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Investigation of the Influence of Rail Hardness on the Wear of Rail and Wheel Materials under Dry Conditions (ICRI Wear Mapping Project)

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Abstract

Some railway managers and practitioners fear that introducing premium rail materials will have a detrimental effect on the wheels of trains that use the line. A review of relevant investigations across all scales in the laboratory, and in the field has been carried out. This showed that, as rail hardness increases, its wear, and overall system wear reduces. Wheel wear does increase with increasing rail hardness, but only for wheels running on rails that are softer than them. Similar trends were observed in all studies, so it seems that the fears were unfounded.

While the wear trends appear well characterised some issues have been identified. One relates to the varying work hardening capability of wheel and rail materials. Often only bulk hardness is quoted, but work hardening can increase material surface hardness by up to 2.5 times and make materials that were initially softer, harder than the opposing material. Another related issue is test length. It is essential that enough cycles are applied such that the materials reach steady state wear, i.e., the point at which work hardening has reached its limit. In previous work it is not always clear that steady state wear has been reached. Some gaps have been identified in the current knowledge base, the largest of which is the failure to determine which mechanisms lead to the wear trends seen.

Analysis of recent work on different clad layers on rail discs and premium rail materials allowed some of these gaps to be addressed. Results indicated that opposing wheel material hardened to the same level independent of rail hardness. Wheel wear is therefore stress driven under the conditions used, and dictated by the wheel material properties only. At higher slip levels relationships become less clear, but here temperature and therefore hot hardness is most influential and is as yet uncharacterised.

Keywords: wheel and rail materials hardness effects on wear; wear rates; work hardening, wear mechanisms; laser cladding of rail

1 Introduction

The wheel/rail interface is critical in determining both the operating performance of a railway network and its safety. Maintaining this contact interface can be extremely expensive: it is unlike any other tribological interface. Not only does it support loads that mean that the yield stresses in the materials are exceeded locally, it is also open, which means that it is influenced by environmental conditions and contaminants. Over the past few decades, demand for improved performance of trains has led to higher accelerations, speeds, and braking forces which have increased the stresses in the wheel/rail interface [1]. The changing loads in the contact have a large effect on the rail and wheel damage mechanisms, such as wear and rolling contact fatigue (RCF), both of which are driven by the contact stresses and relative sliding in the wheel/rail contact.

Materials can be chosen to try to control the damage occurring at the interface, and increasingly durable wheel and rail materials have been developed [2, 3]. Ideally materials would be selected to give the optimal system response. In the UK, however, the rails and wheel have different owners, both of whom want what is best for them. While track access charges are intended to recompense the infrastructure manager for the wear and tear caused by each vehicle, and are a function of the vehicle's mass and suspension characteristics (its 'track-friendliness'), they are not sufficiently granular to account for all changes in wheel characteristics. Any changes to material properties on either side of the interface, especially those involving the introduction of harder, more durable, materials, are viewed with suspicion by those responsible for the opposite side of the interface; they are fearful that such changes may lead to their component wearing more. It is critical, therefore, that the effect of changing the wheel or rail material on both its own wear and that of the opposing surface is completely understood.

There are a number of methods that can be used to modify the properties of the wheel or rail: a different material can be used; a material can be heat treated; or a layer of harder, more durable, material can be clad or coated onto the wheel or rail. Of course, in all of these it is not the hardness alone that is being altered. The microstructure and is also different in different steel grades is also altered by heat treatment. It is therefore important to not only understand how hardness affects wear, but also to consider the effect of microstructural features on wear.

The aim of this paper was to draw together three fields of work:

1. Work carried out to look at the effect of changing rail or wheel hardness on the wear of the opposing material to identify the common trends and to identify gaps in available data or knowledge of the prevalent mechanisms of wear.
2. To try to fill some of the identified gaps, data from recent work on laser cladding of rail using materials with a wide range of hardness' and microstructures. In this work, detailed information on both wheel and rail materials was available from which it was possible to enhance understanding of the mechanisms occurring.

3. Results from testing on premium rail materials, which was carried out over a range of interface conditions to see if the trends hold as slip (and the contact patch frictional work, $T\gamma$) is changed.

This work was carried out as part of the International Collaborative Research Initiative (ICRI) initiative which aims to bring together wheel/rail interface researchers from across the world to collate data and knowledge to try to solve some of the common problems that are faced.

2 Review of Extant Work on Hardness Effects

2.1 Rail and Wheel Wear Data

Before the year 2000, very few of the studies of the wear of wheel and rail materials had focused on the effects of changing hardness. Research up to that date was summarized in a report by Burstow [4]. This highlighted the conclusion drawn from one review that "the belief that an increase in the hardness of the rail, while giving a decrease in the rail wear rate, will give an increase in wheel wear is not generally felt to be justified" [5]. The effect on wheel wear of increasing rail hardness, however, varied across all the studies reviewed. In a British Rail twin disc study on different Pearlitic rail steels it was found that wheel wear was independent of rail hardness. A British Rail full-scale test program, however, showed that wheel wear reduced with rail hardness increases [6]. This lack of a consistent pattern was backed up by research carried out in other laboratories (for example [7] and [8]). However, while no clear trend in wheel wear emerged, it was noted that rail hardness increases almost always led to a drop in overall system wear.

In the studies mentioned above, the wheelsteel was not changed, and it was generally softer than the various rail materials used. Markov [9] took the opposite approach and kept rail disc hardness the same and increased the wheel disc hardness in twin disc tests. Testing was carried out over a wide range of conditions, but the conclusions were that increasing wheel hardness decreased wheel wear and increased rail wear. The overall wear appeared to be independent of wheel hardness. Sato et al. [10] ran twin disc tests keeping the wheel material constant, and changed rail hardness, but all the rail materials had the same or lower hardness than the wheel material. Two rail microstructures were tested, Pearlitic and Bainitic. It was found that the rail wear reduced with increasing rail hardness. The wheel wear did not change a great deal as the Pearlitic rail hardness increased, although for the wheel wear against a Martensitic rail there was a slight increase.

Steele and Reiff [11] reported on some field trials from which similar trends to those described above were seen. These were used to propose trends for wheel, rail, and whole system wear depending on the ratio of rail to wheel hardness. This will be discussed later.

Most regions of the world now have a set of standard rail and wheel material grades with a range of properties, refined over many years in an effort to improve wear and RCF performance. Those established for Europe are shown in Table 1 along with two Japanese materials (CrB1400 rail steel and CM64 wheel steel). The European rail steels are Pearlitic and consist of R260, the stock material, used in the UK, and the heat-treated ("head-hardened") grades R350HT and R400HT (details in EN 13674-1). The Japanese CrB1400 is a Bainitic steel. Bainitic rail steels were developed as the maximum hardness that could be achieved by heat treating Pearlitic rail had been reached [12]; to reach higher levels different microstructures were required. Wheel material ER8 is most commonly used on multiple units, ER7 on freight cars and the Japanese CM64 is found mainly on high-speed vehicles.

After the year 2000, there have been a number of studies, both small and full-scale, to investigate the wear when the different standard grades of wheel and rail material are run against each other. A wide-ranging full-scale study was carried out very recently by Heyder & Maedler [1]. They considered the standard European materials as well as the Japanese steels shown in Table 1 for comparison. As shown in Figure 1, overall system wear reduced below that for R260 versus ER7 if a harder rail steel (R350HT) was used. This harder rail reduced rail wear with a simultaneous reduction in wheel wear to almost the same order of magnitude. Higher strength wheel materials reduced wheel wear, but did not give a simultaneous reduction in rail wear.

	Rail Steels				Wheel Steels		
	R260 (E)	R350HT (E)	R400HT (E)	CrB1400 (J)	ER7 (E)	ER8 (E)	C64M (J)
Tensile Strength (MPa)	≥880	≥1175	≥1280	≥1400	820-940	860-980	940-1100

Table 1: European (E)/Japanese (J) Wheel and Rail Steels (adapted from [1])

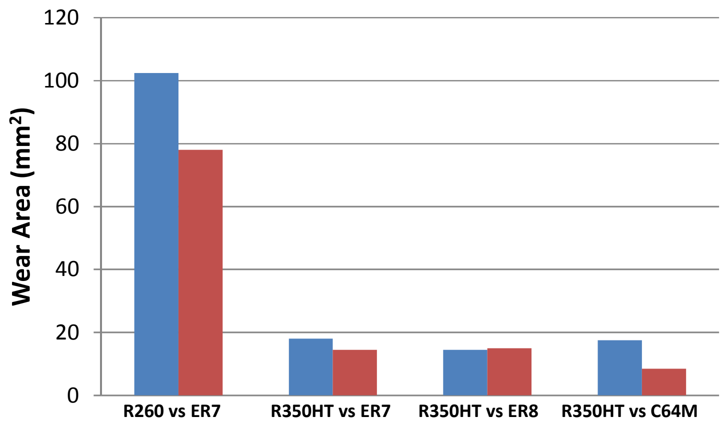

Figure 1. Wheel and Rail Wear from Full-Scale Laboratory Tests (adapted from [1])

Stock et al. [13] have seen similar trends in full-scale laboratory tests on ER7 wheel material against R260, R350HT, and R400HT rail. This consistency gives confidence that these trends are real, but in neither case was any examination of the mechanisms leading to the effects made.

Twin disc testing carried out within the EC funded *Innotrack* project [14] using combinations of ER7, ER8 wheel steels, and R260, R35HT and R400HT rail steels, showed that increasing rail hardness decreased rail wear. Tests were run for either 5,000 or 15,000 cycles. It was found that after 5,000 cycles the wear rate of the wheels rose when running against harder rails, but after 15,000 it reduced. Clearly the wheel material was work hardening which was affecting the wear rate. The effect of work hardening has also been noted in full-scale tests carried out by Jin et al. [15] using standard Chinese wheel and rail materials. A rail hardness increase from 250 HB to 380 HB reduced the wear rate of the rail gauge corner by half and gave a slight wear reduction for the rail head. The wear rate of the wheel flange increased with an increase in the rail hardness when tested for 1.26 million cycles. After 2.1 million cycles, the wear rate of wheel flange decreased below that of the wheel run against the softer rail.

It should be noted that, in the studies referred to so far, hardness was not measured after the tests, so relationships have been assessed based on bulk pre-test values.

Work hardening effects on Pearlitic versus Bainitic rail steels have been examined in detail by Lee & Polycarpou [12]. This was in response to field testing of both materials that showed, contrary to expectations, that the Pearlitic rail wore less than the Bainitic material despite having a lower bulk hardness (for details see [16]). Vickers micro-indentation testing of rail sections revealed that the Pearlitic steel had work hardened far more than the Bainitic material to the point where the surface hardness was higher. Tyfour et al. [17] also noted considerable work hardening in a Pearlitic rail steel. Run against W8A wheel material, surface hardness values 2.5 times higher than the bulk hardness were measured.

2.2 Discussion of Extant Knowledge

2.2.1 Wheel/Rail Interface System Wear

As mentioned earlier, the field studies reported by Steel & Reiff [11] led to the proposed relationships between wheel, rail, and whole system wear, and the ratio of rail to wheel hardness (see Figure 2). The explanation proposed for the trends shown is based around the material dictating the contact patch size. In the left side (rail/wheel hardness ratio ≤ 1), the rail is softer compared to the wheel. The rail, therefore determines the size of the contact patch. With increasing rail hardness, the rail wear will fall, and as the contact patch size decreases it is hypothesised that the wheel wear will increase (due to the higher contact stress). However, the system wear decreases as the fall in rail wear is greater than the rise in that of the wheel. On the right hand side where the wheel is softer and dictates the contact size (rail/wheel hardness ratio ≥ 1), if the wheel material is kept constant the size of the contact patch remains constant and independent of the rail grade. This would lead to constant wheel wear as shown. The rail wear decreases as rail hardness is increasing and system wear also decreases. Of course this is all based on bulk hardness measurements, which, as shown earlier can be misleading.

Most of the work reviewed in earlier sections falls to the right hand side of the 1:1 ratio, i.e. rail is harder than wheel. On the whole the work follows the trend proposed: which states as rail hardness increases and wheel material remains relatively constant, rail and system wear decrease and wheel wear remains constant. There may be some exceptions to this, which may result from microstructural features varying. The work carried out by Markov [9] and Sato et al. [10] involved rail hardness to wheel hardness ratios of less than one and therefore it falls on the left hand side of the chart. Again, their relationships approximately follow those proposed by Steel & Reiff [11].

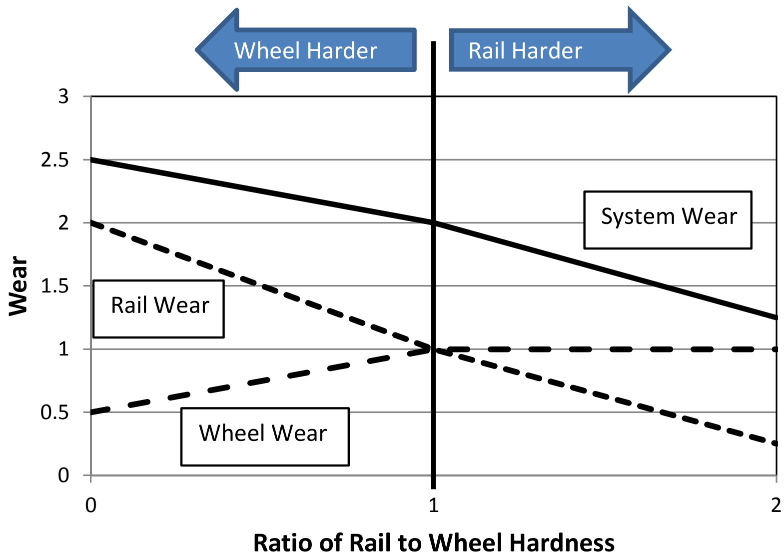

Figure 2. Wear in a Wheel/Rail System versus Ratio of Rail to Wheel Hardness [11]

2.2.2 Work Hardening and Steady State Wear

The observations made on work hardening show how it can vary considerably between materials. Typically all that is measured is the bulk hardness of the materials, but clearly in making comparisons, hardness values measured just below the surface after work hardening need to be considered. Analysis of how the corresponding wheel material work hardens may help reveal more about the underlying mechanisms behind wheel and rail wear. As mentioned previously, in most cases this kind of information is not always captured.

Another issue is that, in most studies, only one contact condition (usually relatively mild) has been assessed. At more severe conditions, temperatures will rise and may reach a level that can affect the material hardness [18, 19]. The effects of this temperature rise would not necessarily be apparent after test when test specimens have cooled to room temperature, but it would affected the measured wear rates and microstructure.

Aside from highlighting the need for measurement of work hardening effects, the outcomes described in the earlier sections with different wear rates for longer tests, raises an issue regarding appropriate test length and in deciding how many cycles to run in order to achieve a steady-state wear regime. This is an issue discussed at length in a recent review by Blau [20]. The only way to really know is to stop the tests frequently to assess wear rate rather than simply measuring material loss at the end of tests. This was done in the Tyfour et al. study [17] and adopted by Lewis et al. [21]. It was found that wear reached steady state at around 20,000 cycles, although this number will varies according to materials used, test conditions, and scales. It is impossible to know in most studies reviewed whether steady state was reached or not, as intermediate wear rates are rarely determined. As highlighted in [21] steady state is not always reached throughout the duration of the test. This means making assessments of whether wheel wear has increased or decreased is less straight-forward. A "standard" approach to wear testing has now been proposed, also as part of the ICRI initiative [22], but it will be a while before this can take effect.

2.2.3 Possible Wear Mechanisms

In the work reviewed, few potential mechanisms were proposed to explain the observations made, except for in the work by Marich & Curcio [8]: it was hypothesized that a reduction in wear of the rail would reduce the amount of wear debris within the interface which may lead to less abrasive wear on the wheel. This highlights another deficiency in almost all wheel/rail interface studies: wear debris analysis is rarely included.

The work by Vasic [14] also showed that with water in the contact there was a clear decrease in wheel wear for harder rails, unlike for the dry case. This may back up the theory that reducing wear debris (in this case by flushing it out with water) affects wheel wear rate.

It is well known that a ratchetting mechanism is the main cause of wear/crack initiation in wheels and rail. In harder materials, however, this is less likely to occur. If a shakedown plot is considered (see Figure 3), it can be seen that the harder rail materials (with higher values of k (shear yield strength)) will be less likely to fall in the ratchetting regime (it can be assumed that all materials will exhibit the same levels of friction for a given slip level).

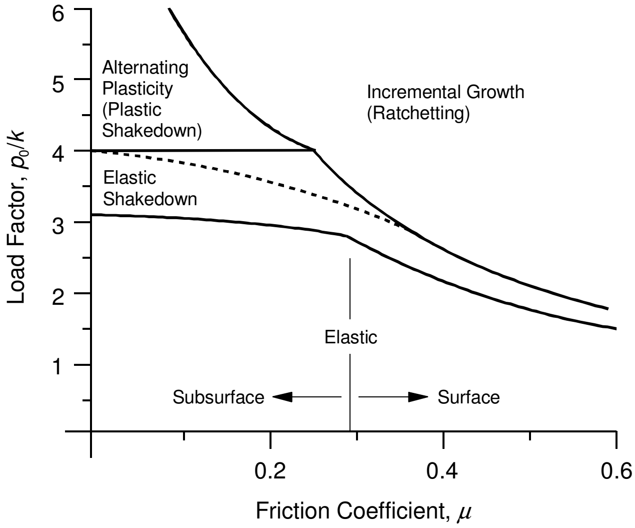

Figure 3. Shakedown Plot (where p_0 is normal contact pressure and k is shear yield strength)

Another issue that should be analysed is the third body layer formed in the contact between wheel and rail. These have been studied in previous twin disc testing by encapsulating discs post-test and then sectioning them [22]. An example of a wheel third-body layer is shown in Figure 4. The third-body layer formed may well vary with different materials which could affect wear rate.

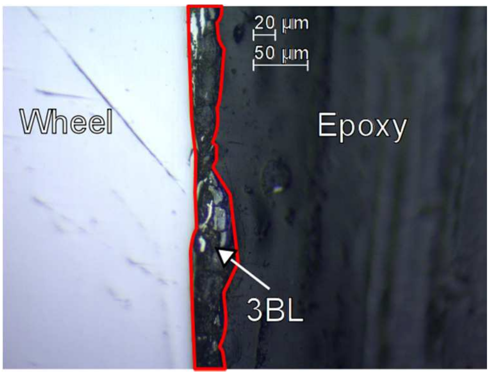

Figure 4. Third-Body Layer on a Wheel Disc

Another issue that may affect the relative wear is whether the wheel or rail disc is driving. In most twin disc tests the rail disc brakes and the wheel disc drives. However, it is not clear, in all the work reviewed, which disc is taking which role.

2.3 Knowledge Gaps

Tests across all scales in the laboratory and in the field have shown similar trends and follow the model proposed by Steele & Reiff [11] based on the rail to wheel hardness ratio (see Figure 2). If the rail is softer than the wheel, then rail wear decreases with increasing rail hardness, and wheel wear increases. If the rail is harder than the wheel, then again rail wear decreases with increasing rail hardness, but wheel wear remains constant. In both cases, however, as rail hardness increases overall system wear reduces. This information will help allay fears held by those that may think that introduction of premium rail or wheel materials will have a detrimental effect on the opposing material.

In order to help understand why the trends seen in wear rate have occurred, the following need to be considered in future work:

- Closer analysis of material on both sides of the contact is needed post-test to understand the prevalent mechanisms.
- Wear rate needs to be more closely monitored to check that steady state wear has been achieved.
- Hardness must be quantified post-test to characterise work hardening.
- Material properties must be considered, other than hardness, as it may not be this alone that dictates wear.
- A wide range of contact conditions should be used so the effect of temperature can be evaluated.

3 Laser Cladding of Rail

Recent testing on hard clad layers [24-25] has shown big improvements in wear performance over unclad rail and has given the opportunity to investigate hardness effects in greater detail, especially those of the opposing wheel material.

3.1 Analysis of Clad Rail Specimens

In a very recent twin disc trial (1% slip, 1500 MPa and 400 rpm) of a wide range of clad layers (of varying hardness and microstructure) [21] it was reaffirmed that a rail hardness increase (note that this is post-test hardness to take account of work hardening in the clad layer) reduces rail wear (see Figure 5a) and it was also clearly shown that overall system (wheel added to rail) wear decreases in most cases (see Figure 5b). The wheel wear was virtually independent of hardness (as shown in Figure 5c).

Sub-surface examination of the clad layers indicated that deformation was too small to measure (see example of Stellite 12 shown in Figure 6, compared to the R260 grade baseline). It is clear that very little ratchetting was occurring and that the likely wear mechanisms were mild adhesion or abrasion. This is confirmed by examination of the surface images shown in Figure 6, where it is apparent that the R260 grade material exhibits classic evidence of ratchetting behaviour, whereas the Stellite 12 is showing mild scoring and some evidence of adhesion.

Rail wear versus time for all the cladding materials is shown in Figure 7. It is clear that in many cases steady-state wear has been achieved. While in some it has not, those seem to be the less promising materials.

3.2 Analysis of Wheel Specimens

The key opportunity from this work was that the wheel discs could also be analysed in the hope that this would reveal more about the mechanisms behind the wear rate observations. Wheel discs run against a range of clad layers were sectioned, mounted, polished and etched before hardness profiles were taken using a Vickers micro-indentation technique and microstructural analysis was undertaken.

Figure 8 shows the pre and post-test wheel surface hardness data plotted against the post-test rail surface hardness values. It can be seen that the final wheel hardness value is completely independent of the rail hardness. Further detail in Figure 9 shows the change of hardness with depth. This reveals that the hardness changes in the same way for each disc as the depth increases.

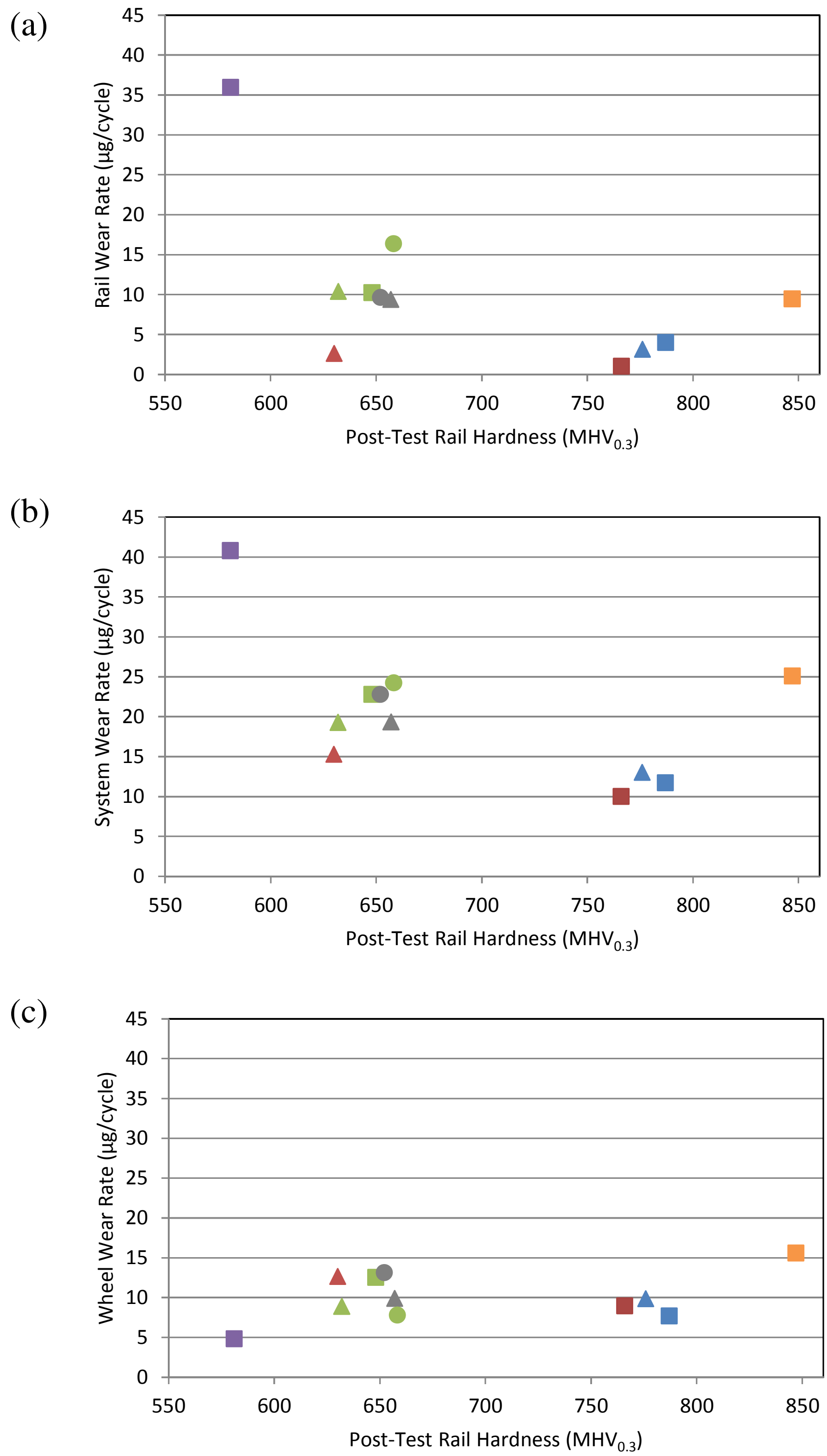

Figure 5. Wear Rates versus Rail Final Hardness (data extracted from work described in [21]): (a) Rail Wear; (b) Whole System Wear; (c) Wheel Wear (where

MHV0.3 is Micro-Vickers measured at a load of 0.3kg)

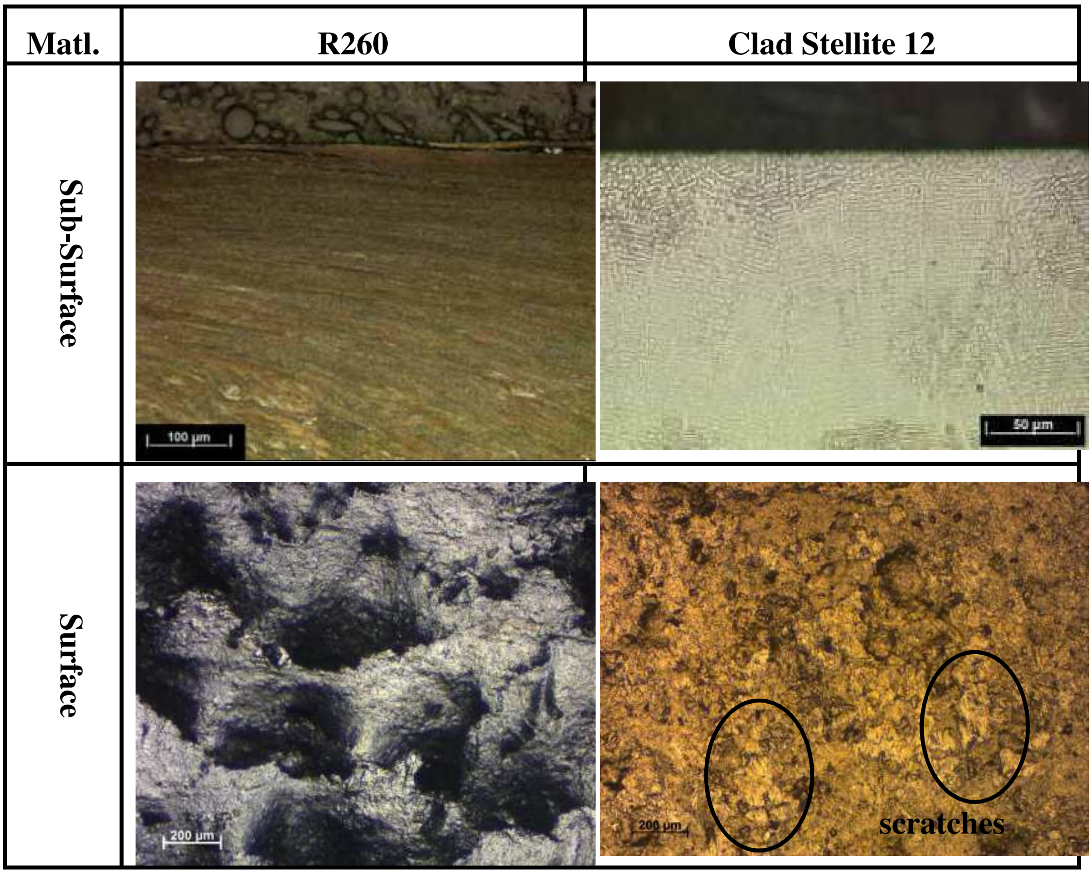

Figure 6. Subsurface and Surface Images of Baseline R260 and a Clad Layer of Stellite 12 (from Optical Microscopy)

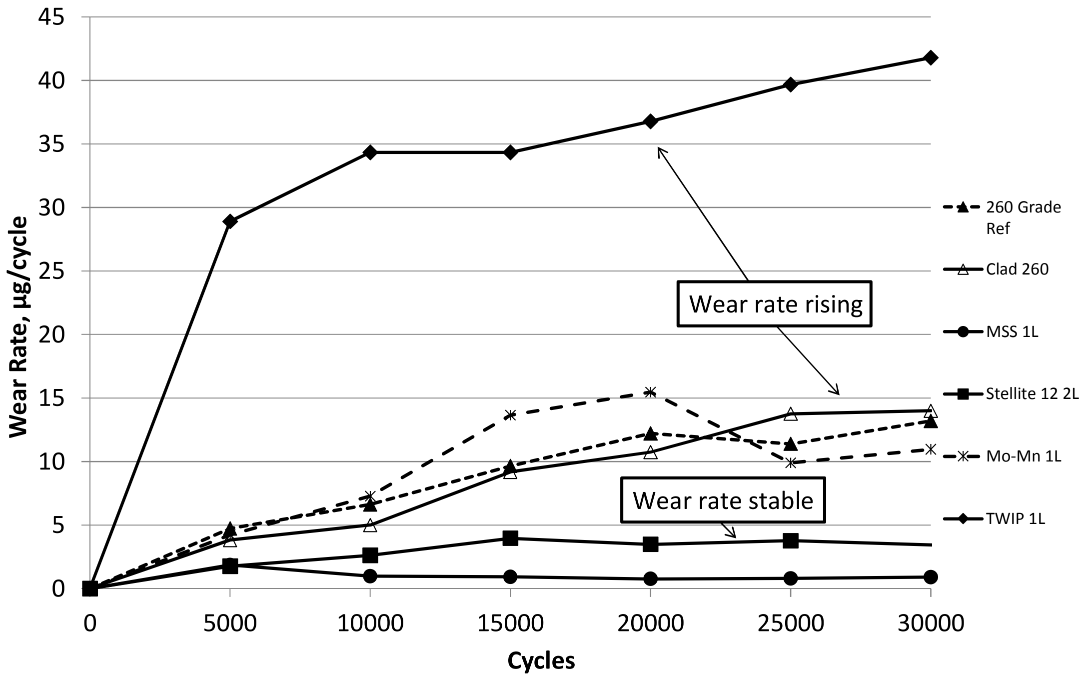

Figure 7. Wear Rates of Clad Layers during Twin Disc Tests (replotted from [21])

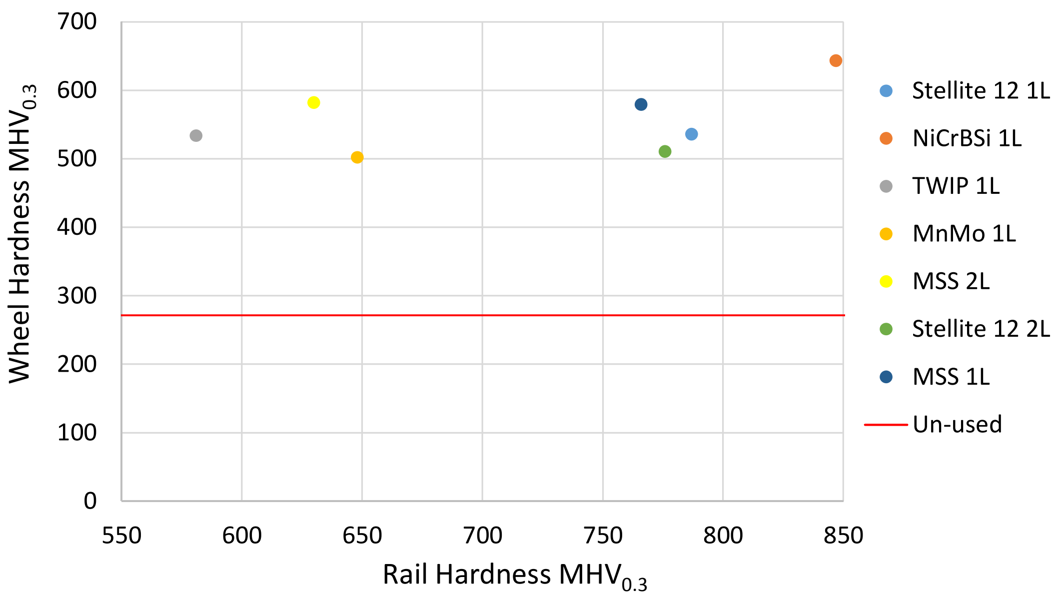

Figure 8. Wheel versus Rail Post-Test Surface Hardness (where MHV0.3 is Micro-Vickers measured at a load of 0.3kg)

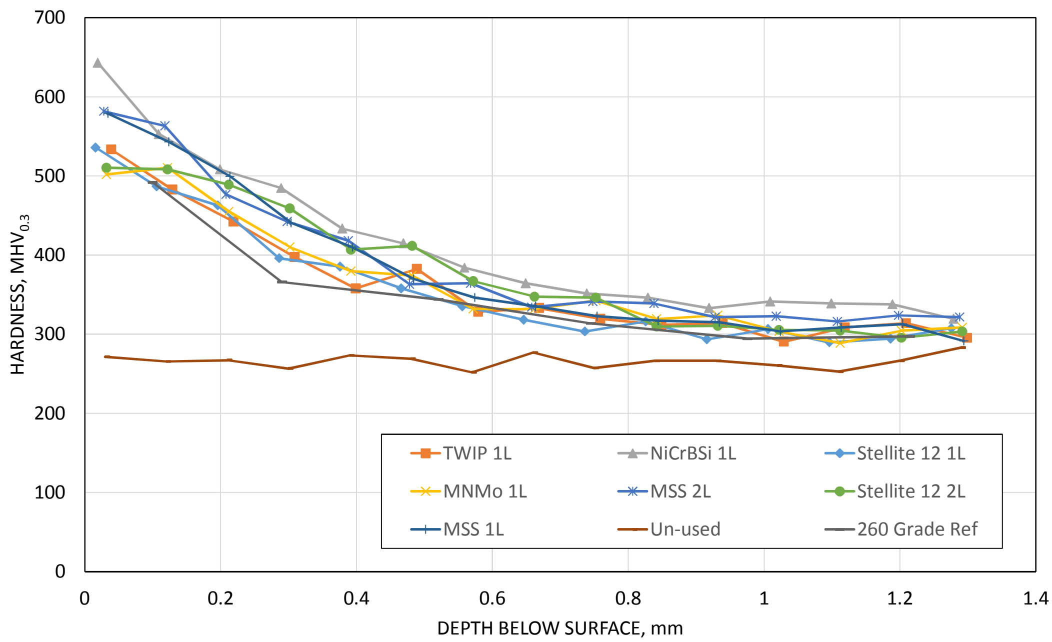

Figure 9. Hardness Change with Depth for Wheel Discs

3.3 Damage Mechanisms

The wheel wear rates determined when running against clad rail discs at one contact condition showed that hardening and wear of the wheel material is completely independent of rail material properties. Wear must therefore be driven by the contact stress and be a result of a ratchetting mechanism rather than abrasion or adhesion.

Where there is evidence of abrasive wear (on wheel and rail) it is driven by third body abrasion rather than two body, i.e., it has resulted from wear debris

Looking at the roughness data in Figure 10, it can be seen that, as the rail surface hardens, there is a step change in roughness evolution. For harder materials, hardness reduces during the test. This suggests a form of abrasive wear is occurring that is relatively mild, acting to "polish" the surface. For the softer rails, the roughness is increasing quite significantly which suggests either more severe abrasion is occurring, or adhesion. Wheel material follows a similar trend, but we know that the wheel wear rate is not changing much as rail hardness varies (see Figure 5c). This suggests that roughness is simply following that of the rail rather than it being influenced by the wheel wear mechanism.

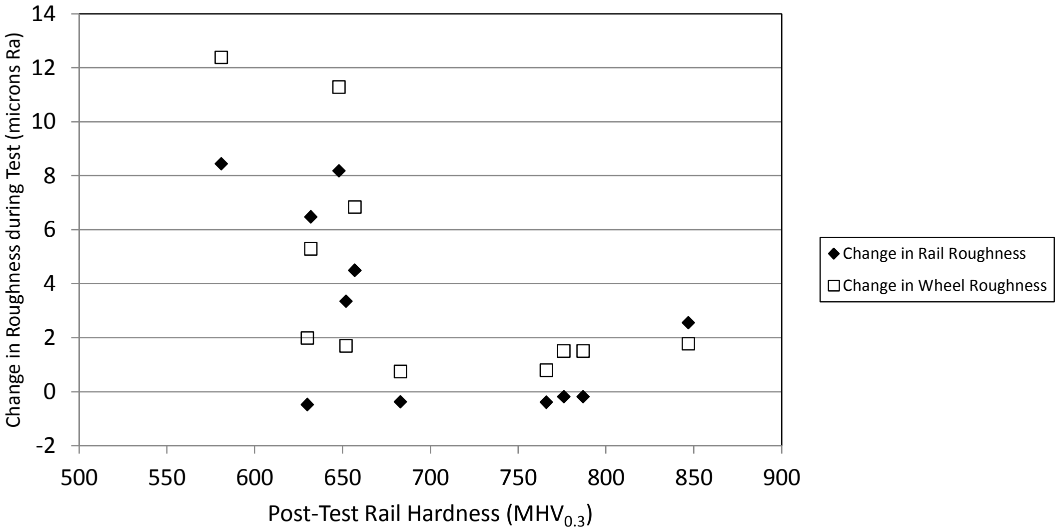

Figure 10. Roughness Change for Wheel and Clad Rails versus Post-Test Rail Hardness

4 Wear of Premium Rail

A series of twin disc tests has been carried out across a range of conditions for a number of premium rail materials (350HT, and two bespoke alloys, A and B) [26]. Slip values of 1, 10 and 20% were used with a contact pressure of 1500 MPa and a nominal rotational speed of 400 rpm.

The rail and wheel wear results plotted against rail bulk hardness are shown in Figures 11 and 12. All previous work looking at hardness effects had been carried out at a single set of conditions and usually using a relatively low slip value. At higher slip, temperature rises and could potentially act to soften the material making relationships harder to draw out. Here hot hardness during the test becomes a more useful indicator of performance. The results at 1% slip reflect those seen in previous studies (e.g. [13]). In this mild regime, wear mechanisms such as oxidation, adhesion, and abrasion would dominate [18, 27, 28]. These reduce with material hardness so the wear rates are as would be expected. At 10% slip the wear rates are relatively independent of hardness. This also ties up with previous observations. In this regime wear is driven by contact pressure and here this was constant. As slip increases to 20%, wear again is reduced by material hardness. In this regime, resistance to high temperatures is key and clearly the harder materials perform better. It is evident that the clad layer gives a much better performance at the more extreme conditions than the premium rail materials.

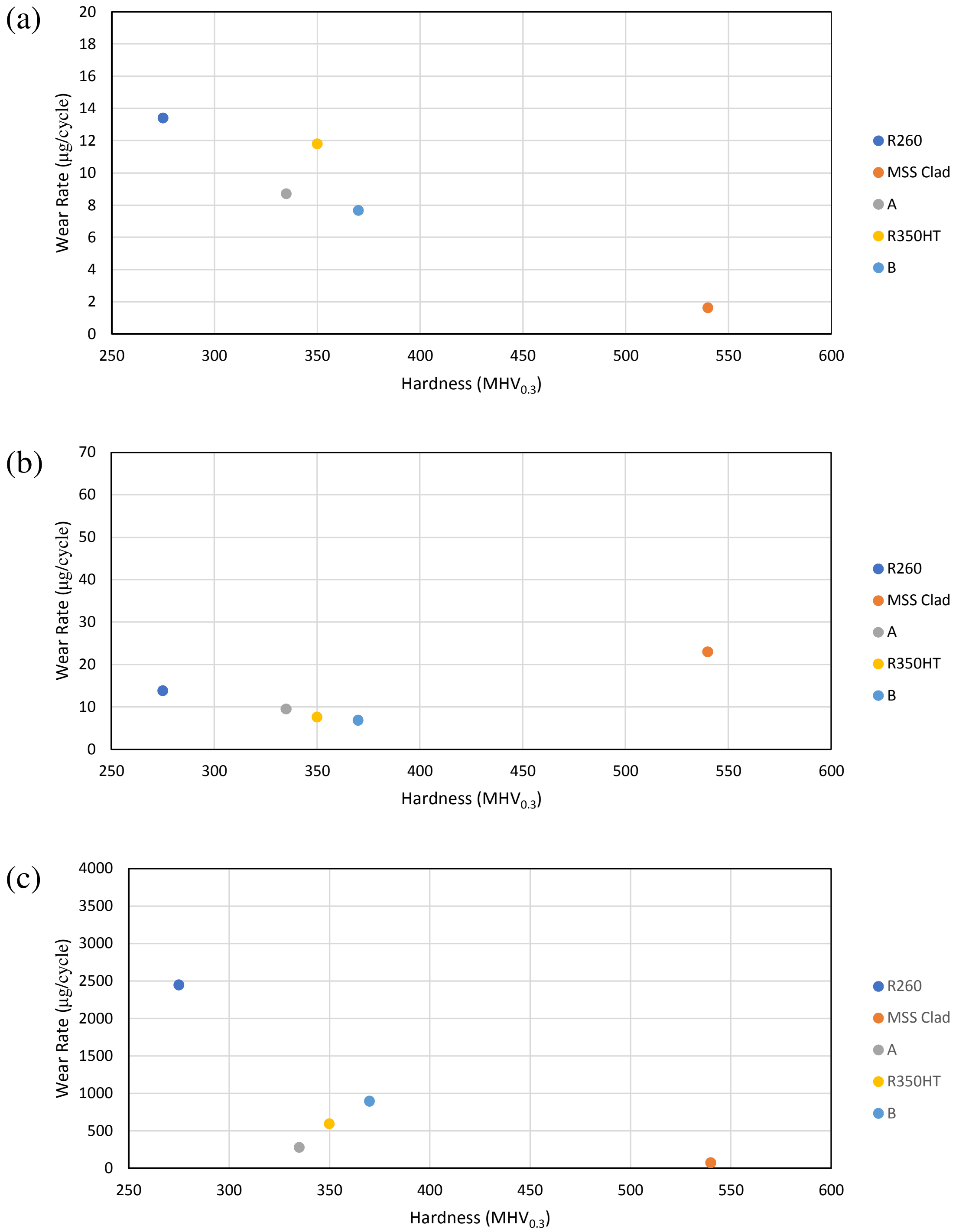

Figure 11. Rail Wear Rates versus Bulk Rail Final Hardness: (a) 1% Slip; (b) 10% Slip; (c) 20% Slip

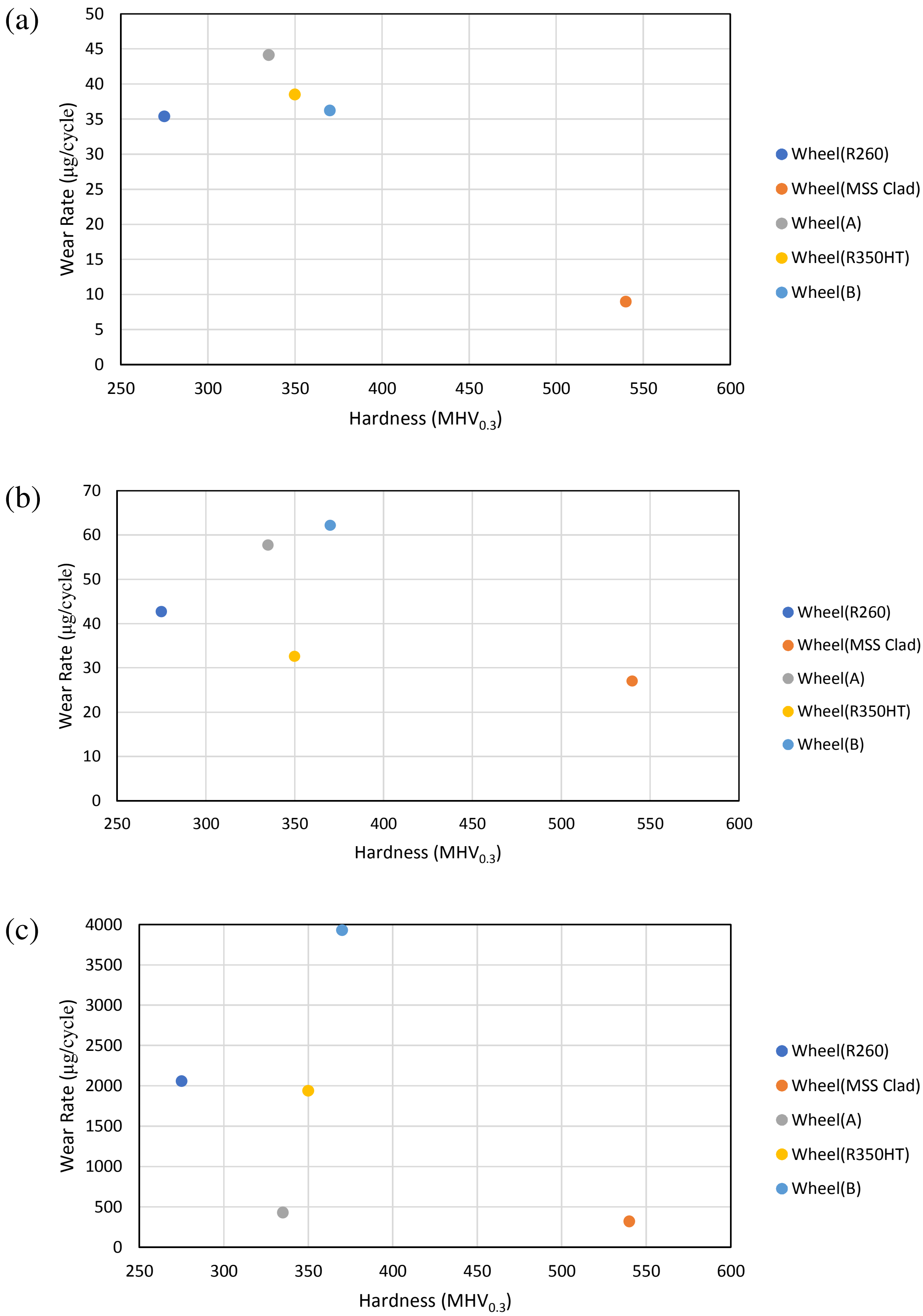

Figure 12. Wheel Wear Rates versus Bulk Rail Final Hardness: (a) 1% Slip; (b) 10% Slip; (c) 20% Slip

The wheel wear rates do not follow the previous trends observed. And fluctuate a lot more. The harder clad layer certainly does not act to increase wheel wear though.

The post-test hardness values have been measured as recommended in the earlier review (Section 2). For these tests, relationships were harder to pull out though. There could be a number of reasons for this. The standard and premium rail materials work harden a lot more than the clad layers, where very little flow of material was observed (see Figure 6). The rate of work hardening would need to be characterized and taken into account to establish the effect on wear with time to provide a better comparison. At high slip, temperatures will be high enough to affect the hardness of some of the materials [18]. As mentioned above, hot hardness would be a more useful indicator than the final hardness of a cooled disc. Further analysis can be done in the future to investigate these and establish if the trends from previous work at low slip really do extend to different conditions based on in-situ hardness or post-test hardness.

5 Conclusions

A review of existing work on the effects of rail and wheel hardness on the opposing material was carried out. There was a consensus on wear trends, but little in the way of explanation or proposed mechanisms. A series of gaps were identified: a lack of knowledge of materials of both sides on contacts in a test; a lack of clarity over whether tests reached steady state wear; no post-test hardness data; a limited number of contact conditions tested.

Analysis of studies on laser-clad layers and premium rails was then carried out. The work on clad layers showed that, as rail hardness increased, wheel wear rates stayed constant, consistent with previous results. However, it was shown that wheel hardness was constant, which indicates that the wear of wheels is dictated only by the properties of the wheel. Different wheel materials need to be tested to see the effect of their properties.

The work on premium rails was carried out at different slip values. At 1% slip wear rates reflect those seen in previous studies. The mild regime seen led to wear mechanisms such as oxidation, adhesion, and abrasion. These reduce with material hardness so the wear rates are as would be expected. At 10% slip, rail wear was independent of hardness. Previous work has shown that in this regime wear is largely driven by contact stress, this was constant across all the tests and therefore it explains the wear trend seen. At the higher slip (20%), the resulting temperatures could have been high enough to soften the materials. This implies that hot hardness during tests is more important than post-test hardness. The harder materials were clearly more resistant to temperature changes.

This work has confirmed the results of previous work, but provided some important new data on wear trends at different contact conditions that will be helpful in making material choices for points on the track where more extreme wheel/rail interface conditions can be expected. Clad layers seem to perform particularly well.

Acknowledgements

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