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Wear and damage transitions of wheel and rail materials under various contact conditions

W.J. Wang[a, b], R. Lewis[b], B. Yang[a], L.C. Guo[a], Q.Y. Liu[a,*], M.H. Zhu[a]

a. Tribology Research Institute, State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China b. Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

Abstract: This study discusses a *Tγ/A* method of plotting wear data from a twin-disc machine for identifying the wear and damage transitions of wheel and rail materials. As found in previous work, three wear regimes (mild wear, severe wear and catastrophic wear) of U71Mn rail material were identified in dry rolling-sliding contact tests. It was determined that the damage mechanism transforms in the different wear regimes. Here earlier studies were extended to establish wear behaviour for the presence of a number of third body materials (oil, water, friction enhancers) and a rail cladding process designed to make wheels and rails more durable. This has provided much needed data for Multi-Body Dynamics (MBD) simulations, and will allow better predictions of profile evolution of wheel and rail over a wider range of conditions.

Keywords: Rail-wheel tribology; Rolling-sliding; Surface topography; Mapping

1. Introduction

The wear at the wheel/rail interface plays a vital role in determining the reliability of railway transportation. With an increase in speed and axle loads, the wear of wheel and rail materials is becoming more and more severe, which results in a significant decrease of wheel/rail system service life. Therefore, many researchers all over the world have explored

*Corresponding author. Tel: +86-28-87603724.

E-mail address: liuqy@swjtu.cn (Q.Y. Liu).

and discussed the wear mechanisms of the wheel/rail system and the methods of alleviating the wear of wheel and rail materials [1-4].

It is well known that both rolling and sliding occur in the wheel/rail interface. When the wheel rolls on the straight track, the wheel tread is in contact with the rail head. In curves, the contact between the wheel flange and rail gauge appears, which results in greater sliding wear. Wear regimes and transitions have been identified using mapping methods and are defined in terms of slip and contact pressure and $T\gamma$ (tractive force × slip in the contact) [5-7]. Furthermore, the wear regimes are related to expected wheel/rail contact conditions and contact points. On the other hand, an Archard's sliding wear model, in which the wear is proportional to (sliding distance × load)/hardness, is often used to simulate the wear prediction of wheel and rail [7-8]. The comparison of results obtained with $T\gamma$ and Archard's law reveals a very good agreement in wear prediction [8].

Different products, such as lubricants, friction modifiers and traction enhancers can be added to the wheel/rail interface to help control friction and reduce damage. As the system is open, substances related to environmental conditions or that are just there accidentally can also be present (e.g. water, oil and leaves). While wear performance in dry conditions is well characterized, there is not enough data in the literature for the effects on wear across a wide range of conditions for the presence of third body materials. This information is very important to help improve wear prediction tools such as those integrated with Multi-Body Dynamics simulations.

As is known, friction plays a vital role in wheel and rail wear [2-3, 9-10] and investigations and applications have indicated that lubrication of the wheel/rail contact is an effective method for reducing the wear of wheel and rail materials. Some investigations have been carried out on wear effects of greases used in curves for lubrication [6, 11-15]. Using a lubricant significantly changes the wear rate of wheel/rail materials and the contact conditions for wear transitions [6]. Lewis et al. carried out some tests for to assess the performance of ten different grease types used as curve lubricants [11]. It was found that there is an inverse relationship between retentivity (how long a fixed amount of grease provides lubrication) and wear rate. Grease retentivity is also greater with lower roughness and with more grease applied. Various lubricants may help reduce noise from the wheel/rail system [12]. It has also been proved that less wear and deformation is found under the water condition compared to dry or other grease conditions [13]. Furthermore, wheel/rail friction management has a strong influence on the power consumption in the wheel/rail contact [14]. Friction modifiers can control the wheel/rail friction coefficient and the level of friction is significantly dependent on the amount applied top-of-rail (ToR) friction modifier [16].

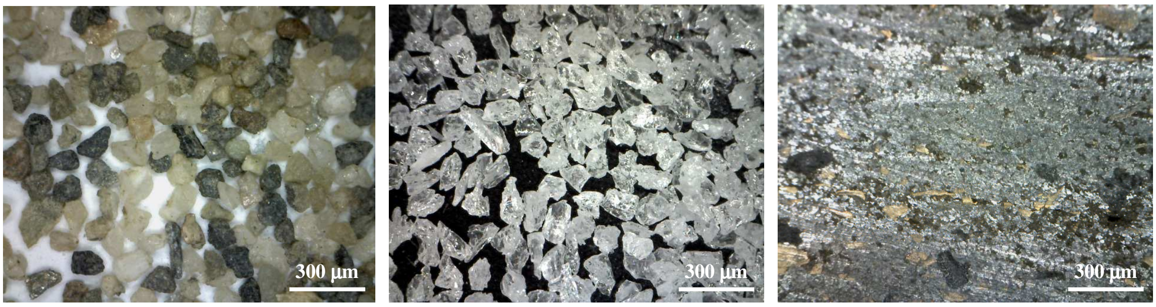
The third body materials presenting in the wheel/rail interface by accident or due to environmental conditions, such as water, oil, leaf, iron oxides, etc. strongly influence the adhesion of wheel/rail and cause low adhesion phenomena [17-19]. When the adhesion in the wheel/rail interface is poor, traction enhancers (sand, alumina, etc) are often sprayed into the wheel/rail interface for improving the adhesion coefficient. However, various traction enhancers can increase wear rate of wheel and rail materials and aggravate surface damage correspondingly. Studies have investigated the influence of sanding particle size, feed rate, and wheel slip on improving adhesion and wear in the wheel-rail contact [17-18, 20-21]. Furthermore, low adhesion is unlikely to occur while thick oxides with a rough surface give an extremely high adhesion and wear [19]. While these previous studies on causes of wear and wear prevention have been wide ranging, very specific contact conditions of wheel/rail are always adopted and there is not a wide range of wheel/rail contact information which is what is really needed for improving the wear prediction.

It is clear that the hardness significantly affects the wear and damage of wheel and rail materials. The high strength, fine lamellar pearlitic structure in rail steels is one of the most important factors for improving the wear resistance of material [22]. In addition, some researchers have explored the influence of laser surface treatment on the wear resistance of wheel and rail materials [23-25]. The results indicated that the laser treatment including laser dispersed quenching and laser cladding can significantly increase the hardness and wear resistance of wheel or rail material.

2. Aims and objectives of the investigation

The aim of this study was to develop wear information, via investigations from a twin-disc machine, to identify the wear regimes and damage transitions for wheel and rail materials with third body materials present in the wheel-rail contact. In order to present the wear data in a way that would allow a direct comparison with previous investigations, the approach of plotting wear rate in mass loss (μg), rolled (m) and contact area (mm^2) versus $T\gamma/A$ was used. This was used initially by Bolton and Clayton [26] and then in a number of subsequent studies [5, 7, 13, 27-30].

In this study, a large amount of data relating to the wear of wheel and rail materials has been generated from a twin-disc machine under various contact conditions, which is composed of two rollers served as a wheel roller and a rail roller. Third body materials including water, oil, friction enhancers (sand, alumina particles and abrasive block) were used in the wheel/rail interface. Water is continuously added to the wheel/rail surfaces using a channel and oil (a typical lubricating oil used in the wheel-rail contact in China) is regularly brushed on the wheel/rail interface. The sand or alumina particles are continuously added to the wheel/rail interface through a pipe by means of gravity. The abrasive block is fixed on the wheel roller using a dead weight, which simulates the full scale contact condition in the field. Main composition of the sands is quartz and its hardness is about 1170 HV [31]. The diameter of sand is about 125 μm (Fig.1a). The diameter of the alumina particles with about 2000 HV hardness is about 150 μm (Fig.1b). The abrasive block with a hardness of about 275 HV is a synthetic resin material with four element composite structure and it is made of binder, friction particles, friction modifier and packing material [31]. It is found in Fig.1c that the surface of abrasive block distributes with metal fibre and metallic particles. Its compressive strength is about 90 MPa and compression modulus is less than 9 GPa.



(a) (b) (c)

Fig.1. Photographs of abrasive materials, (a) sand; (b) alumina particles; (c) abrasive block.

The wheel and rail rollers were clad with different alloy powders using a multimode cross flow CO_2 laser (TR-3000). Two kinds of laser clad layers (Co-based and Fe-based alloy layers) were used to explore the wear and damage characteristics of wheel and rail materials.

They have uniform and compact microstructure and there are no visible crack and blow hole. Co-based alloy layer consists of dendrite and eutectic and the surface hardness is about 440 $HV_{0.5}$ [32]. Fe-based alloy layer is composed of F (Fe, Ni) solid solution and Cr_7C_3 carbide and the surface hardness is about 670 $HV_{0.5}$ [33]. Detailed information on the twin-disc machine and experimental approaches including the contact conditions (contact pressure, sliding speed, slip ratio, test duration, etc) can be found in previous publications [25, 30-38]. The wear rate and $T\gamma/A$ value are calculated by means of the wear loss (measurement accuracy: 0.001 g) of wheel or rail rollers and contact conditions from previous publications.

3. Wear and damage transitions under various contact conditions

3.1 Dry wear

It is clear in Fig.2 that the wear rate of U71Mn rail material has a distinct change with an increase in $T\gamma/A$ value. There are three wear regimes (mild wear, severe wear and catastrophic wear) in rolling-sliding wear tests. The transition of rail material wear results from different contact conditions. In the contact between the wheel tread and rail head, mild and severe wear are likely to occur. When the wheel flange and rail gauge corner contacts, large or full slip may present, which causes severe to catastrophic wear. Furthermore, high temperature of wheel/rail contact resulting from the slip would cause thermal softening of material and lead to catastrophic wear. It is clear in Fig.3 that the damage characteristic of the rail material is closely related to the wear regimes. When mild wear occurs, the surface damage is slight and the oxidation wear is dominating [7, 26]. There is no obvious sub-surface damage (Fig.3a). When the wear is in the catastrophic stage, serious spalling damage appears and there is visible fatigue cracking in the sub-surface (Fig.3b). In the severe wear regime, the damage should transform from slight damage and oxidation to spalling and fatigue cracks.

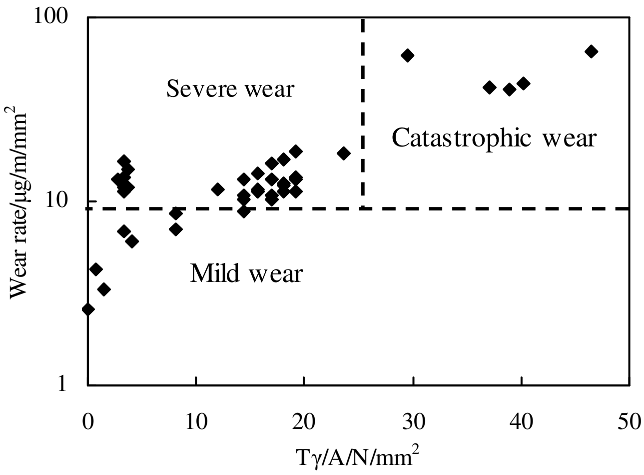
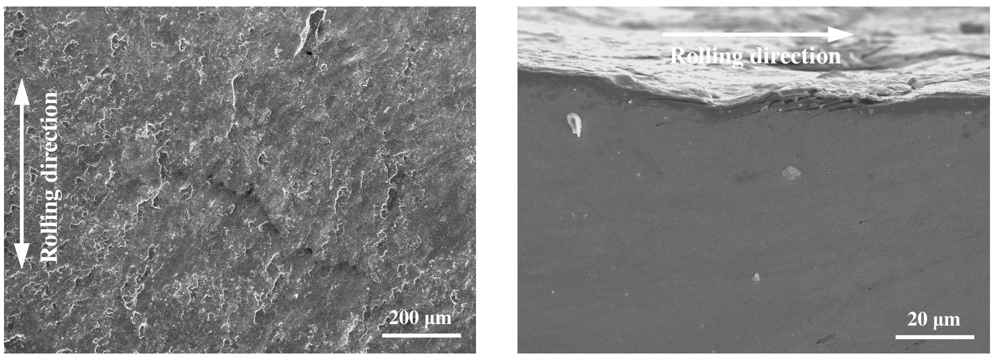
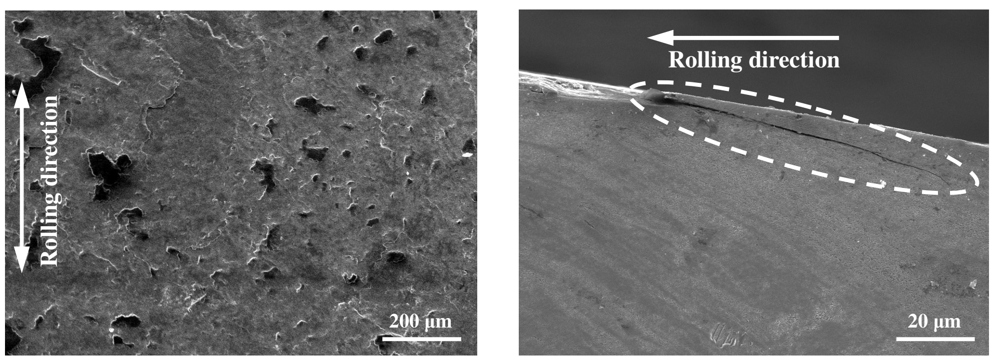


Fig.2. Wear rate of U71Mn rail material resulting from a twin-disc machine.



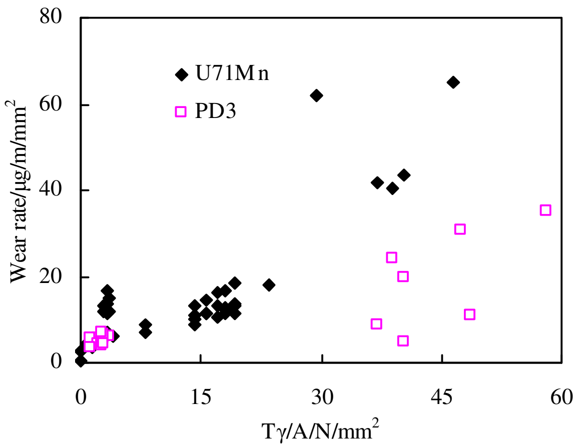
(a)



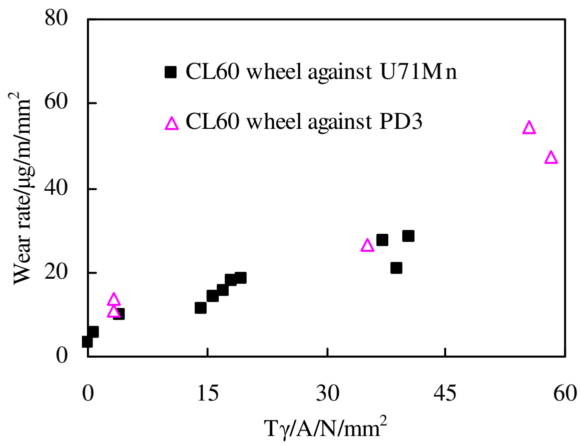
(b)

Fig.3. Damage of rail material running at, (a) $T\gamma$/A =0.78; (b) $T\gamma/A$ =46.56.

It is evident from the wear data of different rail materials against CL60 wheel material presented in Fig.4a that the wear rate decreases when rail material with high strength is developed and used. As is known, PD3 rail material has higher hardness and strength compared to U71Mn rail [39-40], shown in Table 1. Therefore, newer premium grade steels with high hardness can be used to improve the wear resistance of rail. Furthermore, it is found from Fig.4b that the wear rates of CL60 wheel material against different rail materials show no obvious difference. This indicates that the rail materials have no significant influence on the wear behaviour of same wheel material against different rail material. Furthermore, the effect of rail hardness on the rail or wheel material has been reviewed and discussed in depth by Lewis et al. [41].



(a)



(b)

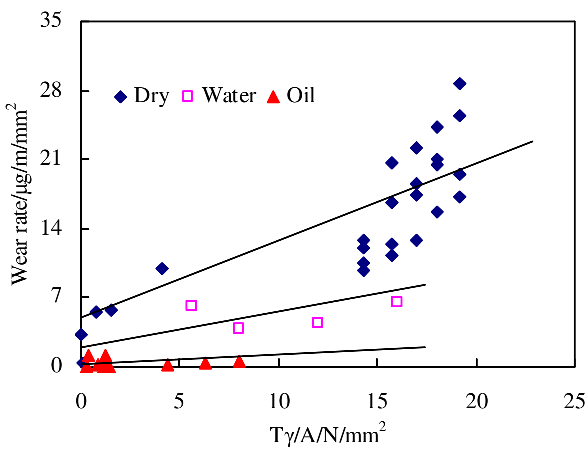
Fig.4. Wear rate of different rail materials against CL60 wheel material resulting from a twin-disc machine, (a) rail material; (b) CL60 wheel.

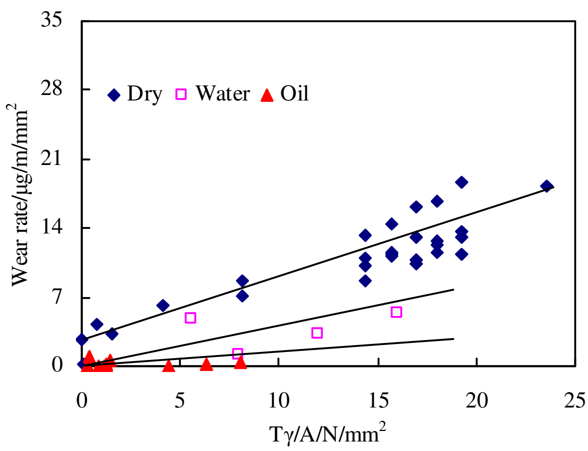
Table 1 Material properties of rail and wheel materials.

Materials	C (wt%)	Si (wt%)	Mn (wt%)	σ_b (MPa)	δ_5 (%)	Hardness ($HV_{0.2}$)
U71Mn	0.54~0.65	0.18~0.78	0.51~0.92	964.0	10.0	295
PD3	0.65~0.76	0.15~0.35	1.10~1.40	1077.5	10.0	325
CL60	0.71~0.80	0.50~0.80	0.70~1.05	910.0	10.0	280

3.2 The effect of third body medium

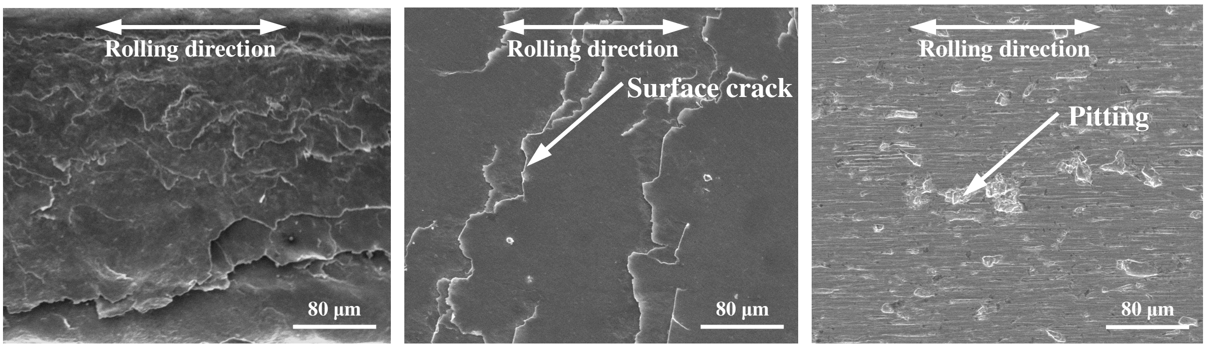
It is found from Fig.5 that the wear rates of rail or wheel material are obviously different under the dry or third-body medium conditions. The wear rate of wheel and rail materials decreases when water or oil is applied to the wheel/rail interface. It is noted that there is distinct wear line by the method for plotting wear rate against *Tγ/A*. The results show that the third-medium in the wheel/rail interface changes the contact condition, which may result in a damage transition. Under the dry condition, severe wear and damage appears on the surface of wheel roller and adhesion wear and spalling are dominating, shown in Fig.6a. When water is present in the wheel/rail interface, the damage lightens and surface cracks occur due to ratchetting mechanism for the wheel roller (Fig.6b). Furthermore, there is distinct pitting damage on the wear surface under the oil condition (Fig.6c). It should be concluded that different third-body medium will influence the wear damage type of wheel or rail material and make a clear transformation. Furthermore, the use of a third-body medium in the wheel/rail interface changes wear regimes and it should be noted that there is mild and severe wear regimes under the water condition. With oil in the contact, the wear will be entirely in the mild regime.





(a) (b)

Fig.5. Wear rate of rail and wheel materials under dry and lubrication conditions, (a) wheel; (b) rail.



(a) (b) (c)

Fig.6. Damage transitions of wheel roller under dry and lubrication conditions, (a) dry; (b) water; (c) oil.

3.3 The effect of friction enhancers

As is known, poor adhesion can occur when the water or oil contamination exists in the wheel/rail interface. So, different friction enhancers are usually used to improve poor adhesion level for assuring adequate tractive or braking force [23]. It is clear in Fig.7 that the use of sand or alumina particles obviously increases the wear rate of rollers under water conditions compared to dry conditions. The wear rate of wheel and rail materials under sand and alumina particle application induces an exponential increase (dotted line 1) in wear with an increase in $T\gamma/A$. This indicates that sand and alumina particles have a similar influence on the wear of wheel and rail. The abrasive block as a wheel tread cleaning material is used in high-speed train-sets in China and it can clear away the contamination on the wheel tread and improve the adhesion of wheel/rail. When an abrasive block is used to improve adhesion and clear contamination at the wheel/rail interface, the wear rate of wheel and rail materials is lower than that with hard particles. Moreover, the wear rate under the abrasive block condition is almost the same as that in dry conditions (dotted line 2). There is no obvious difference of wear rate under water and oil conditions when the abrasive block is applied.

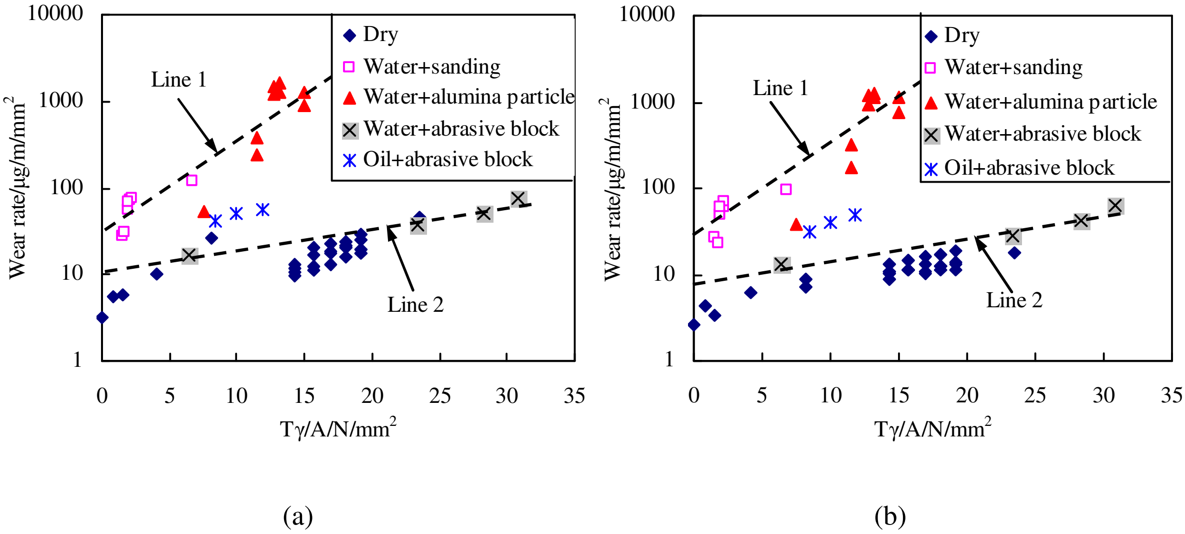
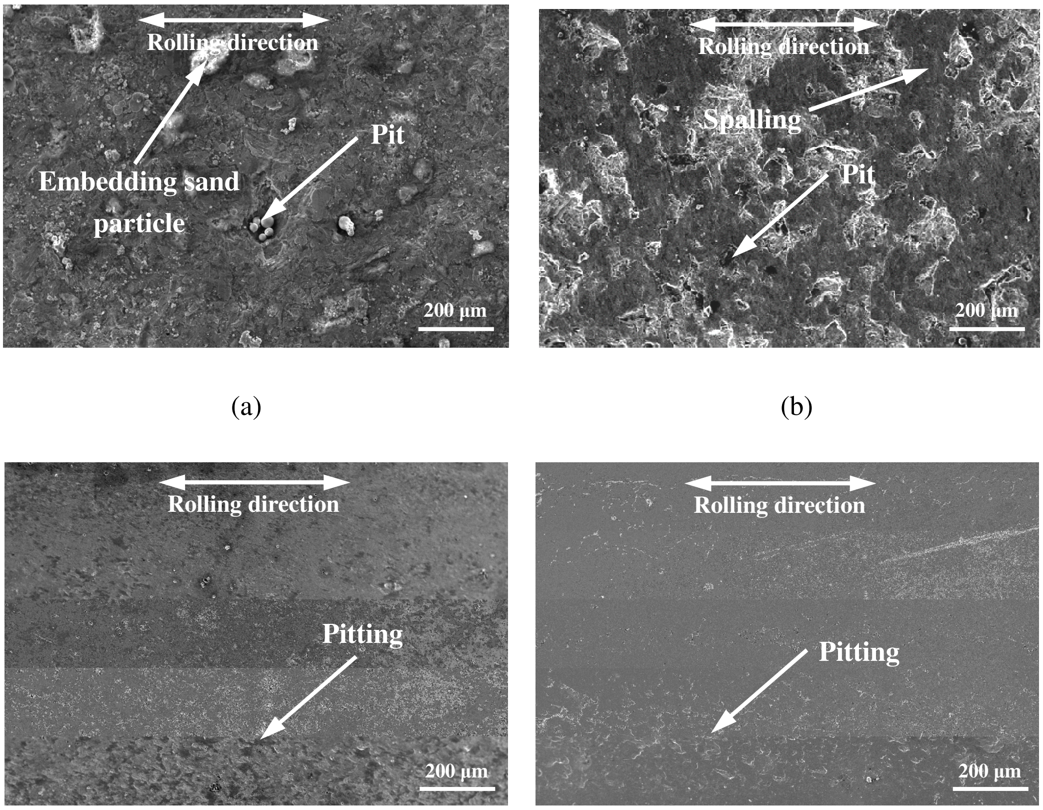


Fig.7. Wear rate of rail and wheel materials under different friction enhancers conditions, (a) wheel; (b) rail.

Different friction enhancers result in different wear rates of wheel and rail materials and the use of sand and alumina particles can give wear in the catastrophic wear regime. It is clear in Fig.8 that severe spalling and large pits are dominating under water and hard particle (sand or alumina) conditions. Under the abrasive block condition, the surface damage is slight and there is some pitting on the wear surface (Fig.8c and d). It should be noted that the hard particles are easily to be crushed and embedded into the contact interface of the wheel and rail materials during the adhesion improving process, which leads to severe plastic flow of material and subsurface fatigue crack formation, shown in Fig.9. However, fine particles worn from the abrasive block, lead to mild wear and damage under the water or oil condition. It is concluded that the friction enhancers not only have different effects in improving traction under low adhesion condition, but have a significant influence on wear regimes and damage transitions of wheel and rail materials.



(a) (b)

(c) (d)

Fig.8. Damage transitions of roller running at, (a) water+sanding; (b) water+alumina particle; (c) water+abrasive block; (d) oil+abrasive block.

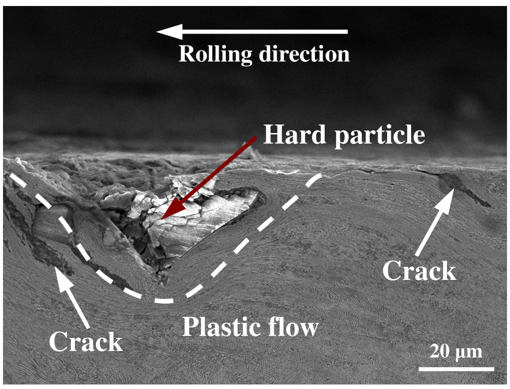


Fig.9. Sectional damage due to hard particle embedding into the roller surface.

3.4 The effect of a laser clad layer

It is clear in Fig.10 that the wear rates of wheel and rail materials decrease significantly when a laser clad Co-based alloy layer is used on the wheel and rail roller. Similarly, a laser clad Fe-based alloy layer can reduce the wear rates of wheel and rail rollers. However, there is a different wear rate of rail or wheel material for the same *Tγ/A* for laser clad Fe-based alloy layer. It is inferred that the microstructure of the laser clad layer affects wear resistance of the wheel or rail material. In this study, lanthanum oxide was used to markedly refine the microstructure of clad Fe-based alloy layer and the microstructure would become finer with an increase in the content of lanthanum oxide, which dramatically decreases wear rates of wheel and rail materials [33]. However, the content of lanthanum oxide has no obvious effect on hardness of a laser clad layer due its high hardness. This indicated that the lanthanum oxide has only significant influence on the microstructure of clad Fe-based alloy layer.

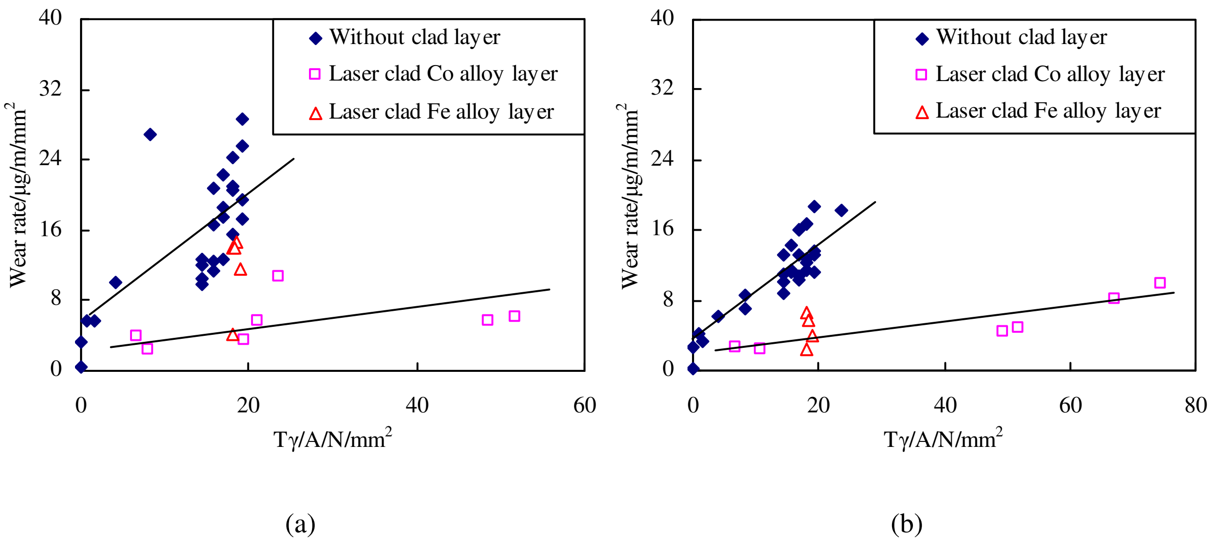
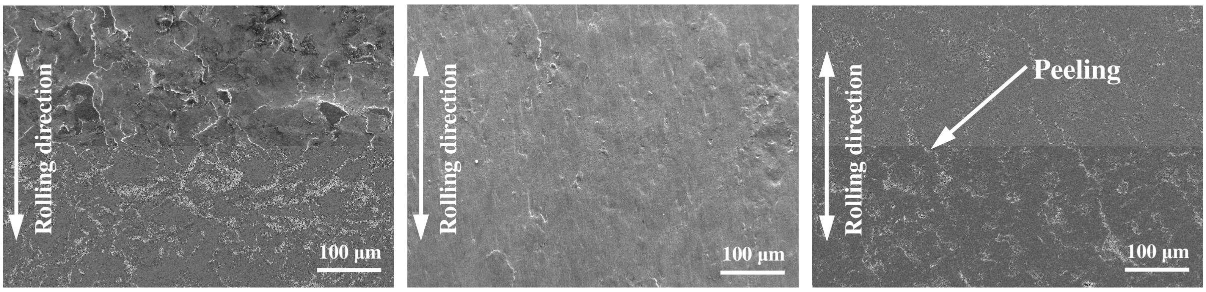


Fig.10. Wear rate of wheel and rail materials suffering different laser clad layer, (a) wheel; (b) rail.

In order to analyze the damage mechanism of wheel and rail rollers, Fig.11 and Fig.12 give the surface damage transitions and sectional damage of rail rollers. It is evident that severe adhesion wear and flake occurs for the rail roller without a clad layer (Fig.11a). There is visible plastic flow and fatigue crack in the sub-surface (Fig.12a). For the laser clad

Co-based alloy layer, the surface damage is slight and abrasive wear and mild ploughing are dominating and no distinct plastic flow and cracking is found in the sub-surface of the roller. The surface with a laser clad Fe-based alloy layer is dominated by peeling and slight spalling. Similarly, there is no visible sectional damage. Therefore, a laser clad layer is helpful to not only improve the wear resistance, but to transfer wear damage type of wheel and rail materials.



(a) (b) (c)

Fig.11. Damage transitions of rail roller running at, (a) without clad layer; (b) clad Co alloy layer; (c) clad Fe alloy layer.

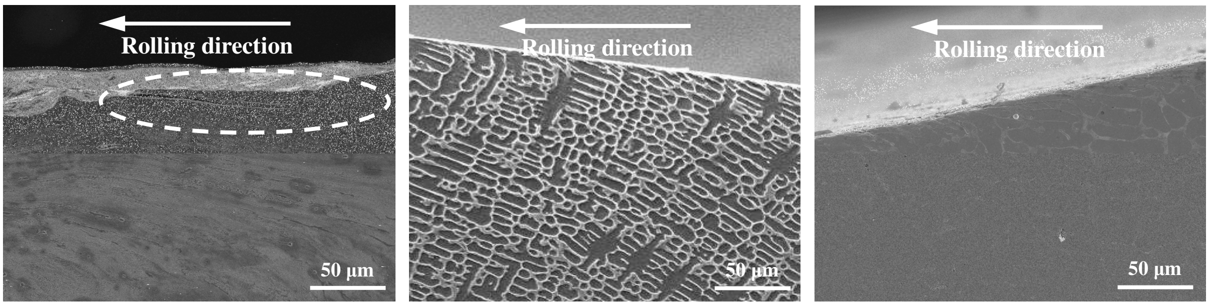


Fig.12. Sectional damage of rail roller running at, (a) without clad layer; (b) clad Co alloy layer; (c) clad Fe alloy layer.

4. Discussion

The objective of this work was to clarify and develop the wear information and damage transitions in wheel and rail materials from a twin-disc machine under various contact conditions using an approach of plotting wear rate against $T\gamma/A$ and microcosmic examination. The results are conducive to understanding greatly the wear damage mechanism of wheel and rail materials when the contact conditions vary. Under dry contact condition, based on the approach plotting wear rate of U71Mn rail versus $T\gamma/A$, three different wear regimes are discussed and clarified. Then, it is evident that the damage has significant transitions with the wear regimes changing under the dry conditions of wheel/rail interface.

As is known, a lot of third body materials (oil, water, friction enhancers) resulting from environmental conditions may be present in the wheel/rail interface, as well as products applied to control friction and wear of wheel and rail materials. The water or oil can decrease the traction coefficient and then bring small $T\gamma$ value. Furthermore, the use of third body lubrication materials obviously change the contact state of wheel/rail interface and bring significant influence on the wear regime, which results in the damage transition of materials. Compared to dry conditions, higher energy input is required to achieve a transition of wear regimes in the water and oil contacts due to a completely different way of energy dissipation. Similarly, the friction enhancers including sand or alumina particles or an abrasive block can improve the adhesion levels and cause the increase in $T\gamma$ value and wear rate of materials. Due to hard particles embedding into the contact surface of wheel/rail, friction enhancers can result in being entirely in the severe and catastrophic wear regimes and bring serious plastic flow and fatigue cracking on the to sub-surface. As the above discussion, the third body materials of wheel/rail interface significantly influences the contact condition as well as the wear and damage transitions.

It is clear that a laser clad layer is beneficial to improve wear resistance of materials and reduce wear rate of wheel/rail. The microstructure and hardness of clad layer will determine the wear rate and damage mechanism and transitions and though $T\gamma$ value may not change obviously. As a result, a Co-alloy clad layer exhibits excellent wear and deformation resistance. However, it should be noted that the laser clad layer should be optimized based on the composition and microstructure for excellent wear resistance and damage of material.

Present work on wear modelling in wheel/rail system relies on a wear coefficient approach [8, 28]. As is discussed, the wear regimes and damage transitions of wheel and rail materials are closely related to the third body materials on the wheel/rail interface (water, oil, various friction enhancers) and the composition and microstructure of the laser clad layer. However, it is known that scaled twin-disc testing with third body materials cannot simulate the real and various contact conditions in the field. For example, relative slip in a wheel/rail contact changes dynamically and then the traction coefficient varies correspondingly. The real contact condition in the field varies as a result of comprehensive influencing factors. So, it is very important to consider the difference between the simulation using a twin-disc machine and field results when the wear data is used to Multi-Body Dynamics simulations. This means that the wear data from a twin-disc machine should be compared and estimated with the results from the full-scale experiments or the field. On the other hand, the wear data from a twin-disc machine is not sufficient for establishing unique wear coefficients that cover the whole operating regime of a wheel/rail contact under various contact conditions. For improving accuracy of wear modelling, the accurate simulation on various contact conditions of wheel/rail and more wear data are critical in future.

5. Conclusions

1. A $T\gamma/A$ approach plotting wear rate method can be used to identify the wear regimes and damage transformation of wheel and rail materials in rolling-sliding wear tests.

2. The wear and damage transitions of wheel and rail materials are altered considerably with the presence of water and oil contamination, friction enhancers (e.g., sand, alumina particles or an abrasive block) as well as the addition of a laser clad layer on the wheel or rail surface.

3. Wear data over a wide range of contact conditions has been generated in this work that could be used in wear evolution prediction tools to increase their applicability to the real wheel/rail operating environment.

Acknowledgments

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