and to analyse the results. The results show that the surface roughness of the specimens in some material pairs do influence wear, friction and the resultant surface damage.

Index Terms: Surface topography, wear, rail/wheel

1. INTRODUCTION

As the wheels and rails are worn beyond the specified allowable limits, their profiles have to be restored to avoid undesired contact conditions in the rail/wheel interface. Rail grinding has been used to restore the rail profile and to remove headchecks. Likewise the wheels are re-turned to rectify their profile and eliminate surface flaws. The need for increased annual tonnage means considerably less time for maintenance activities. Owing to this, the rail grinding activity has to be performed as quickly as possible to minimize the interference with the regular traffic on the track. This requires higher material removal rates during grinding through the use of coarser grinding stones, higher stone pressures and higher grinding speeds. Speeding up the grinding activity through control of these parameters may adversely affect the resultant surface topography of the rails. The re-turning of wheels at more than one workshop can lead to variations in the surface topographies of re-turned wheels in the absence of clear roughness specifications. It has been seen that the surface roughness characterisation of re-turned wheels produced at one of the two workshops was as large as 5 times [1] rougher than those produced at the other workshop. In the same study, the field

...
measurements have shown that the initial surface roughness did not influence the running-in time, and the surfaces run-in to the same surface roughness irrespective of their initial roughness. However, in these field measurements, it was not possible to study the influence of surface roughness on wear and friction behaviour. There are some indications that wheels running on newly ground rails, especially locomotive wheels, show an increased wear rate. This increase in wear rate could be the result of a rougher rail surface or the changes in contact conditions introduced by the modified profile of the ground rail. Earlier studies concerning surface topographical aspects of wheel/rail interface have mostly focused on noise due to railway traffic, which is the main concern in urban areas but the influence of wheel/rail surface topographies on wear, traction and surface damage has not been studied adequately. The aim of this study is thus to investigate the influence of surface roughness on running-in behaviour, wear, friction and resultant surface damage for different wheel/rail materials. The influence of initial surface topographies of rails and wheels has been experimentally investigated by using a two-disc rolling/sliding machine. The disc specimens were machined from actual rails and wheels to closely simulate the wheel/rail interface. The rail steel specimens were made from UIC 1100 and a hardened high strength boron steel which has potential for re-rail applications. The wheel steel specimens were made from Blue Light (69-JDG-8) and a bainitic steel (Concept 30).

2. METHOD

A Design of Experiment (DOE) approach has been used for investigating the influence of various parameters on the wear and friction behaviour of the rail and wheel specimens. A $2^4$ full factorial design was chosen which made it possible to obtain an interaction model. This design consists of four factors at 2 levels, one high +, and one low -. Wheel material low: Blue, wheel material high: bainitic; rail material low: 1100, rail material high: boron; wheel roughness low: 1.4 μm, wheel roughness high: 14 μm; rail roughness low: 0.5 μm, rail roughness high: 2.0 μm. In a full factorial design, each factor has been investigated at both levels of all the factors. This arrangement enables the effect of one factor to be assessed independent of all the other factors [2]. A commercially available software, MODDE 7 [3], was used in the DOE set up and analysis.

The geometry of the supplied rails and wheels led to restrictions in the size of the test specimens. A maximum diameter of 43 mm could be produced from the rails. Two different rail materials, UIC 1100 and a hardened high strength boron steel, and two different wheel materials, Blue Light (69-JDG-8) and a bainitic steel (Concept 30), were used in these experiments. The UIC 1100 rail material and the Blue Light wheel material are commercially available materials whereas the hardened high strength boron rail steel and bainitic wheel steel are materials under development and are not yet available on the market as rail and wheel materials. The chemical composition and hardness of these materials are given in Table 1.

In this study pertaining to the influence of surface roughness, a contact within the same grinding facet has been simulated e.g. influence of grinding facets within the contact has not been investigated. Two different roughness values were produced on the surfaces of the test discs from the two different rail steels through grinding operation. The direction of grinding was made perpendicular to the direction of rotation. Since it was not possible to grind the test specimens to the same surface roughness as that of the newly ground rail, the discs were ground to the roughest surface roughness without losing the set tolerances in order to simulate a rough rail. The other rail discs were ground to a smoother surface to simulate a fine ground rail surface. The roughness of the rail specimens were $S_a = 2.0 \text{ μm}$ on the rough specimens and $S_a = 0.5 \text{ μm}$ on the smoother disc surfaces. The roughnesses of the wheel discs were produced through a turning operation with a view
to simulate the surfaces of a new or re-turned wheel. Two different roughness values $S_a = 14 \, \mu m$ to $S_a = 2 \, \mu m$ were produced in the turning of the wheel specimens.

### Table 1. Chemical composition and hardness of disc specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>Specification</th>
<th>Rail (UIC 1100)</th>
<th>Blue</th>
<th>Light</th>
<th>Bainitic</th>
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</thead>
<tbody>
<tr>
<td>Chemical composition (wt.%)</td>
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<td>0.60-</td>
<td>0.25-</td>
<td>0.67-</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>0.30</td>
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<td>0.77</td>
</tr>
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<td>Si</td>
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<td>0.15</td>
<td>0.30</td>
</tr>
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<td></td>
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<td>Mn</td>
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<tr>
<td>Cr</td>
<td>0.18</td>
<td>&lt;0.04-</td>
<td>0.08</td>
<td>0.25</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>0.25</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>&lt;0.025</td>
<td>0.025</td>
<td>&lt;0.05</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.05</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.18</td>
<td>&lt;0.04-</td>
<td>0.08</td>
<td>0.25</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>&lt;0.05</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Cu</td>
<td>Al</td>
<td>B</td>
<td>0.035</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average hardness, $HV_{30}$</td>
<td>324</td>
<td>525</td>
<td>380</td>
<td>325</td>
<td></td>
</tr>
</tbody>
</table>

The experimental studies to simulate the rail-wheel contact, a rolling-sliding contact under dry conditions, were conducted by using a UTM 2000 Wazau two-disc machine. In this machine, both specimens are arranged in a horizontal position next to each other and the load is applied by means of a dead weight loading system. The cylindrical disc specimens are mounted on separate shafts, each driven by a separate servo drive. The speed of the drives can be independently controlled. This enables in conducting tests under pure sliding, pure rolling and rolling/sliding conditions. The test disc specimens are mounted on the end of each shaft of the servo drives and secured with a conical clamping unit. The clamping unit automatically centres the specimen on the shaft. The applied load is measured with a force sensor and a maximum load of 2000 N can be applied in this machine. One of the two servo drives is mounted on a linear guide and this enables the use of disc specimens in the diameter range 40 to 80 mm. The speed of the drives can be controlled independently in the range 0.1 to 3000 rpm. The friction force is calculated as the ratio of the measured traction force between the disc specimens and the normal force times the radius. In rolling/sliding tests, one of the servo drives acts as a “brake” and the other as a “motor”. The slip can be controlled in the range from 0.5 % to 20 % with an accuracy of 0.5 % by adjusting the rotational speed and is defined as:

$$S = \frac{(n_1 - n_2)}{n_1} \quad (if \ n_1 > n_2)$$

with $n_1$ = rotational speed of drive 1 [min$^{-1}$],

$$n_2 = rotational \ speed \ of \ drive \ 2 \ [min^{-1}]$$

The maximum contact pressure $p_0$ (MPa) is calculated by the formula suggested by Timoshenko and Goodier [4].

$$p_0 = 0.418 \left(\frac{F_N E}{T R}\right)^{1/2}$$

Where $F_N$ is the load (N), $T$ is the line contact length (mm), $E$ is the modulus of elasticity of steel (MPa) and $R$ is the equivalent radius.

All tests were conducted at the maximum load of 2000 N, which resulted in an initial maximum Herzian contact pressure of 0.81-0.88 GPa depending on the diameter of the disc specimens (2). A slip ratio of 1 % was used in all tests according to (1), with the wheel disc as driving and rail disc as driven. The rotational speed was 200 rpm and the duration of the tests was 5 hours or 60 000 revolutions for the driving wheel specimen. The resultant sliding distance was approximately 85 meters and all tests were conducted at room temperature. All test specimens
were cleaned in an ultrasonic cleaner and weighed before and after the tests by using a Mettler Toledo balance with an accuracy of 0.00001 g. To prevent wear debris from entering the contact during the tests, a vacuum cleaner nozzle was placed directly above the two contacting discs.

3. RESULTS AND DISCUSSION

The main effects and the corresponding confidence interval of different factors on wear and the steady state friction are tabulated in Table 2 and Table 3 respectively. The wear results have been transformed to a logarithmic function since the normal probability plot of the residuals showed signs of a curvature and tails. The steady state friction is defined as the mean friction after 3000 seconds as the friction in all tests stabilized after this duration. The main effect of a factor is defined as the change in response by varying one factor from its low level to a high level while keeping the other factors at their average values. The most significant effect on log wear was that of the wheel material and the most significant effect on steady state friction was that of the wheel roughness. The abbreviations used are: WM = Wheel Material, WR = Wheel Roughness, RM = Rail Material and RR = Rail Roughness.

A strong interaction was found between the wheel material and the rail roughness as can be seen from Fig. 1. If the wheel material is changed from Blue Light to Bainitic, the rail roughness is of high importance for the log wear result, as rougher surface resulted in more wear. The observed versus predicted plot shows that a good regression fit to the responses is obtained. In a perfect model, the responses would be situated on a diagonal line from the lower left corner to the upper right corner in Fig. 2.

![Fig. 1. Interaction plot for WM*RR log wear](image)

![Fig. 2. Observed versus predicted for steady state friction](image)

**Table 2. Main effects on Log wear**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Conf. int(±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM(Bainitic)</td>
<td>0.1150 0.0378</td>
</tr>
<tr>
<td>RM(Boron)</td>
<td>-0.0923 0.0374</td>
</tr>
<tr>
<td>WM(Bainitic)*RM(Boron)</td>
<td>-0.0782 0.0373</td>
</tr>
<tr>
<td>WM(Bainitic)*RR(Rough)</td>
<td>0.0744 0.0379</td>
</tr>
<tr>
<td>RM(Boron)*RR(Rough)</td>
<td>-0.0582 0.0373</td>
</tr>
<tr>
<td>RR(Rough)</td>
<td>0.0538 0.0378</td>
</tr>
<tr>
<td>WR(Rough)</td>
<td>-0.0430 0.0379</td>
</tr>
</tbody>
</table>

**Table 3. Main effects on steady state friction**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Conf. int(±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR(Rough)</td>
<td>-0.0474 0.0196</td>
</tr>
<tr>
<td>RM(Boron)</td>
<td>-0.0385 0.0194</td>
</tr>
<tr>
<td>WM(Bainitic)</td>
<td>0.0320 0.0195</td>
</tr>
<tr>
<td>RR(Rough)</td>
<td>0.0260 0.0195</td>
</tr>
</tbody>
</table>
3.1. Wear
Four specific tests were repeated in the test series to be able to estimate the reproducibility of the experiments, see Fig. 5. The mean values of the two responses are displayed for the four repeated tests and the error bars show the maximum and minimum result for the total wear in case of the repeat tests. Generally, the wear of the driving wheel disc is higher than that of the driven rail disc. If the 1100 rail material is used, both wheel material and wheel roughness seems to be important. In all experiments with the Blue Light wheel material, the rougher wheel specimen has resulted in lower wear than that with a smooth wheel specimen. It is also obvious that there is a larger variability in the results in tests with the 1100 rail material as compared to that with boron rail material. It seems that the 1100 rail material is more sensitive to the changes in operating conditions. From Fig. 5 it can also be seen that the wear rate of the wheel discs are less dependent on changes in counter face material and surface roughness than the rail disc.

3.2. Friction
From the friction plots (Fig. 6-9), it can be seen that there are generally two types of friction break-in curves. In all cases except one, the friction curves in tests including the 1100 rail steel have a distinct peak within the first 2000 seconds of the commencement of the test. In an earlier study, Blau [5] published eight types of friction break-in curves based on a survey of sliding contacts. It was concluded that a shape of the friction curve especially seen in the bainitic-boron material combination is characteristic of a dry, non-intentionally lubricated metal couple having a small amount of surface contamination, oxide, or adsorbed species that are quickly worn away to cause a greater degree of adhesion and an increase in friction. The shape of friction curve with an initial peak is common for non-lubricated metals in which the initial roughness of the surface produces a momentary rise in friction until surface conformity and smoothening occur, thereby reducing the friction. The drop after the initial peak can also be due to surface texturing by shear, or by the development of a low-shear transfer film, depending on the materials and conditions involved. This curve is typically seen for Blue Light-1100 combination with smooth surfaces.
In the legends of Fig. 6-9, the roughness combination can be found. The first letter states the roughness of the wheel specimen and the second letter states the roughness of the rail specimen, S = Smooth, R = Rough.

The mean steady-state friction has been recorded after 3000 seconds of the commencement of the test and can be seen in Fig. 10. In all combinations of materials, tests with a rough wheel surface and a smooth rail surface shows the lowest coefficient of friction after running-in.
3.3. Disc specimen hardness

Vickers hardness tests were performed on the surfaces of the Blue Light wheel specimens and the 1100 rail specimens after the tests, see Fig. 11. The surface hardness of the wheel and rail specimens differed depending upon whether the wheel specimen had an initially rough or smooth surface. When the wheel was smooth, the hardness of the rail and wheel surfaces does not differ significantly. The values shown are the mean values of three measurements and the error bars show the minimum and maximum values.

Fig. 11. Vickers hardness on disc surfaces after test

<table>
<thead>
<tr>
<th>Vickers hardness</th>
<th>Smooth</th>
<th>Rough</th>
<th>Smooth</th>
<th>Rough</th>
<th>Smooth</th>
<th>Rough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Light</td>
<td>1100</td>
<td>1100</td>
<td>Blue Light</td>
<td>1100</td>
<td>Blue Light</td>
<td>1100</td>
</tr>
</tbody>
</table>

3.4. Resultant surface damage

Pictures of the different specimen surfaces from tests with 1100 rail steel and Blue Light wheel steel were taken in an optical microscope, and the typical rail surfaces can be seen in Fig. 12-15. From these pictures with 40X magnification, it can be seen that the surface roughness influences the nature of surface damage. The surface damage during rolling/sliding is predominantly due to adhesion effects and the 1100 rail surfaces have shown more severe surface damage in the case of a smooth wheel counter face (Fig. 12 and Fig 14). It can also be seen that the surface damage is somewhat less severe in the test with a rougher rail surface, although this effect is not as significant as that of the wheel roughness.

It may be pertinent to add here that the experimental test parameters were chosen keeping in view the conditions prevalent in heavy haul operations. As such it may not be possible to extrapolate and interpolate these results for other operating conditions. Future studies will be conducted keeping in view other operating conditions.
4. CONCLUSIONS

A systematic experimental study based on design of experiments has been conducted to study the influence of surface roughness on tribological performance of wheel rail interface in the laboratory by using a two disc rolling/sliding machine. The salient conclusions of this study are given below.

The influence of surface roughness as well as the type of mating wheel material on wear of 1100 rail material is quite significant.

In all experiments with the Blue Light wheel, the rougher wheel specimen has resulted in lower wear than that with a smooth wheel specimen, especially the wear of the rail disc.

Wear rates of the wheel discs are less dependent on changes in counter face material and surface roughness than the rail disc.

Rough wheel surfaces do not result in the initial friction peak during the commencement of the test.

In all combinations of materials, tests with a rough wheel surface and a smooth rail surface show the lowest coefficients of friction after running-in.

References

INFLUENCE OF SURFACE TOPOGRAPHY AND WATER LUBRICATION ON TRIBOLOGICAL BEHAVIOUR OF WHEEL/RAIL MATERIALS

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ABSTRACT
The grinding of rails and re-turning of wheels in wheel/rail interface maintenance result in different surface topographies on the rail and wheel surfaces. However, presently there are no scientifically derived guidelines regarding the surface topography of ground rails and re-turned wheels. The specifications of maximum surface roughness given to the contractors today, is mainly based on thumb rules and experience. Further understanding in this area is essential in order to improve the maintenance operations of the wheel/rail interface. As the wheel/rail system is an open system, it is of interest to investigate the tribological behaviour in presence of water. The aim of this study has therefore been to investigate the influence of surface roughness on wear, friction, work hardening and resultant surface roughness in a two-disc tribometer under dry and water lubricated conditions. The work includes a two-level full factorial Design of Experiments (DOE) approach for determining the relation between the investigated factors and the responses. The study has focused on wheel/rail materials that are presently in use. Advanced analytical instruments including 3D optical surface profiler, micro hardness indenter, light microscope and SEM/EDS were used to analyse the results. It is shown that the mechanism seen in dry tests clearly differs from the mechanism seen when the contact was lubricated with water.

KEYWORDS Rail grinding, surface roughness, wear, water lubrication.

1. INTRODUCTION

Rail grinding is nowadays frequently used as a maintenance practice to rectify the worn rail profile and to remove other surface defects such as headchecks, surface corrugations etc. When the rails are ground, the surface within each grinding facet is rough, generally about 8-10 μm. The maximum permissible Rₐ value after grinding, which is primarily based upon experience and rules of thumb, differs among railway companies. In Europe, these days it is common to specify a maximum surface roughness, Rₐ-value, of 10 μm. This value has also been incorporated in the draft specifications for CEN-standard prEN 13231-3 and is considered to be a good compromise between surface roughness and metal removal. However, this is not based on any prior scientific investigation. There are also no scientifically derived roughness specifications that can be employed in re-turning of wheels due to wear, wheel flats or other defects. The influence of surface roughness of newly ground rails and re-turned rails on the performance of the wheel/rail interface has been highlighted [1-3], but has not yet been investigated thoroughly. There is thus a distinct need for further studies to clarify the impact of
surface roughness on wear, frictional behaviour and resultant surface damage of rails and wheels. In an earlier work, the authors conducted studies by using a two-disc tribometer under dry conditions and showed that the initial surface roughness do influence the tribological behaviour of wheel/rail material pairs [4]. During service, the wheel/rail interface is exposed to different types of contaminants and varying environmental conditions. These factors can be controlled to some extent (for example the presence of lubricants) but it is impossible to control other factors such as the weather conditions and presence of contaminants (such as water, leaves, and dust from ballast and environment) although their presence strongly influences the tribological behaviour of the wheel/rail interface. In past some studies have been carried to investigate the role of some of these factors. It has been reported that the precipitation and relative humidity have a significant influence on friction and rail wear [5, 6]. In a study by Nilsson, the field measurements revealed that the rail wear decreased with increased daily precipitation and at lower temperatures. It was concluded that the precipitation creates a natural lubricating layer of water at the rail/wheel interface and may also absorb energy when transformed from solid or liquid phase to gaseous phase. Beagley and Pritchard [7] have investigated the influence of water on the coefficient of friction in a simulated wheel/rail contact in the laboratory and concluded that water reduces the coefficient of friction to 0.3 or even lower values depending upon the amount of oil contamination. Beagley et al. [8] reported that rust particles were observed to spread on the running band in wet weather and worn off under dry operating conditions. The presence of these particles helped in maintaining adhesion during the wheel/rail interaction. In humid conditions, adhesion was reduced on those surfaces bearing sustainable debris coverage. Surface damage caused by water in the two-disc contact has been reported by other researchers also [9, 10]. Sato et al. reported that the wear of the rail specimens always exceeded the wear of the wheel discs for all slip ratios and that an increase in slip increased the wear. A relationship between surface hardness and wear was also observed on the rail discs as the harder rail discs suffered less wear than the softer one. These tests were run at relatively low contact pressures with maximum elastic contact stress of 525 MPa. However, influence of the surface roughness of the specimens on wear was not considered. Depending on the wheel/rail contact conditions, the materials work-harden in different ways. It has been found that higher friction increases the stress intensity, as the maximum stress region moves closer to the surface [11]. The resultant friction force during the wheel/rail interaction will affect the depth of the work hardening. Therefore, micro-hardness depth profile measurements were done on the disc specimens before and after each test to investigate the depth of the work-hardened layer. The aim of this study has been to investigate the influence of surface roughness on wear, friction, work hardening and resultant surface roughness under dry and water lubricated conditions by using a two-disc tribometer.
2. METHOD

In this study, a UTM 2000 two-disc tribometer has been used to simulate wheel/rail contact. This test machine has been previously described in [12]. The slip in the contact is produced by independently controlling the rotational speed of the two servo motors driving the disc specimens and can be expressed by equation (1) given below.

\[
\text{S} = \frac{(n_1 - n_2)}{n_1} \quad \text{(if } n_1 > n_2) \tag{1}
\]

where
- \( n_1 \) = rotational speed of drive 1 [rev/min]\(^{-1}\)
- \( n_2 \) = rotational speed of drive 2 [rev/min]\(^{-1}\)

The maximum contact pressure \( p_0 \) (MPa) is calculated by the formula suggested by Timoshenko and Goodier [12] given in equation (2).

\[
\text{p}_0 = 0.418 \left( \frac{F_N E}{TR} \right)^{\frac{1}{2}} \tag{2}
\]

where \( F_N \) is the load (N), \( T \) is the line contact length (mm), \( E \) is the modulus of elasticity (MPa) and \( R \) is the equivalent radius.

The machine is equipped with a torque transducer which enables the measurement of frictional torque. The coefficient of friction is obtained from the frictional torque. All tests were conducted at a load of 2000 N, which resulted in an initial maximum Herzen contact pressure of 0.81-0.88 GPa depending on the diameter of the disc specimens. A slip ratio of 1% was used in all tests, with the wheel disc as driving and rail disc as driven element. The rotational speed was 200 rpm and the duration of the tests was 5 hours or 60 000 revolutions for the driving wheel specimen. The resultant sliding distance was approximately 85 meters. All tests were conducted at room temperature, and the disc specimens used in the experiments were manufactured from actual wheel and rail materials. Rail steel UIC 1100, and two different wheel materials, Blue Light (69-JDG-8) and a bainitic steel (Concept 30), were used in the experiments. The chemical compositions of the rail and wheel materials are given in Table 1.

Table 1. Chemical composition (wt.% of test specimens)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>S</th>
<th>P</th>
<th>V</th>
<th>Cu</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIC 1100</td>
<td>0.60-0.80</td>
<td>0.50-0.80</td>
<td>0.80-0.12</td>
<td>0.80-1.20</td>
<td>0.25</td>
<td>0.025</td>
<td>0.020</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue Light</td>
<td>0.67-0.77</td>
<td>0.15</td>
<td>0.6-0.85</td>
<td>0.25</td>
<td>0.30</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04-0.08</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Bainitic</td>
<td>0.29</td>
<td>0.77</td>
<td>0.99</td>
<td>0.31</td>
<td>0.32</td>
<td>0.40</td>
<td>0.002</td>
<td>0.006</td>
<td>0.025</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The rail discs were produced from the rail head with their axis of rotation normal to the base of the rail. The surfaces of the disc specimens were ground to two different surface roughnesses with the grinding marks parallel to the disc axis. The wheel discs were produced from the wheel
thread, with the axis of rotation on a tangent to the wheel. The wheel discs were turned by using different machining parameters in order to obtain disc test specimens having different surface roughness values oriented perpendicular to the axis. Wear was measured through weight loss obtained by using a Mettler Toledo semi-micro electronic weighing balance. All test specimens were cleaned before and after the tests in an ultrasonic cleaner and dried before weighing. Tap water (pH value of 8.6) was used in the water lubricated tests and has been applied by dripping the water into the contact by using an IV-bag. This method enables in applying a controlled amount of water into the two-disc contact (in this case 15 ml/min) and to ensure that the contact remains flooded during the test. In dry tests, a vacuum cleaner was used to remove the wear particles. Otherwise their presence in the contact may influence the tribological process. This aspect was also investigated by conducting a set of tests in which the wear particles were allowed to remain in the contact during both the dry and water lubricated rolling/sliding conditions. Micro-hardness depth profiles of the test specimens before and after the tests were obtained by using a Matsuzawa MXT-α micro hardness tester at a load of 50 g. Indentations were made on the disc cross section up to a depth of 1 mm below the surface. Work hardening and plastic flow were investigated with a view to understand the changes in hardness and metallurgical structure in the test specimens due to friction and wear. An Olympus Vanox-T light microscope was used to observe the cracks, inclusions and the mechanically affected layer close to the surface. The specimens were then etched in nital solution (HNO₃ in ethanol), in order to reveal changes in the microstructure and the deformed top layer of the specimens. The surfaces and cross sections of some selected specimens were also analysed by using SEM/EDS. The rough wheel and rough rail specimens were chosen for SEM/EDS analysis.

A design of experiments (DOE) approach was used to investigate the influence of various test parameters. In this approach, all relevant factors are varied simultaneously and since the experiments are distributed in a rectangular fashion, a direction will be obtained in which a better result is likely to be found. More information on DOE can be found in [14, 15]. A $2^4$ full factorial design was used which consists of four factors at two levels. The factors and their levels are given in Table 2.

### Table 2. Factors and levels in the factorial design

<table>
<thead>
<tr>
<th>Factor</th>
<th>High level</th>
<th>Low level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel material</td>
<td>Bainitic</td>
<td>Blue Light</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Dry</td>
<td>Water</td>
</tr>
<tr>
<td>Wheel roughness</td>
<td>14 μm</td>
<td>1,4 μm</td>
</tr>
<tr>
<td>Rail roughness</td>
<td>2,0 μm</td>
<td>0,5 μm</td>
</tr>
</tbody>
</table>
3. RESULTS AND DISCUSSION

3.1 Friction

The main effects of steady state friction can be seen from Fig. 1. The most significant effect is located in the left hand side of the diagram. The error bars show a confidence level of 95%. A positive main effect shown in Fig. 1 initiates an increase in the response. The abbreviations used on the x-axis in Fig. 1 and Fig. 4 are: WM: wheel material; Lub: lubrication; WR: wheel roughness; and RR: rail roughness.

![Fig. 1. Main effects of steady state friction](image-url)

The steady state friction is the mean friction after 3000 seconds as the friction in almost all tests stabilized after this duration. The friction coefficients from all the tests are given in Fig. 2-3. The abbreviations used in the legend show the roughness combinations used in each test with the wheel roughness as first and the rail roughness as the second alphabet.

3.1.1 Friction in dry conditions

The frictional characteristics of different pairs from the dry tests are given in Fig. 2. These results show relatively stable friction behaviour after the running-in period. Irrespective of the wheel materials, the combinations with smooth wheel surfaces have resulted in higher friction than those with rough wheel surfaces. In dry tests with Blue Light wheel material (Fig. 2), the friction coefficients are somewhat lower than those with bainitic wheel material. Smooth wheel specimens have however resulted in an initial friction peaks during the running-in period. From the friction curves in Fig 2, it can be seen that the initial surface roughness has a significant influence on the coefficient of friction. Initially rough wheel surfaces result in lower coefficients of friction than those with initially smooth wheel surfaces despite the fact that their resultant surface roughness values at the end of tests are quite similar.
3.1.2 Friction in water lubricated conditions

The friction coefficients in presence of water, see Fig. 3, are significantly lower as compared to those run in dry conditions, Fig. 2, although some instability in frictional behaviour has been observed. As in case of dry conditions, the initially rough wheel surfaces have resulted in lower and more stable coefficient of friction, especially in tests with Blue Light wheel material.

3.2 Wear

From the DOE analysis, the main effects of specific wear can be seen in Fig. 4. The most significant effects are located in the left hand side of the diagram. The error bars show the confidence level of 95%. A positive main effect shown in Fig. 4 indicates an increase of the response.
3.2.1 Wear in dry conditions

The wear results from tests run in dry conditions are shown in Fig. 5. In both wheel material combinations, a rougher wheel has resulted in lower wear in all cases except one. The difference in total wear is mainly because of the changes in wear of the rail specimens, as wear of wheel test specimens is almost of the same magnitude in all tests. It can also be seen that a smoother rail surface has resulted in lower wear and use of bainitic wheel material has resulted in more wear on both wheel as well as rail specimens. From the additional set of tests without use of the vacuum cleaner for removing wear particles, it was seen that wear of both rail and wheel specimens increased. This implies that the presence of wear particles generated in the contact act as abrading particles and result higher wear.

Fig. 4. Main effects of Specific wear [mm³/Nm]

Fig. 5. Specific wear of dry tests
### 3.2.2 Wear in water lubricated conditions

The total wear of different wheel/rail material pairs increased significantly in presence of water, Fig. 6, as compared to that under dry conditions. This increase in wear in water lubricated conditions occurred mainly due to large increase in wear of the rail material specimens. On the contrary, the wear of all the mating wheel specimens decreased in presence of water and the most significant reduction occurred in case of smooth wheel specimens. The effect of surface roughness of rail specimens was not as clear as that in case of wheels. This can be due to the differences in orientation of the surface roughness on rail and wheel specimens. The wear rate of the rail specimens increased in all cases in presence of water and the smallest increase was in cases involving Blue Light wheel material test specimens and rough rail surfaces. As in the dry tests, the bainitic wheel material has led to higher wear of rail specimens as compared to that involving Blue Light material. Rough rail specimens have resulted in higher wear in all combinations and rough wheel specimens have resulted in lower wear in all tests except one. In experiments performed with brushes removing wear particles during the water lubricated tests, it was found that the presence of wear particles in the contact has reduced the wear. This implies that wear particles formed a protective layer on top of the disc surfaces and hence reduced the wear. The protective layer is most likely formed by the compacted wear particles from the softer rail specimen as wear of rail disc in case of water lubrication is very high as compared to that of wheel specimens. These results are in line with those reported by Beagley et al. [8].

![Image of specific wear of water lubricated tests](image)

Fig. 6. Specific wear of water lubricated tests

### 3.3 Work hardening and plastic flow

The hardness profiles of the cross section of test specimens before and after the tribological tests were measured for tests run with 1100 rail steel and Blue Light wheel material.

#### 3.3.1 Work hardening in dry tests

The micro-hardness depth profiles for test specimens from two different tests under dry rolling/sliding conditions i.e. Blue Light rough – 1100 rough (in black colour) and Blue Light smooth – 1100 rough (in grey colour) are shown in Fig. 7. The difference in hardness at a depth of 15 μm from the surface and the bulk hardness of the 1100 rough rail steel disc specimens is ~300-350 Hv. The wheel test specimens work-hardens by ~150 Hv for both roughness
combinations during the dry tests. Both discs from the smooth wheel – rough rail combination, show a thicker work-hardened layer than the rough wheel – rough rail combination. This difference can be caused due to the higher coefficient of friction in this test (Fig. 2) consequently resulting in higher surface stresses, plastic flow and consequently a thicker work-hardened layer.

![Graph showing Vickers hardness vs. depth from surface](image)

**Fig. 7. Work hardening of test specimens in dry tests**

### 3.3.2 Plastic flow in dry conditions

The cross-sections of the disc specimens from dry tests were examined by using an optical microscope and the typical images from these observations are given in Fig. 8. As can be seen, the driving wheel discs did not show any sign of plastic flow. The absence of plastic flow pattern in the wheel disc cross-section may be attributed to the higher wear rate of the wheel discs. As was reported from the hardness profiles in Fig. 7, the rail specimen from the smooth wheel – rough rail combination, show a thicker work-hardened layer than the rough wheel – rough rail combination, see Fig 8.

![Images of disc specimens](image)

**Fig. 8. Left: 1100 rail disc from smooth wheel – rough rail combination in dry conditions, right: 1100 rail disc from rough wheel – rough rail combination in dry conditions**
3.3.3 Work hardening in water lubricated tests

The micro-hardness depth profiles for the water lubricated test specimens from two different tests i.e. Blue Light rough – 1100 rough (in black colour) and Blue Light smooth – 1100 rough (in grey colour) are given in Fig. 9. It is quite evident from these results that there is hardly any change in surface hardness of the test disc specimens after rolling/sliding tests in presence of water. This could be attributed to the lack of work hardening and/or formation of tribochemical layer consisting of a mixture of oxide and hydroxide under water lubricated rolling sliding conditions. The formation of a mixed oxide/hydroxide tribochemical layer has also been reported by Baek et al [16]. Similar results have been reported by other researchers from two-disc tests with water lubrication [9]. In contrast, Beynon et al. [10] concluded from a similar two-disc test, that both rail and wheel specimens work harden when water was used as lubricant. The difference in work hardening behaviour is not surprising in view of the differences in operating conditions as contact pressure, rail and wheel material, test duration, resulting wear etc.

![Fig. 9. Work hardening of test specimens in water lubricated tests](image)

3.3.4 Plastic flow/surface damage in water lubricated conditions

Both wheel and rail discs from tests under water lubricated conditions showed signs of plastic flow in the upper most layers. The difference in plastic flow as compared to that in the dry tests is owing to the lower stresses induced into the contact because of lower coefficient of friction in presence of water. Further, rail discs surfaces from water lubricated tests are characterised by surface initiated cracks, Fig 10. These cracks may grow by pressurisation of water into the surface fatigue cracks as suggested by Beynon et al. [10] and other researchers [17-19]. The surface roughness of the mating wheel specimen did not influence the occurrence of these surface cracks.
3.4 SEM/EDS analysis

Selected rail and wheel test specimens were analysed by using scanning electron microscopy incorporating energy dispersive spectroscopy (SEM/EDS). From SEM investigations of the test specimens with initial rough surfaces, Fig 11, it can be seen that the nature of surface damage differs between the driving wheel specimens and the driven rail specimens under dry and water lubricated conditions. In dry rolling/sliding tests, the worn surface of the wheel disc specimen is characterised predominantly by plastic deformation and adhesive wear. The worn surface of the mating rail disc specimen however shows mainly an adhesively worn surface. The worn surfaces of the wheel and rail disc specimens from tests under water lubricated conditions show severe plastic deformation of asperities and delaminated (sheet-like) features respectively. The presence of oxide layer in case of both the dry tests and water lubricated tests imply that tribochemical wear mechanism also contributes towards wear of wheel and rail materials. Similar results have been reported by Deters and Proksch from experiments in two-disc machine [20].
Results from EDS analysis of the wheel and rail disc test specimens from dry and water lubricated tests are shown in Fig. 12-13. In these results, the weight percent of oxygen at different depths from the surface up to 250 μm down into the material is shown. The rail disc specimen run in dry condition show sign of oxygen only near the surface whereas the rail disc specimen run in water lubrication contain oxygen up to a depth of ~ 250 μm. This could be caused due to the formation of oxide/hydroxide tribochemical layer during tests under water lubricated conditions as mentioned earlier.

Fig. 12. Oxygen content of wheel specimens

Fig. 13. Oxygen content of rail specimens
3.6 Resultant surface roughness

The resultant surface topographies of rail and wheel specimens were compared with those of the original surfaces before the tests, see Fig 14-19. In tests where the initial surface roughness has been worn down, the driving wheel disc has a smoother resultant surface than the driven rail disc. The resultant surface roughness has been found to be independent of the initial roughness on both wheel and rail discs.

Fig. 14. New wheel surfaces, left: wheel – rough ($S_a= 14 \, \mu m$), right: wheel – smooth ($S_a= 2 \, \mu m$)

Fig. 15. New rail surfaces, left: rail – rough ($S_a= 2 \, \mu m$), right: rail – smooth ($S_a= 0.5 \, \mu m$)
Fig. 16. After dry test, left: Blue Light (smooth), $S_a=0.6 \, \mu m$. Right: 1100 (rough), $S_a=3.4 \, \mu m$

Fig. 17. After dry test, left: Blue Light (rough), $S_a=1.3 \, \mu m$. Right: 1100 (rough), $S_a=0.6 \, \mu m$

Fig. 18. After water lubricated test, left: Blue Light (smooth), $S_a=1 \, \mu m$. Right: 1100 (rough), $S_a=1.5 \, \mu m$

Fig. 19. After water lubricated test, left: Blue Light (rough), $S_a=15 \, \mu m$. Right: 1100 (rough), $S_a=2 \, \mu m$
5. CONCLUSIONS

An experimental study based on Design of Experiments (DOE) approach has been conducted to investigate the influence of surface topography and water lubrication on tribological behaviour of different wheel/rail material pairs. The salient conclusions of this work are given below.

1. Initially rough wheel specimen surfaces result in lower coefficients of friction than those with initially smooth wheel specimen surfaces both in dry and water lubricated conditions. It is also interesting to note that the resultant surface roughness values of all test specimens at the end of tests are quite similar.

2. The friction coefficients of all the wheel/rail material pairs studied under water lubricated conditions decreased significantly as compared to those in under dry conditions.

3. The tribological pairs with smooth rail specimen surfaces and rough wheel specimens have shown lower wear under dry conditions. In the water lubricated tests, the wear has been lower with rough rail specimen surfaces.

4. The total wear of different wheel/rail material pairs increased considerably under water lubricated conditions. This increase is primarily due to very high wear of rail materials in presence of water. Interestingly, the wear of wheel materials decreased in presence of water as compared to their wear under dry conditions.

5. Bainitic wheel material has resulted in increased total wear under both dry and water lubricated conditions.
References
