Wear Particle Analysis and the Evolution of the Plastically Deformed Layer on Australian Rail Steel

Asitha C. Athukorala\textsuperscript{1,a,}*, Dennis V. De Pellegrin\textsuperscript{1,b}, Ben T. Battaglia\textsuperscript{1,c}, Kyriakos I. Kourousis\textsuperscript{3,2,d}

\textsuperscript{1} Queensland University of Technology, Brisbane, QLD 4000, Australia
\textsuperscript{2} University of Limerick, Castletroy, Co. Limerick, Ireland
\textsuperscript{3} RMIT University, Melbourne, Victoria, Australia
\textsuperscript{a} asitha.athukoralalage@qut.edu.au, \textsuperscript{b} d.depellegrin@qut.edu.au, \textsuperscript{c} ben.battaglia@connect.qut.edu.au, \textsuperscript{d} Kyriakos.Kourousis@ul.ie

Abstract. Particle analysis methodology is presented, together with the morphology of the wear debris formed during rolling contact fatigue. Wear particles are characterised by their surface topography and in terms of wear mechanism. Rail-wheel materials are subjected to severe plastic deformation as the contact loading progresses, which contributes to a mechanism of major damage in head-hardened rail steel. Most of the current methodologies involve sectioning of the rail-wheel discs to trace material damage phenomena such as crack propagation and plastic strain accumulation. This paper proposes methodology to analyse the development of the plastically deformed layer by sectioning wear particles using the focussed ion beam (FIB) milling method. Moreover, it highlights the processes of oxidation and rail surface delamination during unlubricated rolling contact fatigue.

Keywords: Wear particle, FIB milling, hardness, rolling contact fatigue, railway

Introduction

The evolution of damage in the rail-wheel contact interface is a critical aspect in the railway technology field, as any new understanding potentially enhances opportunities for effective preventive and corrective maintenance in industry. The main source of damage and wear arises from repetitive plastic deformation of the rail surface, also known as ratcheting, which contributes to defects and ultimately the formation of wear particles. This phenomenon has been investigated empirically and simulated numerically using non-linear material models. The hardened plastically deformed layer has been observed on worn rail samples under excessive braking and acceleration and is often named the white etched layer (WEL). As the name suggests, this phenomenon produces a layer that has a white appearance when analysed microscopically, and is typically found in generated wear particles. This type of wear is important as it’s commonly due to the severe plastic deformation of rail materials. Its microstructural properties include very hard martensite in combination with pearlite, which can lead to hardness values up to 1300 HV (Vickers Hardness). Furthermore, researchers have concluded [1] that the cause is due to surface temperatures generated by the wheel-rail contact. This is generally in the region of up to 700°C under intense localised wheel-rail sliding. Rolling contact fatigue cracks on the rail surface have also been linked with the WEL [2, 3] and they are identified as studs [4]. Many research methodologies, eg. [5], involve the examination of rail disc cross-sections at the end of twin-disc tests. Detailed analysis of the formation of the WEL during repeated contact loading cycles is difficult as it is not possible to section the rail discs during the same test. Consequently, this research proposes a new methodology to study the development of the plastically deformed layer using the wear particles generated during rolling contact fatigue experiments. This approach has the potential
to greatly enhance the understanding of various related phenomena, including the formation of material damage and crack initiation in the rail-wheel contact interface.

**Experimental Method**

A twin-disc test rig was used to simulate the rail-wheel contact interface and the generated particles were collected at predefined sampling intervals to observe the development of the plastically deformed metal layer. The particles were cross-sectioned using a Quanta 3D Focused Ion Beam Milling (FIB) instrument and the hardness of the particles was measured using a berkovich tip (~150 nm tip radius) in a Hysitron Triboindenter (TI950). The data were then analysed for each separate interval.

Initially, the collected particles were stored in a dehumidified cupboard to control further oxidation until the ion milling process could take place. Particles were randomly distributed on an adhesive-lined stub after being blown with compressed air to remove any loose particles. This stub was then placed in the FIB instrument to complete the milling process. The areas of greatest interest were selected based on the presence of metal particles according to backscatter electron images. Furthermore, a platinum layer was deposited on the particle in order to reduce any curtaining effects and limit further damage to the sectioned surface, as shown in Fig. 1 a). The regular cross-section used a 5 nA aperture to accelerate the milling process. Further apertures of 1.0 and 0.5 nA were used to perform cleaning of the cross-section to achieve a finely polished surface for proper channelling contrast. A number of particles were sectioned to confirm repeatability of the results. As the particles were largely composed of iron-oxide material, the test-samples were prone to becoming positively charged, which sometimes caused difficulties with the milling process as the quality of the ion image was unstable.

![Fig. 1: Particle sectioning process; a) Pt layer deposition; b) subsequent sectioning with FIB mill](image)

Another sample of the particles was rigidly mounted on a metal stub/epoxy mount in order to perform nano-indentation. The surface irregularity and porosity of the worn particles has a negative effect on the single indentation process. Therefore, a partial loading function was used to perform the indentations. This function was applied using 33 loading cycles and 50% of each unloading cycle segment. Before making the indentation, particles were observed using an optical microscope to determine the high contrast regions of the particles where more metallic material existed. Indentation was performed at these selected locations with the use of automated indentation arrays. The machine has a load limit of 10,000 µN and 5 µm, therefore there was the possibility that the indentation might not be able to reach the desired depth in the particle.
Results and Discussion

The collected particles at each interval were sectioned to produce electron and ion images that are illustrated in Fig. 2. According to these images, the particles generated after 10-thousand cycles were primarily metallic (Fig. 2a), and plastic accumulation can be observed in the ion image after sectioning (Fig. 2b). This was due to the directional deformation in the grains which is enhanced by using channelling contrast. Furthermore, it is evident that there are cracks aligned with the deformation. The hypothesis of the authors is that these are surface initiated cracks due to large plastic strain accumulation, specifically during the initial contact cycles. In the 50-thousand cycle interval, oxidation has taken place on the disc surface as apparent from the oxide content of the wear particles. The metallic inclusions (flakes/slivers) are debris from the disc surface that is consistent with the surface properties of the rail-wheel material. Overall, Fig. 2 shows the structure and metal/oxide content in the wear particles during the experiment. At the 500-thousand cycles and beyond, the particles were severely oxidised and had become more porous. Consequently, nano-indentation was not possible due to the brittle nature of these particles.

In theory, the material plastically deformed with an increase in contact cycles and a combination of thermal effects. A hardened layer is therefore accumulated in the rail-wheel contact interface potentially leading to severe damage in the rail material surface. Interestingly though, this surface layer is not evident in all cases [6], as the deformed layer can wear off before reaching the critical state. Researchers [7] have attempted to study and produce numerical models to reflect this phenomenon, which can significantly reduce the life span of the rail material. Twin-disc testing will generate a considerable thermal effect due to the repetitive and adherent nature of the disc surfaces, which would help recreate any thermal effects occurring under more severe railway operating conditions.

![Images of wear particles at different intervals](image1)

- a) 10-thousand cycle interval (electron)
- b) 10-thousand cycle interval (ion)
- c) 50-thousand cycle interval (electron)
- d) 50-thousand cycle interval (ion)
- e) 100-thousand cycle interval (electron)
- f) 100-thousand cycle interval (ion)
The particle features were characterized using imageJ software. The average thicknesses of the particle and metal inclusions were measured and tabulated in Table 1. Metal debris at 50-thousand cycles has a thicker layer which may have resulted due to a combination of initial metal fatigue and oxidation. But as wear progresses, particles become more oxidised and less of the metal layer exists. For example, after 100-thousand cycles, more of the particles consisted of brittle iron oxide and the thickness of any metal layers was much lower. As the number of contact cycles progresses, plastic strain accumulates and surface temperature rises which leads to further oxidation. As a result of this wear mechanism, the thickness of the metal debris in the worn particle increased with the number of contact cycles. A statistical analysis of the particle size distribution over each contact interval is illustrated in Fig. 3.
After 500-thousand cycles, larger wear particles detached from the surface, as shown in Fig. 3, resulting in a considerable deformed metal layer being removed from the rail-wheel discs. Furthermore, it is evident in Fig. 2 i) that the average metal flake thickness of the worn particles was above 3 μm, suggesting a relatively deep surface delamination had taken place. The worn particles were more porous and brittle towards the final contact intervals. Some metallic debris was evident but oxidation dominated the surface metal wear process as a result of the higher surface temperatures.

Multiple indentations were made on the wear particles at each interval to acquire the hardness profile of the particles. The surface irregularities and brittleness of these particles caused an initial error on some results. The average hardness distribution of the particles at each contact interval is illustrated in Fig. 4. As expected, hardness increased with an increase in the number of cycles due to development of the work hardened layer. However, it was difficult to reach the desired indentation depth due to limitations with the nanoindenter’s maximum load capability. Some particles presented a thin oxide layer even when the surface was bright and reflective when observed in the optical microscope. As shown in Fig. 3, the hardened metal debris layer thickness is 75-125 nm. These irregular metal slivers are shown in each cross-section in Fig. 2. Every indentation had been developed through the metal layer, except for the 10-thousand-cycle interval particles as hardness considerably dropped when the indenter reached the oxide region through the metal layer. Overall, the data shows that the rail-wheel disc surface developed a hardened layer, as a result of both plastic accumulation and thermal effects.

According to the particle’s characteristics, a severe oxidation process has influenced the wear mechanism of the rail-wheel contact interface. However, the hardened metal debris shows
resistance to oxidation due to its deformed and irregular structure. Furthermore, cross-sectioning revealed crack formation due to the brittleness of the oxide layer. Consequently, such behaviour accelerates the frequency of oxidized particle generation during the contact intervals. Surprisingly, as shown in Fig. 2, particles were oxidized at each plane. The authors’ hypothesis is that particles were oxidized after the delamination process, mainly due to higher contact surface temperatures and oxide powder which was pressed and rolled into the larger and irregular particles as they squeezed through the contact zone. Furthermore, this hypothesis proved the occurrence of thin metallic layer of debris that was identified during the sectioning process. This debris contains thin delaminated metal particles from the disc surface which is covered with an oxide layer, as shown in Fig. 5. Therefore, these particles are holding metallic delaminated fatigue flakes arising due to the development of plastic accumulation on the disc surface.

Conclusion

The present research has attempted to quantify and correlate particle generation in terms of the wear mechanisms using detailed particle analysis; representing an approach which has not been found in the current literature. The sectioned particles provide significant information about the generation of metal debris, oxidation, actual morphology metal debris, critical ratcheting and delamination depths at the surface. Furthermore, this study showed the development of the deformed hardened layer over a number of cycles. Severe delamination was observed with accumulated damage after the 500-thousand cycle interval. In summary, although the approach presented is time consuming, it is highly effective in characterising the damage mechanisms at different stages of the wear process.

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References