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A TWIN-DISC STUDY OF THE ROLE OF THE SURFACE QUALITY ACHIEVED BY GRINDING ON THE WEAR RESISTANCE AND ROLLING CONTACT FATIGUE BEHAVIOR OF WHEEL/RAIL PAIRS

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Abstract: The tribological behavior of wheel and rail material twin-disc samples prepared under laboratory-controlled grinding operations was studied. A laboratory grinding device was designed and validated to produce similar results to those found in the field in terms of surface quality and presence of white etching layer (WEL). The test samples were evaluated in a twin-disc machine under dry and lubricated conditions. The results showed that the surface finishing parameters and the microstructure change greatly depending on the surface preparation procedure, and that such changes affect the tribological response of the samples. The wear rates of the tribological tests for the different rail surface qualities showed a reduction of 47.4% for the lubricated tests and 7.3% for the dry tests when the surfaces of the rail specimens were finished by grinding. This only applied when the WEL thickness was less than 4 μm.

Keywords: Friction Coefficient, Grinding, Rolling Contact Fatigue, Twin-disc tests, Wear Mechanisms, White Etching Layer.

1. INTRODUCTION

One of the fundamental questions in wheel-rail system maintenance is which rail grinding strategy should be applied and/or developed to reduce wear and Rolling Contact Fatigue (RCF) of rails. Currently new rail grinding strategies are based on the specific operating conditions of each rail system [1–3] as each system has unique loading and weather conditions, vehicle velocity, and modes of operation. Rail grinding is used to control wear and friction since it removes surface irregularities and defects. It also helps to control the wheel-rail contact by maintaining profiles[4]. However, the effect of the surface quality of grinding is not completely understood. Furthermore, surface quality specifications (standard CEN EN 13231-3) only indicate a maximum average surface roughness of the rail of Ra = 10 μm, but the detailed effect of rough surfaces on wear and friction is still under study [5].

Rail grinding has been investigated from two perspectives: (1) in-field developments to modify rail profiles [1–4,6–10], or to optimize grinding parameters [8,11–17], and (2) laboratory study including disc grinding tests used in disc-disc tests, to study their effect on surface finish, microstructure and wear behaviour, but this has only been achieved in one study [18], and twin disc tests have not been attempted before to confirm predictions of the effect that different grinding operating conditions may have, and thus enable a discussion of the possible effect on wear behaviour. Only two laboratory studies have evaluated the tribological effect, but for surfaces with prior wear and then with a grinding process [18,19].

Laboratory studies for rail samples include strategies for re-profiling by the grinding process [9,20], mitigation of RCF or metal-removal rates and also optimization of profile designs for mitigation of RCF [1,3,9,14,21,22]. Hashimoto et al. evaluated the surface integrity and fatigue resistance for hard turned and ground surfaces, Ra, and heat treatment variables were investigated, rolling/sliding conditions were not taken into consideration [23]. Other research includes the development of grinding stones, in-field interaction between the head of the rail and the grinding stone [13,24], the influence of pressure [25], residual and thermal stress effects [22,26] on RCF have been also reported [27,28]. Noise reduction through the appropriate grinding parameters has also been a concern [29].

Uhlmann et al.[30] developed a testing machine with a brake to perform grinding tests to evaluate performance of grinding stones and the effect of white etching layer and roughness by grinding, the authors concluded that friction generates heat promoting the formation of a white etching layer, producing a plastically deformed layer of about 20µm to 30µm and also concluded that the arithmetical mean roughness (Ra) can be used as a diagnostic for the surface quality after grinding to predict possible trends on the wear of the component.

Regarding twin-disc tests to evaluate wear and friction in the laboratory, only Lundmark et al. [11,31] have conducted a systematic study to investigate the influence of surface roughness on the tribological performance of wheel-rail twin-disc systems. They concluded that surface roughness and material of the wheel affect the tribological response. In their experiments, samples with higher roughness (Ra) presented lower wear than smoother samples. However, the effect of the grinding-operation conditions such as speed and cut on the surfaces of the discs were not explored.

Rail grinding technology has been widely used all over the world and has produced great economic benefits to the railway industry [24]. Therefore, it is important to evaluate this effect as this technology may be applied not only to alleviate damage to the rail surface or to improve the safety of rail transport, but also to increase the useful life of rails.

In this work, the tribological response of rail material with ground surfaces in contact with wheel materials was tested in a laboratory. The laboratory set-up used to apply the grinding process was explained in previous research [32]. A surface grinding machine was developed to create disc textures and also surface quality features resembling those obtained by re-profiling in the field. This machine allows control of the depth of cut and linear velocity during grinding in order to evaluate their effect on the surfaces. Grinding stone rotational speed is kept constant. After grinding, samples were tested in a twin-disc machine to evaluate wear and RCF of the ground surfaces. Tests were run under dry and lubricated conditions using a contact pressure of 1.1GPa and 5% creepage and pure rolling at a contact pressure of 0.8GPa. The conditions of the grinding process and tribological tests were determined by the variables of the Medellín Metro's rail system.

2. METHODOLOGY

2.1. Materials

Rail and wheel specimens were taken from R370CrHT rail sections and ER8 grade wheels respectively. The chemical composition and mechanical properties of the rail and wheel materials (Table 1), are in accordance with EN 13674-1: 2011 and EN 13262: 2004 [33].

Vickers hardness of disc contact surfaces and sub-surface on disc sections was measured in a universal durometer OTTO WOLPERT-WERKE Dia Testor 2Rc with a load of 31.25 Kgf. Tensile tests were performed on a WPM z10 universal testing machine.

Two sets of specimens for testing in the twin-disc machine were produced: ground discs and turned discs. The roughness parameters of the specimens were measured using a Mitutoyo Surface SJ210 (software *Truesurf)* roughness tester with cut-off length of 0.8 mm of and total sampling length of 8.0 mm. In all cases, five measurements were performed in the transverse direction on the specimen and approximately every 70°. Surface quality parameters were measured in accordance with ISO 4287 [34]. The analyzed parameters were Rp (maximum profile peak height), Rv (maximum profile valley depth), Rq (root mean square deviation of the assessed profile), Rsk (Skewness of the assessed profile), Rku (kurtosis of the assessed profile: sharpness of the height distribution, defined on the sampling length) and the hybrid parameters RPc (peak count number), which provides the density of peaks per unit of length.

The average values and standard deviation of the roughness parameters measured in the turned samples are displayed in Table 1. The roughness parameters before the grinding process are relatively low with respect to those resulting from the grinding, indicating of a "smooth" surface quality.

Table 1 *Properties of wheel and rail materials*

Chemical composition of the rails and the wheel (% by weight)												
	C	Si	Mn	P	S	Cr	Al	V	Cu	Ti	Ni	Mo
R370CrHT	0.762	0.394	1.062	0.0011	0.015	0.506	0.000	0.002	0.038	0.002	0.058	0.019
ER8	0.542	0.253	0.734	0.011	0.006	0.141	0.027	0.006	0.165	0.002	0.120	0.048

Mechanical properties of wheel and rail materials					
Specification		**Tensile strength (MPa)**	**Yield strength (MPa)**	**Strain (%)**	**Hardness HV (HB)**
Rail	R370CrHT	1373	767	9.97	386.9 (366.4)
Wheel	R260	951	731	15.45	288.3 (273.4)

Roughness parameters of turned samples			
Sample	**Ra (µm)**	**Rp (µm)**	**Rpc (pks/mm)**
Rail	1.25±0.017	3.48 ±0.51	18.57±1.95
Wheel	1.24±0.03	4.15±0.12	10.33±1.02

"[insert Figure 1]"

2.2. Laboratory Grinding Tests

The rail grinding parameters used in the field are shown in Table 2 along with the conditions selected for this study. The velocity (V), depth of cut (D), cutting angle, and stone type were controlled in the test rig schematically represented in Figure 1.

Table 2 *Grinding conditions in the field and in laboratory.*

Parameter	**Field**	**Laboratory**
Travel velocity	from 1.6 to 13 km/h.	**Low velocity condition (LV):** 3 km/h. 156 RPM in test rig. High velocity condition (**HV**): 10 km/h. 1129 RPM in test rig
Depth of cut *Removal passes/cut: 40 passes/cycle	Low power mode: 0.01 mm (6 W)* High power mode: 0.5 mm (14 W)*	**Low Depth of Cut (LD):** total depth of cut (0.6 mm) removed in three (3) cuts, each of 0.2 mm **High Depth of Cut (HD):** total depth of cut (0.6 mm) removed in one (1) cut. *
Cutting angle	Front motors: from 20° to 70° and Four rear motors: from -45° to 45°.	0°
Vitreous bonded Stone	16 or 32 abrasive particles per cm^2. Grinding stone rotational speed from 4200 to 4800 RPM.	16 particles per cm^2. Grinding stone abrasive rotational speed 3600 RPM

The experiments were performed using four grinding conditions (LV-LD, HV-LD, LV-HD, HV-HD, all of which are defined in Table 2). After grinding, the samples were sectioned, and a metallographic inspection was performed near to the surface.

2.3. Twin-disc Tests

The tribological tests were performed using a twin-disc testing machine, so it is representative of the typical wheel tread/rail head contact conditions in many railway systems. A detailed description of the testing machine can be found elsewhere[35].

Twin-disc experiments were performed in two stages: the first was designed to determine which of four combinations of grinding parameters was the best with respect to wear resistance for pure rolling tests (0% creepage, 0.8 GPa and dry conditions for 10,000 cycles). The parameters with the highest mass losses were discarded and those with best wear response were analyzed in a second stage.

For stage 2, the grinding operations with the parameters showing the highest wear resistance in stage 1 were used to grind new discs. In stage 2 three different test conditions were applied using 5% slip and a contact pressure of 1.1 GPa. In the first condition, the discs were run under dry conditions up to 14,000 cycles. The second condition was to run dry for the first 4,000 cycles and then the discs were lubricated with a friction modifier for the next 10,000 cycles, and the third condition was lubricated from the beginning of the tests up to 14,000 cycles (Table 3). In all cases, ground rail samples were compared with turned samples. Additionally, during twin-disc tests, friction coefficient was measured and at the end of the tests, images of worn surfaces were taken to observe wear mechanisms.

Table 3 *Testing Conditions during Stage 2.*

Testing Contact Conditions	Cycles	Details
Dry	4000	Dry
	9000	Dry
	14000	Dry
Dry + lubricated with friction modifier (FM)	14000	4000 dry cycles followed by 10000 lubricated cycles with FM1
Lubricated with friction modifier (FM)	9000	FM added from the beginning of the test
	14000	FM added from the beginning of the test

3. RESULTS AND DISCUSSION

3.1. Stage I: Pure Rolling

Figure 2 depicts the roughness parameters for both ground and turned surfaces before and after pure rolling tests. Values for ground rail (GR) discs are a mean value of all test conditions, i.e., results include high and low velocity, high and low depth of cut. Selected roughness parameters are presented that showed statistically significant differences between GR surfaces and turned surfaces or Rail Not Ground (NG) in accordance with the ANOVA test with α=0.05.

"[insert Figure 2]"

GR samples showed an equal surface quality, in other words, all combinations of the grinding processes (HV-LD, HV-HD, LV-LD and LV-HD), produced equal values of roughness. Among the reasons to explain this, is that the same total length of cutting of 0.6mm, measured in the longitudinal direction of the specimen, and the same grain size of the stone were utilized in all conditions. The only variation in the parameters from the grinding process was for Rku. For the high velocity condition (HV) Rku was 3.1, while for the low velocity condition (LV) produced a Rku of 2.7. Rsk varies with respect to the depth of cut, for low depth of cut (LD) they yielded negative values and, for high depth of cut (HD) they yielded a positive value. The Skewness parameter Rsk was positive only for the tests where there was high depth of cut, the positive Rsk indicated that the amplitude of the curve distribution was biased upwards with respect to the mean, that is to say, the peaks distribution on the surface were more dominant than the valleys distribution. In the low depth of cut tests the parameter Rsk was negative indicating that the amplitude of the curve distribution was biased downwards with respect to the mean.

The NG and GR surfaces both showed decreases in parameters such as Rp, Rv and Rq. The contact occurs at a finite number of asperities. Due to the pressure applied at the contact plastic deformation and/or removal of the peaks occur due to abrasion at the contact, reducing the Rp of the surfaces. However, the deviation was greater than 35% for most of the parameters for the NG rail surface. This indicates a non-homogeneous surface quality (see Figure 3) with defects such as cracks and spalling as was eventually observed in the mechanisms of wear. The average change in the GR surfaces was less than 10% which indicated a more homogeneous change in the surfaces, which is associated with progressive plastic deformation in the peaks reducing their height during the loading cycles in the twin disc tests. This deformation of the peaks was evidenced by the fact that the roughness parameter associated with the height of the peaks (Rp) and the number of the peaks (Rpc) were lower than in the initial conditions.

The Rp parameter, while not typically quoted in surface measurements, is one that can be easily measured in the field with a portable profilometer. In this study it was considered an important parameter that was also linked with the deformation and wear and had a relationship with the white etching layer (see Figure 3). The results obtained in the reduction of Rp are established in µm and are displayed in Figure 3.

Figure 3 depicts the wear rate, Rp, coefficient of friction (COF) and, also the white layer thickness obtained from the samples evaluated after pure rolling tests under different conditions. Even though the surfaces were very similar in terms of roughness at the beginning of the tests (Rp, Rq), there were significant differences in mass losses. The highest mass losses were found for low velocity and Small Depth of Cut (LV and LD). The lowest mass losses were found for surfaces ground with a high velocity and Large Depth of Cut (HV and HD). Another relevant result is that the lowest mass losses were found for turned surfaces. The differences in mass losses are not only related to the Rp parameter, but also with localized heating caused by several passes of grinding stones. Even though the final cutting depth was constant during the experiment, the procedures had a different grinding time. For instance, for HV and HD the grinding time was 4s given that the simulated linear speed was 10km/h, while for HV and LD the grinding time was 13s for a simulated linear speed of 10km/h. Longer grinding times mean either higher temperatures or more time for a given temperature to start to decrease, which, in turn, may generate a thicker white etching layer. Figure 3 depicts this correlation, in the case of ground surfaces submitted to pure rolling of 10,000 cycles in dry conditions with 0.8GPa pressure. The surface with the lowest mass loss was the combination of HV and HD which corresponds to a thicker white etching layer. On the contrary, a thicker white etching layer, with a deeper hardening effect, delays the deformation of the peaks, as may be confirmed by a comparison of Rp before and after the test, producing a higher wear rate.

"[insert Figure 3.]"

Non-significant COF changes may be due to detachment of asperities during the rolling process (see Figure 3). In the loss of mass there are factors of the process that make the surface wear higher, namely, the process of grinding a thickness of white etching layer greater than 17.5μm which makes it a more fragile surface for peak fracture, since the density of peaks is lower, with hardened surface and asymmetry of profile, the combination of these variables generates greater wear. On the other hand, if the process is conducted with high velocity and high depth, the surface has a greater number of peaks in contact, reducing contact efforts, and also with a positive profile asymmetry that makes the contact more homogeneous, and therefore, the generation of martensite is lower and the white layer is 3.3μm in thickness, which allows less wear, so it can be asserted that, as a hypothesis, the wear may be observed by the fragility of the white layer released, and as it is small it generates little loss of mass and then continues with the deformation of the surface and subsequently, the Rp decreases only by 16% (see Figure 3).

3.2. Stage 2, creepage: Tribological Tests with 5% creepage and 1.1 GPa

Figure 4 shows Rp and Rq obtained after twin-disc tests with 5% creepage. They were selected because they were the best indicators of changes during the test and allowed assessment of the behavior against wear. Before the twin-disc tests, turned surfaces were smoother (lower Rp and Rq) compared to ground surfaces. Tests were performed up-to a different number of cycles. While the roughness for ground surfaces increased, the roughness of turned surfaces decreased after the twin-disc tests.

Figure 4 also shows the mass loss results and COF during twin disc tests. The COF was similar for all dry tests, whether the samples were ground or turned. The addition of a lubricant (Friction modifier - FM) decreased the COF by an order of magnitude. COF was equal for all lubricated conditions. This indicates that the COF does not change due to surface roughness in this case.

Mass losses were lower during lubricated tests when compared with dry tests. The dry tests were evaluated at 4,000, 9,000 and 14,000 cycles. It was observed that the wear rate was higher for ground surfaces at low cycles, at 9,000 cycles the rate was the same for ground and non-ground (turned) surfaces. For higher cycles, 14,000, the wear rate was lower for the ground surfaces (26.9µg/ cycle) compared with turned samples (29.5µg/cycle). With respect to ground samples, the Rp and Rq parameters after 14,000 cycles under dry conditions were reduced 2.6 times and 1.8 times, respectively. As in the case of pure rolling, the deformation of peaks could be partially controlled by the white etching layer formation. On the other hand, compared with the turned surface, Rp and Rq after 14,000 cycles under dry conditions increased by 3.6 and 6 times respectively, which is directly associated with the presence of delamination and spalling and other wear mechanisms, as will be eventually discussed.

For ground samples the tests performed in the sequence 4.000 cycles under dry conditions followed by 10,000 cycles under lubricated conditions, there was a reduction of wear rate of about 1.9 times with respect to 14,000 cycles under dry conditions. As for the tests with lubrication from the beginning, the wear rate was reduced about 3.6 times from 14,000 cycles under dry conditions.

Finally, there was a wear rate reduction when comparing results of completely lubricated tests of 14,000 cycles of 3.6 times for ground samples and by 2.2 for turning samples indicating that the surface features obtained by the grinding process mitigated the wear rate. With respect to ground samples, while the Rp and Rq parameters after 14,000 cycles were reduced 2.6 times, for the non-ground surfaces there was a 3-fold increase, indicating surface damage had occurred.

Observing the Rp and Rq parameters for the completely lubricated test, it was observed that there was slight wear for the ground surface (GR) due to plastic deformation. The fact that at 4,000 cycles the wear rate for GR is higher than the NG samples is explained by the process of accommodation or running-in of the surfaces which determines part of the wear mechanisms until a conformal contact is reached.

At 9,000 cycles there is no difference in the wear rate between NG and GR surfaces, but the wear mechanisms are different (see Figure 5) and at 14,000 cycles the dry GR surface has a much lower wear than for the NG.

This is mainly caused by the wear mechanism in GR characterized by a hardening of the surface due to the grinding process which generates a layer of martensite.

Furthermore, during the test there is plastic deformation that generates a hardening of the surface, that is, as a hypothesis, that if the layer of martensite is removed during the state of accommodation of the surfaces, this layer is approximately 7µm and a good part of the Rp remains that will be plastically deformed which will generate an increase in residual stresses and hardening, this will generate a resistance to wear by rolling and slip.

"[insert Figure 4]"

4. WEAR MECHANISMS

Figure 5 shows the wheel and rail samples surfaces after tests at 1.1 GPa and 5% slip. It also shows the wear mechanisms for dry and lubricated tests for NG and GR surfaces. For dry conditions, at the beginning of tests for the GR rail surfaces, the surface peaks abraded the surface of the wheel. This is due to the burrs generated by the grinding process. There was also a crushing of peaks by gradual plastic deformation from 4,000 cycles to 14,000 cycles, this was evidenced by the monitoring of surfaces (see Figure 5) and by the roughness parameters.

The dominant wear mechanism for both ground and turned specimens is plastic deformation followed by ratchetting. There is an increase in shear stress in the material that leads to strain accumulation and produces material rupture by delamination (ratchetting), that is, by an incremental growth of stresses in each loading cycle, plastic deformation accumulated which in turn alters the microstructure of the material, then there is a deformation followed by crack growth and subsequent elimination of material (see Figure 5t). But, because of the roughness of the turned samples the contact pressure over each peak is lower compared with the ground samples, therefore, in the case of ground samples the mechanism of plastic deformation was "greater" or more prolonged in time when the surface was ground more severely at the beginning, therefore helping promote an adhesion wear mechanism, which explains the higher wear rate at the beginning compared to turned samples. For a turned surface finish, with respect to the peaks of the surface, the plastic deformation is smaller, this is the reason why the ground samples show a higher plastic deformation of the peaks, since there is an increase in the spacing and a decrease in the height of the peaks (see Figures 5d, f, j, l, m, p and q).By observing the images, it can be seen that the surface quality is directly related with the mechanisms of wear and that high peaks (higher than 20µm) with thin white layers (lower than 5 µm) allows to slow down the growth of cracks and therefore mitigates the damage by RCF, .

Furthermore, detachment of material occurs, and tiny marks are visible. A similar roughness profile for the wheel is observed too, due to the abrasive roughening process imposed by the rail profile. There was deformation and some percentage of large pits, which are known in the literature as spalling [9,36–39], were also present.

Ratcheting is also observed, and abrasion took place in some areas of the wheels. Tests of ground surfaces on rail specimens show that no cracks are present, i.e. no signs of RCF are observed (see Figure 5a and n). No spalling or other significant wear mechanism is identified either. The untreated rail specimens in dry tests (0% slip), unlike treated rail surfaces, display RCF features similar to those of the wheel specimens, although less severe (see Figure 5b and c). In Figure 5a and n, the surface modified by grinding is observed, which shows evidence of the abrasion marks made by the stone used to remove material. Material removal seems to be homogeneous in terms of peak spacing height, although there are peaks that stand out.

For tests run for 14,000 dry cycles, grinding surfaces show in the 40X zoom (bar equal to 500µm) a deformation of the peaks and the crushing of most of them; at a 700X zoom (bar equal to 20µm) delamination and spalling of material were observed. For non-ground surfaces, the evolution of fatigue worn surfaces was observed (lubricated with HLK, at1.1GPa and 5% sliding). It can be seen that from 9,000 to 14,000 cycles there is an increase in the fatigue cracks on the surface of rail specimens. In lubricated tests, for the ground specimens, the wear mechanism is deformation of the peaks in the first place and at higher conditions accumulation of plastic deformation occurs (ratcheting), which degrades and cracks the material surface, although to a lower extent than in trials where the specimens were not ground. Here, it can be seen there are deeper cracks compared with dry tests, because the tangential force in the dry specimens is greater, producing higher deformations at lower depths, thus cracks are more superficial.

In the completely lubricated test, the surface roughness profile is slightly deformed compared with the pre-test profile. According to the micrograph of the surface without a twin disc test, that grinding causes a superficial change in martensite. It is clear from the images that after the tests, there is a removal of the white etching layer, more noticeable in dry conditions and less noticeable for full lubrication, in addition to an observed deformation.

"[insert Figure 5]"

4.1. Effect of Surface Quality in Wear

For the condition of 5% of slip and 1.1 GPa of mean contact pressure, ground surfaces displayed a significant difference in wear and in mass loss. Compared to specimens without grinding, the surface tended to have deformation of peaks and valleys which allowed a delay in the growth of cracks in the surfaces in contact, as a result of a reduction in the factors of stress concentration. When lubricant was applied, this growth was even slower and the mass loss was less than if the surface did not have a ground surface profile. According to quantitative test results reported in the literature [9], this initial condition yields a reduction of the normal RCF life by roughly a factor nine, which is in accordance with both observations in the field and in the literature on rail spalling defects. There is an effect of the surface quality obtained by the grinding process and the behavior may be predicted against wear rate and friction control. Using the wear results in relation to the roughness parameters Rq and Rp, the number of cycles before the grinding process needs re-performing could be estimated for the completely dry and thoroughly lubricated conditions evaluated. This means that in the field roughness measurements could be used to predict when maintenance is needed.

Since data for roughness parameters Rp and Rq were obtained for both ground and unground surfaces of rail specimens at 0, 4,000, 9,000 up to 14,000 cycles, the number of cycles could be estimated by regression analysis. The life of the rail specimen was considered to end when the value of Rq reached 10µm.

For the dry condition, the ground surface took an estimated 23,000 cycles for Rq to reach 10µm and the unground surface 17,000 cycles, Rp values were 0µm and 21µm respectively at these points. For the lubricated condition, the ground surface took 153,000 cycles to reach 10µm and the unground surface 28,000 cycles. This was a life increase of the rail specimen of around 7 times compared to dry conditions for ground and 9 times compared to the unground surface. It should be noted that in order to more accurately estimate the number of cycles between each reprofiling process, the rolling contact fatigue (RCF) wear mechanism [18] and the failure frequency associated with the curve type must be taken into account [40].

5. COMPARISON OF FIELD, LABORATORY TESTS, AND RAIL GRADES

Figure 6 shows the different thicknesses of white etching layer for the first set of tests. They are thicker for Low Depth of cut (LD) with Low Velocity condition (LV), and thinner for High Depth of cut (HD) and High Velocity conditions (HV). The thickest white etching layer occurs for a combination of low depths of cut and low cutting velocity (LD LV). On the contrary, a lower WEL thickness occurs for high velocity and depth of cut.

Two main regions were observed in the cross-sections of samples submitted to field grinding tests. A white etching layer exists near the surface and a deformation zone below. White etching layer thicknesses were 13 ± 5 microns (see Figure 6f) and the deformed layer thicknesses were 400, 250, and 300 microns for the specimens [41] and in other reports of field measurements the WEL thickness is in these values [42]. As a result of the operating procedures in the field, the white etching layer was found in almost all inspected rails, where the aspect and the results of hardness measurements indicated that it consisted of untempered martensite, which was formed due to localized heating and rapid cooling during grinding. This was confirmed in this work with the hardness data obtained after testing and using optical microscopy.

"[insert Figure 6]"

To study WEL formation in 400HT premium rail, the grinding process was carried out using a disc of this type of rail. The chemical composition of the materials was measured by optical emission spectroscopy (OES) and the results can be found in previous reports [35,43,44]. For the condition of high speed and high depth of cut, WEL of approximately 15 µm in thickness was obtained (see Figure 7 e), which may indicate that for higher hardness and carbon percentage of the material the WEL thickness increases, and in this case is approximately twice as much. The tribological behavior of this type of rail was not evaluated in this work, but it is hypothesized that it can be said that according to the thickness of the WEL for pure rolling, a behavior equal to the E3 test (LV, LD) would be expected, and for tests with a contact condition of 5% slip.

That thicker WEL's correlate with higher wear rates. And for the same WEL thickness of 3 µm, when the slip percentage was increased from 0 to 5% the wear rate increased by 20.7 times in dry contact conditions (see Figure 3 and 4).

Another hypothesis is that the lifecycle of the rail may be increased, the life cycle is expected to be higher than for 370 rail. This is because the discs do not present fatigue before going through the grinding process since when there is an initial fatigue process, the defects are not removed and if the deformed layer is completely deformed, the wear may be greater. Compared to the previous study where rail discs with previous wear were evaluated and then went through a grinding process with this same assembly and afterward were taken back to twin disc tests, it was evidenced that even though it was for another rail, it increased the RCF wear mechanics by a factor of 9 with respect to no grinding process [18]. Unlike these results, the wear in this work was reduced by a factor of nine. This indicates that by completely removing the defects and deformed layer, with the grinding process, it is plausible to increase the life of the rail, but with a minimum martensite thickness.

In previous studies [18,19], different grinding tests were carried out in the laboratory, in which the effect of the operating conditions of the grinding process and the type of grade of the rail specimens on the surface quality and the formation of WEL were demonstrated. These characteristics found during grinding in the laboratory were similar to those found in the field [42].

6. CONCLUSIONS

The main rail grinding variables found in the field were replicated in a laboratory rig allowing control of the velocity and depth of cut and to maintain a fixed contact angle.

The lowest wear rate in the pure rolling test at a pressure of 0.8 GPa occurred when the rail was ground with operating conditions involving high velocity (HV) and high depth of cut (HD). This HV-HD condition is the one with the WEL thickness, indicating that the best condition to extend the life of the rail is a grinding operation condition that generates a white layer less than 4 μm in thickness.

The wear rate for rolling/sliding contact is lower when the samples are lubricated from the beginning of the test, that is, when the mechanical damage to the rail is small, and twice the wear rate when the rail disc was ground. This result indicates that grinding and lubrication increases the life of the rail.

The roughness parameters that did vary by combining high and low pressure and high and low velocity were Rku and Rsk, which provided information about the distribution of peaks and the asymmetry of the profile and had a verifiable correlation with mass loss in the tribological tests.

Grinding has a great impact not only on the surface quality, but also on the rail's mechanical properties, as the temperature peaks and the fast-cooling rates imposed in localized regions of the rail promote the martensitic transformation of the steel. During re-profiling procedures, layer hardness varied between 410 and 800 HV. Thus, the significant parameters are related to cutting velocity, allowing a more homogeneous surface quality between the distribution of peaks and valleys, being better when the velocity is high.

In conclusion, the roughness parameters may indicate the predominant wear mechanism, and this is influenced by the initial parameters of roughness. In addition, they influence the acceleration or mitigation of other mechanisms of wear. Deformation of peaks is observed by analyzing the Rp parameter. In this research, a correlation was found with roughness parameters that are not frequently used, such as Rp and Rq, with respect to wear. These parameters can be indicators of maintenance time and can be easily measured. It is proposed that the twin-disc tests carried out with high velocity and a depth of cut equal to the total material removed led to lower wear rates because with a faster operation less heat is transferred into the material, which reduces the amount of martensite formed by quenching.

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Although the results presented in this paper are specifically for this contact and tribological conditions studied here, the invitation in this research is for each company in the railway sector, using similar materials and tribological conditions, to use high speed and high depth of cut to reduce grinding time and to reduce the white layer thickness. As a final conclusion, results suggest that the twin disc tests correctly evaluate the effect on the surface quality due to the grinding process.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

P.Cuervo: Substantial contribution to the concept or design of the work, acquisition, analysis or interpretation of data, drafted the article. **J.M. Meza**: Analysis of data, revised it critically for important intellectual content, approved the version to be published. **A. Toro**: Supervision, contribution to the concept or design of the work, revised it critically for important intellectual content, approved the version to be published. **J.F. Santa:** Analysis of data, revised it critically for important intellectual content, approved the version to be published. **R. Lewis**: Supervision, revised it critically for important intellectual content, drafted the article, approved the version to be published.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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