

Article

Influences of Pearlite Interlamellar Spacing on Wear and Rolling Contact Fatigue Behaviors of Pearlitic Rails on Field Tracks

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Abstract

As a core load-bearing component for railway vehicles, rails are largely responsible for the safety and stability of train operation, and their service performance is inherently governed by material microstructure. In this study, rails with varied pearlite interlamellar spacing were prepared and laid on field tracks for 8 months of service testing to investigate the influence of pearlite interlamellar spacing on rail wear and rolling contact fatigue (RCF). The results indicate that decreasing pearlite interlamellar spacing facilitated tread work hardening and reduced cumulative wear loss of rails. At the early service stage, rails with coarse pearlite lamellae exhibited earlier RCF crack initiation and longer crack morphologies, while rails featuring finer pearlite lamellae exhibited the latest-occurring crack initiation. With prolonged service duration, wear loss rose continuously, and the tread hardening rate first increased sharply and then tended to gradually become stable. Obvious differences in damage evolution were observed for rails with different pearlite interlamellar spacing. Coarse-lamellar rail suffered sparse short cracks dominated by wear; fine-lamellar rail developed dense fast-growing cracks controlled by RCF; and medium-lamellar rail achieved a relatively good balance between wear and RCF. A competitive relationship exists between wear and RCF during rail service. Reasonable regulation of pearlite interlamellar spacing facilitates a balanced evolution of wear and RCF, which provides a feasible microstructural optimization strategy for improving the service performance and service life of pearlitic rails.

Keywords: pearlitic rails; pearlite interlamellar spacing; service performance; wear; rolling contact fatigue



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1. Introduction

As an indispensable backbone of transportation infrastructure, railways underpin efficient national economic operation and convenient passenger travel. Serving as the directly bearing and guiding component for train vehicles, rails exert a decisive influence on the safety and stability of train operation, and their service reliability has become a prominent bottleneck restricting the development of high-speed and heavy-haul railway transportation [1]. In field track service, rails endure combined vertical wheel loads, lateral contact forces, and rolling–sliding friction from repeated wheel–rail interactions [2]. Such complex loading readily induces plastic deformation and subsequent premature damage, dominated by wear and rolling contact fatigue (RCF) [3,4]. Premature rail failure inevitably

elevates track maintenance expenditures and poses severe hazards, including rail fracture and train derailment.

Pearlite and bainite represent the two dominant microstructural categories for current rail products. Although bainitic rails deliver outstanding strength–toughness synergy and superior RCF resistance [5,6], high production cost and poor microstructure controllability restrict their widespread field deployment; consequently, pearlitic rails remain the predominant choice for domestic and overseas railway tracks [7,8]. Pearlite interlamellar spacing acts as a critical metallurgical parameter governing the mechanical properties and further dictates the service performance of pearlitic rails [9–11]. Heat treatment serves as the prevailing industrial route for regulating pearlite interlamellar spacing for improved mechanical properties and service performance of rail steels [12–14]. In recent years, extensive laboratory studies have focused on correlations between rail microstructure and wear, as well as RCF performance; the existing findings confirm that microstructural characteristics exert pronounced effects on both the wear and the RCF performance of rails [15,16]. At present, two contradictory academic viewpoints exist regarding the influence of pearlite interlamellar spacing on rail wear and RCF behaviors. The first viewpoint holds that reducing pearlite interlamellar spacing elevates the hardness and strength of rail steel simultaneously. Improved mechanical properties effectively restrain surface plastic deformation under cyclic wheel loads, delivering superior wear resistance and enhanced resistance to RCF crack initiation and propagation, thereby alleviating the severity of contact fatigue damage. Wu et al. [17] used a tribometer to reveal the wear failure mechanism of U75V rails with varying pearlite interlamellar spacing; the results demonstrated that finer pearlite interlamellar spacing decreased the friction coefficient and wear loss, thus upgrading the wear resistance of rails. Arun et al. [18] reported that reducing the pearlite interlamellar spacing can remarkably elevate rail hardness, which directly reduces the volumetric wear loss and therefore improves wear resistance. Zhou et al. [19] fabricated a high-alloy wheel steel with fine pearlite lamellae. Twin-disk wear tests revealed that the fine-lamellar wheel steel exhibited a substantially enhanced RCF life compared with conventional wheel steel, with its fatigue life increased by 2.7 times under oil-lubricated conditions. Wang et al. [20] investigated the individual effects of pearlite and proeutectoid ferrite on RCF crack propagation in hypoeutectoid rails. The results demonstrated that coarse pearlite lamellae greatly reduce the proportion of transgranular crack propagation, while refined pearlite lamellae can strengthen the resistance against transgranular crack growth and suppress further crack extension. Johnson et al. [21] compared the crack growth rates of R260 and R370CrHT rails, and found that the R370CrHT rail, with a finer pearlite lamellar structure, possessed a much lower fatigue-crack propagation rate.

By contrast, the second argument proposes that rails with finer pearlite lamellae exhibit remarkably low material removal rates during wheel–rail contact. Without sufficient surface wear to eliminate nascent micro-cracks generated within the plastic deformation layer, these tiny RCF cracks remain as retained on the contact surface and rapidly propagate into severe macroscopic fatigue cracks as service proceeds. Han et al. [22] utilized the JD-1 wheel–rail simulator to investigate rolling wear and RCF performance of pearlitic and bainitic rails under diverse operational parameters; overall damage severity was lower for bainitic rails, while hypereutectoid pearlitic rails suffered greater wear loss and more serious RCF damage relative to hypoeutectoid pearlitic counterparts. Meanwhile, Fei et al. [23] adopted a tribometer to clarify the dependence of U75V rail wear and RCF behaviors on pearlite interlamellar spacing; the finer lamellar microstructure enhanced wear resistance but impaired RCF resistance, alongside a shift in wear mechanism from abrasive wear toward adhesive wear. Tosangthum et al. [24] explored the friction behavior of rail specimens with varied pearlite interlamellar spacing; microstructural refinement of pearlite elevated

rail hardness and induced a gradual transition of the wear mechanism from adhesive wear to fatigue wear. Subsequently, Xu et al. [25] adopted an MJP-30A rolling wear and RCF testing machine to assess rolling wear damage for welded joints of three types of pearlitic rails; the results indicated that increasing pearlite interlamellar spacing initially triggered a sharp rise in damage severity; however, aggravated subsequent wear shortened existing cracks stepwise and accordingly mitigated the overall RCF damage level. The above studies demonstrate that refining pearlite interlamellar spacing markedly increases the hardness of rail steel. This improvement not only boosts wear resistance and modifies the wheel–rail wear mechanism, but also raises the stress threshold for fatigue-crack propagation, thus optimizing the RCF performance of rail steel. Nevertheless, as wheel–rail contact progresses, a low material removal rate of the surface plastic deformation layer fails to eliminate nascent micro-cracks. These retained micro-cracks instead propagate rapidly and aggravate RCF damage. At present, laboratory research on rail wear and RCF behaviors mostly relies on twin-disk testing machines. Such indoor equipment can precisely control fixed experimental parameters, such as wheel/rail material, operating speed, equivalent curve radius and loading cycles. Nevertheless, it cannot fully reproduce various uncertain interfering factors existing on actual track lines, such as real-time varying wheel–rail contact states, alternating weather conditions, regular track maintenance operations, and fluctuating traffic tonnage, which impose significant effects on long-term rail service performance [26]. It is difficult to reproduce authentic on-site contact states via bench-scale simulation.

Field monitoring of rail service performance enables acquisition of authentic wheel–rail contact features and track conditions. Nevertheless, full-scale field tests require substantial time and financial investment and are susceptible to variable operating environments, resulting in relatively few relevant research reports. Zhang et al. [27] investigated the service performance of PG4 heat-treated pearlitic rails laid on sharp radius curved tracks. In the early service stage, the rails exhibited minor wear but were prone to surface spalling. After the rails were worn to a certain extent, appropriate lubrication strategies could effectively mitigate rail wear and RCF. Furthermore, Li et al. [28] investigated the service performance of hypereutectoid pearlitic rails laid on straight and curved tracks. The results verified that hypereutectoid rails possessed higher hardness and delivered substantially better wear resistance compared with heat-treated U75V rails. In field microstructure analysis of retired rails, Yuriev et al. [29] explored the evolution mechanism of surface carbide phases. Two dominant microstructural evolution modes were identified: the cutting and migration of cementite particles, as well as the dissolution and reprecipitation of cementite particles. Stocka et al. [30] further evaluated the wear and RCF properties of pearlitic and bainitic rails with different strength grades via field tests. The results revealed that the improvement in rail hardness contributed to enhanced wear resistance and RCF performance. Nevertheless, the anti-fatigue advantage of high-hardness rails was insignificant under mild wear conditions. Walia et al. [31] comparatively analyzed the wear behavior of two contact interfaces (brake block–wheel and wheel–rail) through field tests. The results showed that the wear loss of the brake block–wheel interface was far greater than that of the wheel–rail interface, and a positive linear correlation existed between brake block–wheel wear and braking energy.

In summary, the existing studies concerning the effects of material microstructure on rail wear and RCF behaviors have been predominantly conducted under laboratory-simulated working conditions. Consequently, it is difficult to accurately reflect the comprehensive influences of complex wheel–rail interaction, fluctuating loads, and variable environmental factors in field track service. Current research on the field service performance of rails mainly focuses on the performance comparison of rails with different

strength grades or diverse microstructural types. However, systematic investigations on the long-term service performance evolution of pearlitic rails with varying pearlite interlamellar spacing on field tracks, especially the evolutionary characteristics of tread hardening rate, wear loss, and RCF cracks, remain insufficient. In this study, rail specimens with different pearlite interlamellar spacing were prepared by different heat treatment processes and laid on field railway tracks for 8 months of continuous service. Multiple service performance indicators of the rails were regularly tracked and recorded. The influence of pearlite interlamellar spacing on rail wear loss, tread hardness, and RCF cracks was systematically analyzed, and the underlying mechanism of pearlite interlamellar spacing dominating the competitive evolution of wear and RCF was clarified. The research findings can provide theoretical guidance for the optimization of rail materials and the improvement of rail service life, and have significant engineering application value for ensuring the safe and stable operation of railway lines.

2. Materials and Methods

2.1. Experimental Materials

The experimental materials were sampled from industrially produced U75V pearlitic rails manufactured by a domestic steel mill. As one of the most widely adopted rails in current railway engineering, the U75V rail exhibits a carbon concentration close to the eutectoid composition and a nearly fully lamellar pearlitic microstructure [32], making it a suitable candidate for the present experimental study. The hot-rolled U75V rails were prepared according to the conventional industrial production process, mainly including billet heating, breakdown rolling, rough rolling, and finish rolling [33]. After hot rolling, the rail temperature ranged from 850 °C to 900 °C. After cooling in air to a certain temperature, the rail, still within the austenitizing range, then entered the on-line heat treatment production line. The rail head was subjected to accelerated cooling heat treatment through a high-pressure nozzle, with compressed air serving as the cooling medium. After a predefined cooling duration, the accelerated cooling was stopped, and the rails were air-cooled to ambient temperature to obtain the finished rails. Detailed parameters of the accelerated cooling processes are shown in Table 1. Different accelerated cooling rates were designed for S1, S2, and S3 rails to reduce the pearlite transformation temperature and obtain distinct interlamellar spacings under various supercooling degrees. The cooling duration was fixed at 120 s to sufficiently lower the rail head temperature below the pearlite transformation range, thereby ensuring complete pearlitic phase transformation within the rail head.

Table 1. The accelerated cooling heat treatment processes of experimental rails.

Cooling Processes	Specimens	Starting Cooling Temperature (°C)	Cooling Type	Cooling Medium	Cooling Rate (°C/s)	Cooling Time (s)
Process 1	S1	800	Air cooling	Air	0.5–1.0	To ambient temperature
Process 2	S2	800	Accelerated cooling	Compressed air	1.8–2.2	120
Process 3	S3	800	Accelerated cooling	Compressed air	3.0–3.3	120

One 6.25 m long rail segment was cut from the rails of the different cooling processes as a test specimen. All rails were melted in the same heat. The chemical composition of the U75V rail was characterized via atomic emission spectrometry. Three repeated measurements were carried out, and the arithmetic mean was taken as the final result, which is shown in Table 2. The rail base metal primarily consists of C, Si, Mn and V, along with a very small amount of P and S. In the U75V rail, Si and Mn are mainly dissolved in ferrite to improve the mechanical properties of the rail [34], while V mainly strengthens

the base metal by precipitating dispersed second-phase particles [35]. As detrimental impurities, P and S need to be controlled at as low a mass fraction as possible. The elemental contents of rails comply with the specification requirements of Chinese railway standard TB/T 2344.1-2020 [36].

Table 2. Chemical composition of experimental rails (wt%).

Rail	C	Si	Mn	P	S	V
U75V	0.76 ± 0.01	0.69 ± 0.02	0.87 ± 0.02	0.011 ± 0.002	0.006 ± 0.001	0.06 ± 0.005
TB/T 2344.1-2020	0.71~0.80	0.50~0.80	0.75~1.05	0.04~0.12	≤0.025	≤0.025

Cylindrical metallographic specimens were taken from the cross-section of the rail head, with sampling positions as illustrated in Figure 1. All dimensions in Figure 1 are given in millimeters. The observation surface was ground and polished, and then etched with 4 vol.% nitric acid alcohol. The metallographic structure was observed using a LEICA DM6000M optical microscope (Leica Microsystems, Wetzlar, Germany).

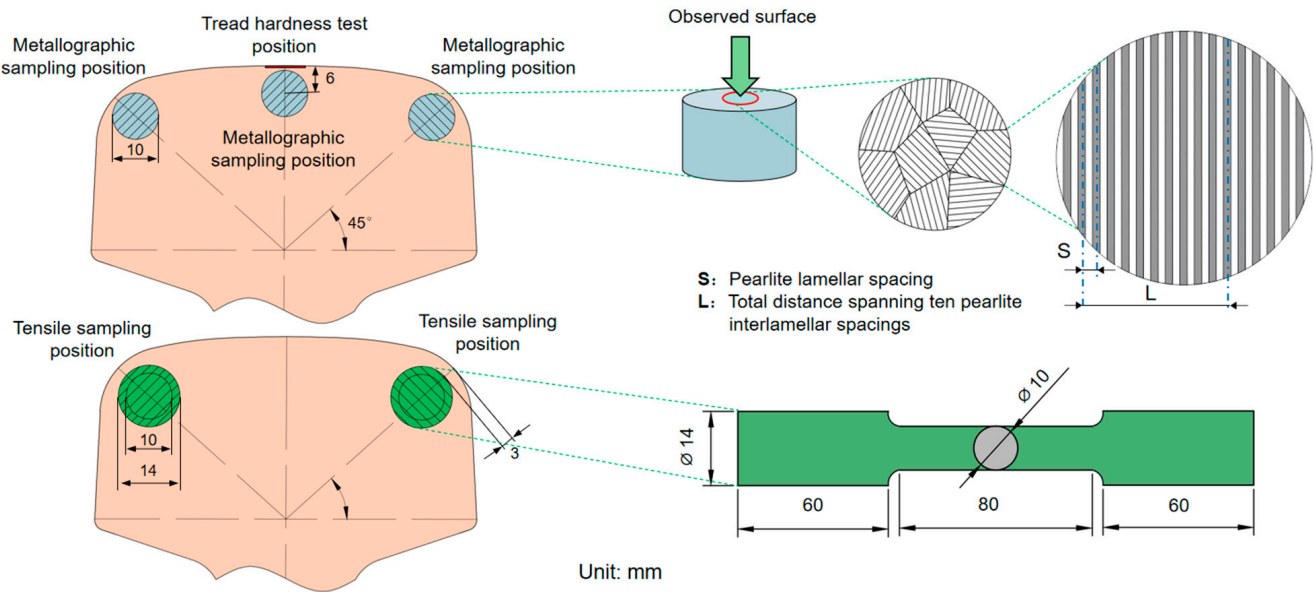


Figure 1. Sampling positions and dimensions of tested specimens.

Microstructural characterization and quantitative measurement of pearlite interlamellar spacing were carried out on metallographic specimens using a Nova Nano 400 field emission scanning electron microscope (FEI, Hillsboro, OR, USA). The intercept vertical line method is the most widely accepted method for pearlite interlamellar spacing measurement [37–39]. In this study, three randomly selected visual fields were selected for each metallographic sample. In each field of view, the total distances of ten groups of continuous pearlite lamellae were measured along the direction perpendicular to the extension direction of the pearlite lamellae, and the arithmetic mean was calculated to obtain the interlamellar spacing value. Representative micrographs of rail specimens are presented in Figure 2. The metallographic structure is composed of pearlite and a small amount of proeutectoid ferrite, as shown in Figure 2a–c. Figure 2d–f further demonstrate well-defined pearlite lamellae with clear boundaries and uniformly distributed cementite lamellae. The measured pearlite interlamellar spacing values of rail specimens are listed in Table 3.

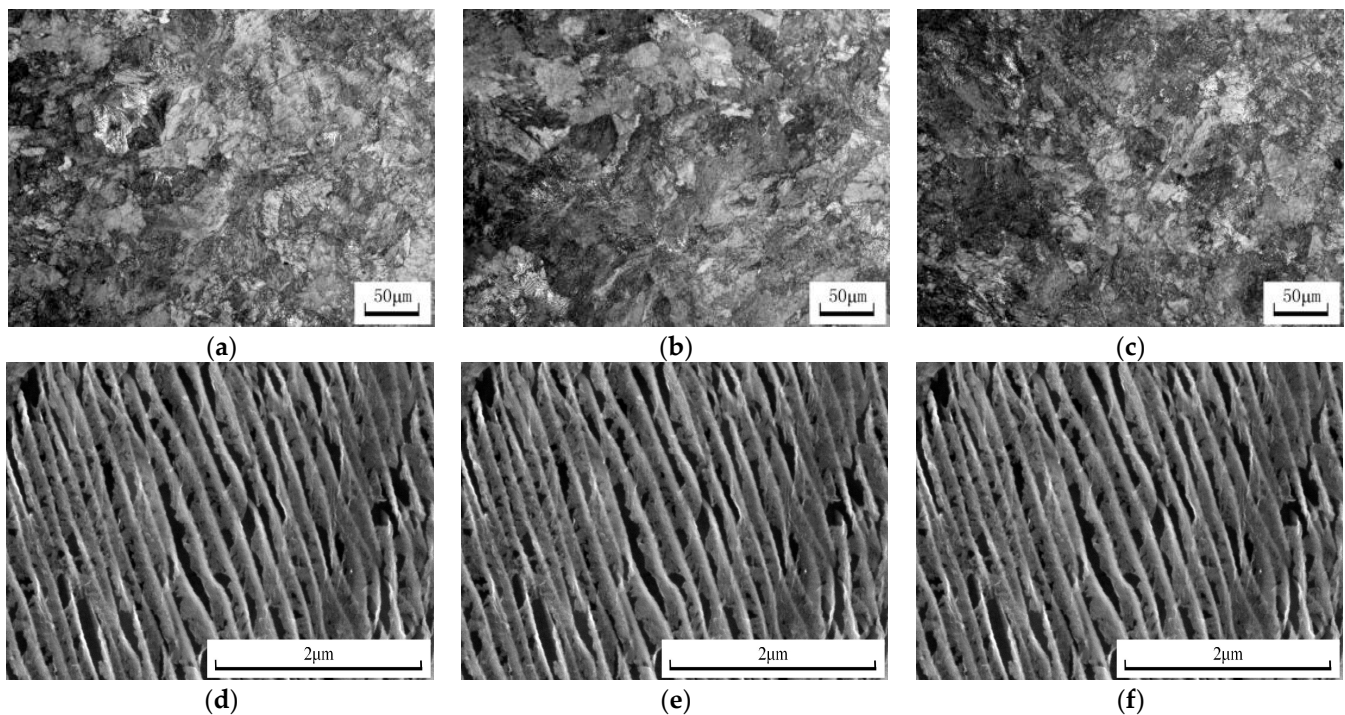


Figure 2. Representative micrographs of rail specimens. Metallographic photos of the middle of the rail head: (a) S1 rail ($\times 200$); (b) S2 rail ($\times 200$); and (c) S3 rail ($\times 200$). Photos of pearlite interlamellar spacing of the middle of the rail head: (d) S1 rail ($\times 50,000$); (e) S2 rail ($\times 50,000$); and (f) S3 rail ($\times 50,000$).

Table 3. The measured values of the lamellar spacing of rail specimens (nm).

Specimens	Left Rail Fillet	Midportion	Right Rail Fillet	Mean Value
S1	225.1	231.6	222.8	226.5
S2	170.4	160.3	161.6	164.1
S3	110.2	119.7	112.7	114.2

The tensile strength and elongation after fracture of the rail specimens were determined with a ZWICK Z600E electronic tensile testing machine (ZwickRoell GmbH & Co., Ulm, Germany). Sampling positions and specimen dimensions are given in Figure 1, and two repeated tests were performed per specimen to obtain the averaged results. A BRIN 200D-TL Brinell hardness tester (Foundrax, Somerton, UK) was used to measure hardness on the rail head tread. The hardness measurement was conducted with a tungsten carbide ball indenter of 10 mm diameter under a constant test force of 3000 kgf (29.42 kN). Prior to hardness testing, a 0.5 mm thick surface layer was ground off from the tread to guarantee a flat test surface; five replicate hardness measurements were acquired, and the average value was taken. Pearlite interlamellar spacing serves as the core microstructural parameter governing the strength and hardness of the rail matrix. As the interlamellar spacing decreases, the number of ferrite–cementite phase boundaries increases remarkably. These dense phase boundaries can effectively pin dislocations and greatly hinder dislocation slip, improving the resistance to plastic deformation, which macroscopically manifests as a synchronous increase in strength and hardness. The mechanical property data of the rail specimens are summarized in Table 4. As the pearlite interlamellar spacing decreases, the tensile strength and tread hardness of rail specimens increase significantly. Compared with the S1 rail, the sample type with coarse pearlite lamellae, the tensile strength of the fine pearlite S3 rail rises by 14.2%, and its tread hardness increases by 21.9%. In contrast,

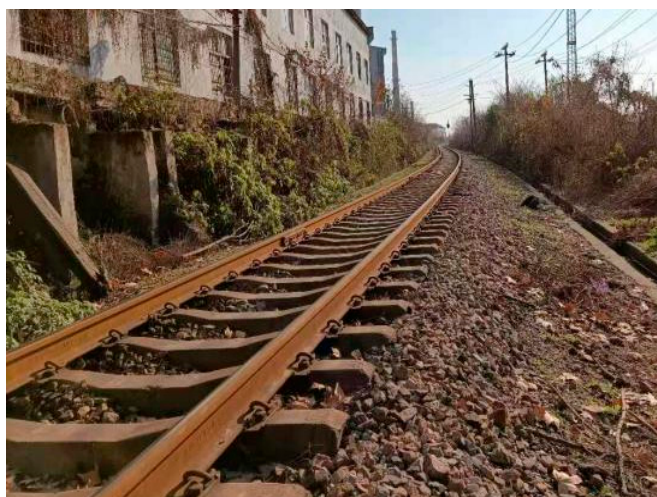
the elongation after fracture shows slight variation across all samples, with the S3 rail exhibiting a marginally lower value than the S1 and S2 rails. All test results verify that both the microstructural characteristics and basic mechanical properties of the rail specimens fully meet the requirements of Chinese railway standard TB/T 2344.1-2020.

Table 4. The basic mechanical properties of the rail specimens.

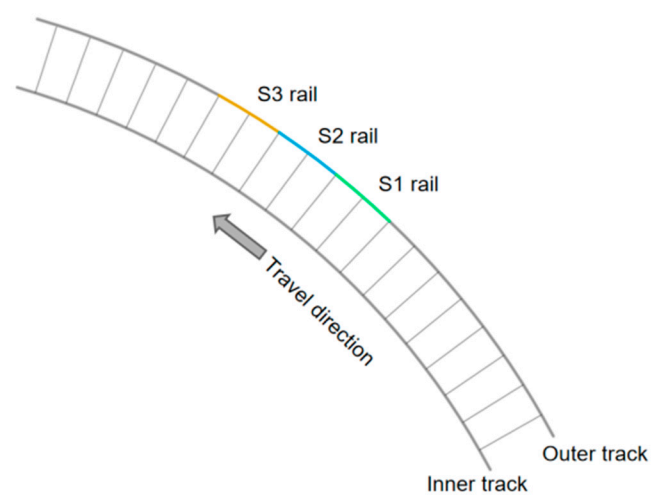
Specimens	Tensile Strength (MPa)	Elongation After Fracture (%)	Tread Hardness (HB) (Error limits: $\pm 2\%$)
S1	1149.2	12.5	309.4
U75V rail in TB/T 2344.1-2020	≥ 980	≥ 10	280~320
S2	1253.7	12.1	352.6
S3	1312.3	11.2	377.1
U75VH rail in TB/T 2344.1-2020	≥ 1180	≥ 10	340~400

2.2. Experimental Methods

A curved track section from an operational freight railway line was selected as the tested track, with an outer track superelevation of 70 mm and a standard track gauge of 1435 mm. The service axle load of passing trains is 23 tons; the annual total passing tonnage of the line is 15 million tons; and the curve radius is 1100 m. The maximum operating speed of the train was limited to 80 km/h, while the typical service running speeds ranged from 50–60 km/h. The wheel tread adopted the standard LM type, and the tested rails were conventional 60 kg/m rail tread profiles. The rail specimens were laid in the middle of the curve and located on the outer track. The on-site photograph of the tested track is shown in Figure 3a, and the schematic diagram of installed rail specimens is presented in Figure 3b. The rail specimens were fastened to the original in-service rails via bolts and fishplates. Train wheels generate a slight vibration when rolling over fishplate rail joints. To minimize the adverse effect of joints on wheel–rail contact conditions and rail service performance, a 1 m long middle segment of each rail specimen was selected as the monitoring region. After installation, multi-index inspections of service performance at these monitored regions were carried out every 2 months over a continuous 8-month service period.



(a)



(b)

Figure 3. The photograph and schematic diagram of the tested track: (a) the on-site photograph of the tested track; and (b) the schematic diagram of the tested track.

The Brinell hardness tests on the wheel–rail contact zone of the rail surface were performed using a TH-110 hardness tester (Time Group Science & Technology Co., Ltd., Beijing, China). This portable instrument adopted a tungsten carbide impact tip with a

diameter of 3 mm and a mass of 5.5 g. During testing, the impactor struck the material surface at an impact energy of 11 mJ. The Leeb hardness value was acquired by detecting the rebound velocity of the impactor, and was subsequently converted into the corresponding Brinell hardness, and the average value was obtained from five successive measurements. A LAD-GT-01 rail head profile measuring instrument (Beijing Luanda Technology Co., Ltd., Beijing, China) was adopted for the measurement of rail head profiles. The measured profile curves were exported to a terminal computer and compared with the standard rail profile, and the wear depth at specified positions, namely the rail head wear loss, was automatically calculated. Three measuring points were tested and averaged. The field measurement scene is displayed in Figure 4a, and the schematic diagram for wear measurement is shown in Figure 4b. Given the limitation of field measurement conditions, manual ruler measurement was adopted to count the total number and total length of RCF cracks distributed within a continuous 10 mm length of the wheel–rail contact zone. The measurement diagram is shown in Figure 5. Three repeated measurements were averaged to quantitatively evaluate the severity of RCF damage on rails.

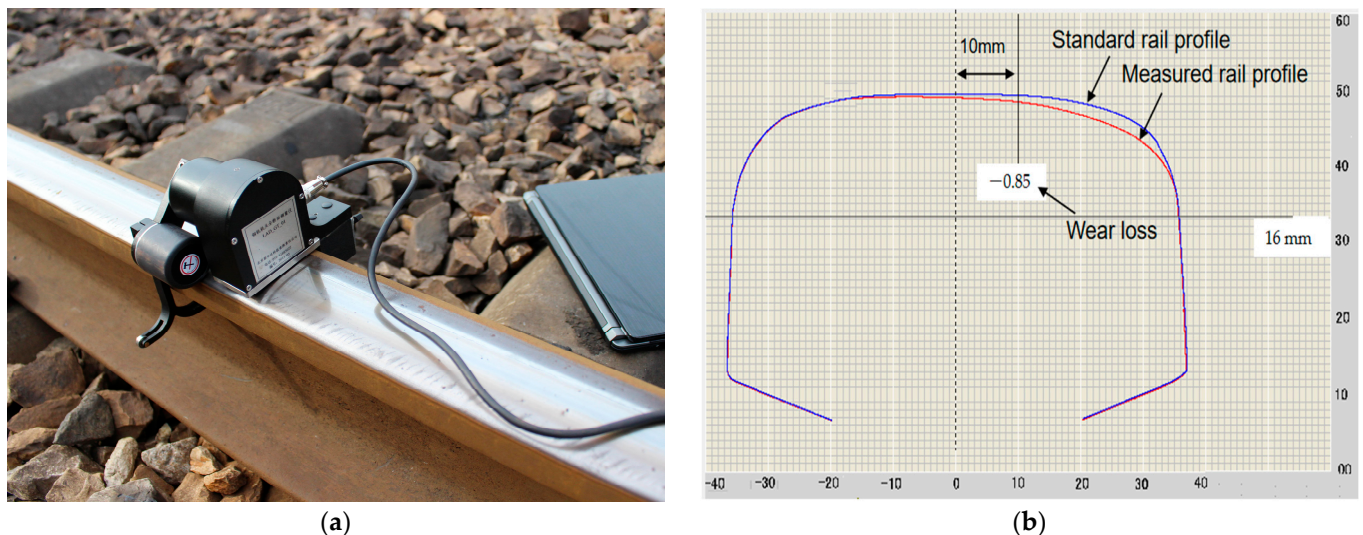


Figure 4. Rail profile measurement: (a) the field measurement scene; (b) the schematic diagram of wear measurement.

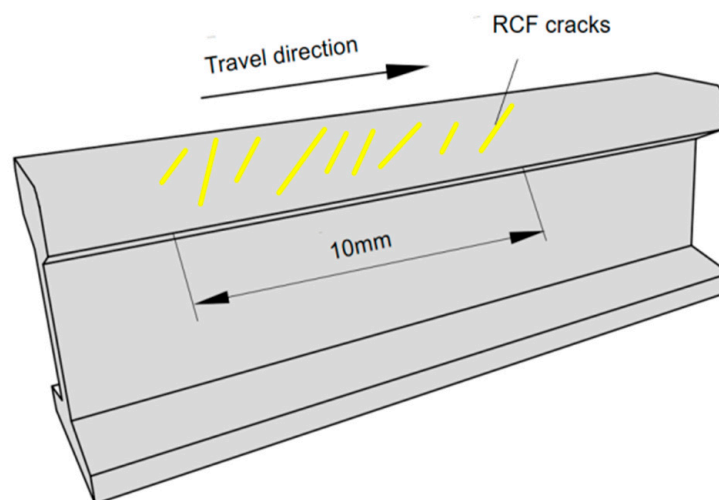


Figure 5. The schematic diagram of the RCF crack measurement of rail specimens.

Equation (1) was used to calculate the evolution rate of each measured index (tread hardness, wear loss, crack number and crack length), so as to quantify the development of rail service performance.

$$\gamma = \frac{x_i - x_1}{x_1} \times 100\% \quad (1)$$

where γ represents the evolution rate of the measured parameter; x_i and x_1 represent the average values obtained from the initial measurement and the i -th measurement, respectively.

3. Results

3.1. Tread Hardness and Hardening Rate

Figure 6 presents the measured tread hardness results of the rail specimens, while Figure 6a shows the distribution of tread hardness at different service times. The tread hardness of all rails rises gradually with increasing service time. Under continuous wheel loads and wheel–rail contact stresses, plastic deformation occurs on the contact surface; grain distortion and fragmentation take place alongside dislocation movement and multiplication inside grains. The resultant remarkable increase in dislocation density induces work-hardening of the material and consequently improves tread hardness [40,41]. The maximum tread hardness of the S3 rail reaches 491.5 HB. Figure 6b displays the evolution curves of tread hardening rates. As observed, the tread hardening rates of rails rise sharply at first and then tend to be stable with increasing service time, and the hardening rates always follow the order $S1 < S2 < S3$ among the rail specimens. At the early service stage (2 months), the tread hardening rates rise sharply, reaching 14.35%, 16.47%, and 24.41% for S1, S2, and S3 rails, respectively. After 4 months of service, the hardening rates increase mildly and gradually stabilize. At the 8-month service stage, the hardening rates of S1, S2, and S3 rails are 20.44%, 25.46%, and 30.52%. Owing to its composition of the finest pearlite lamellae, the S3 rail exhibits the highest tread hardening rate throughout the service observation period.

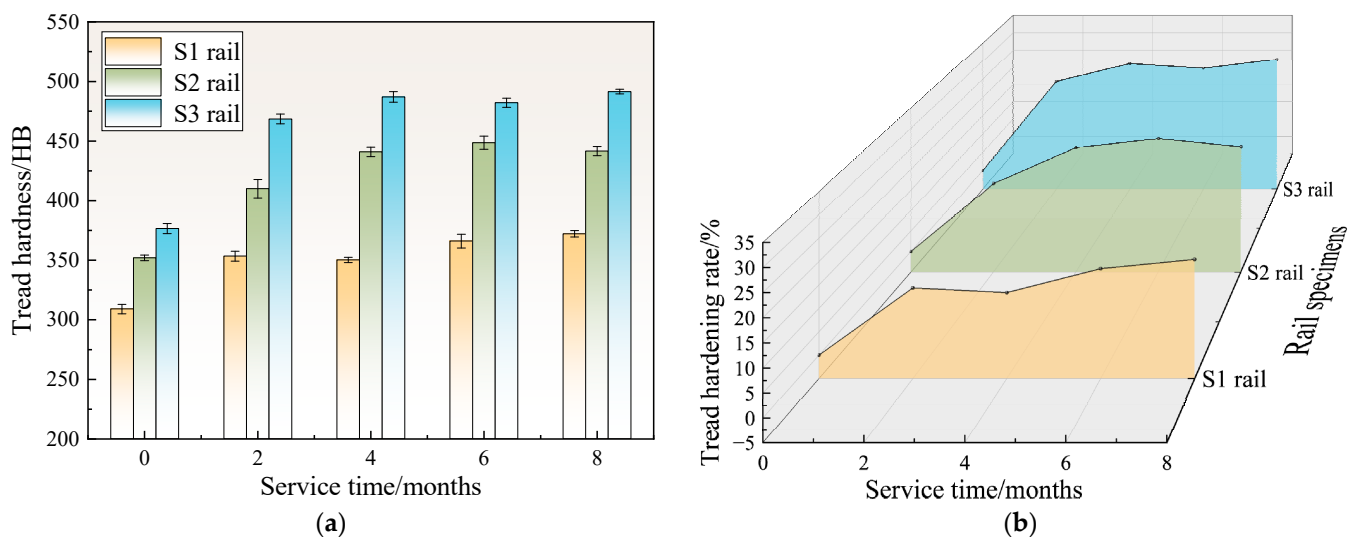


Figure 6. The tread hardness measurement results of rail specimens: (a) tread hardness distribution; (b) tread hardening rate curves.

Pearlite features a typical lamellar microstructure. The smaller pearlite interlamellar spacing corresponds to thinner and more uniformly distributed cementite lamellae, which show enhanced resistance to fracture under cyclic wheel–rail contact loads. Densely arranged ferrite–cementite phase boundaries continuously restrict dislocation motion. During dislocation slipping, numerous dislocations are blocked and pile up at phase interfaces,

leading to a continuous rise in dislocation density inside the matrix, which further inhibits subsequent plastic flow and macroscopically yields a higher work-hardening rate [23]. Combining the trends presented in Figure 6b, it can be seen that in field track service, rails with finer pearlite lamellae exhibit higher tread hardening rates and more severe work hardening within the wheel–rail contact zone.

3.2. Wear Loss and Wear Rate

During rail service, the sliding and rolling friction in the wheel–rail contact area leads to wear in the surface material [42]. The measured wear loss and wear rates of the rail specimens are summarized in Figure 7. Figure 7a shows the evolution of the wear loss of the rail specimens. With increasing service time, the wear loss of all rails increases progressively, and the S1 rail exhibits the most prominent increment. At the 2-month service checkpoint, the S2 rail shows marginally larger wear loss than the S1 rail. After 4 months of service, the S1 rail consistently maintains the maximum wear loss, followed by the S2 rail, while the S3 rail retains the minimum value. Upon completion of the 8-month test, all rails reach their peak wear loss, at 0.74 mm (S1), 0.47 mm (S2), and 0.27 mm (S3), respectively. Figure 7b presents the temporal evolution of wear rates against service duration. The wear rate of the S1 rail shows an approximately linear positive correlation with service time, while the wear rates of the S2 and S3 rails increase slowly with milder curves. At all service stages, the wear rates follow the order $S1 > S2 > S3$. After 4 months of service, the wear rates of S1, S2, and S3 are 98.44%, 68.57%, and 44.79%, and the wear rate of the S1 rail is more than twice that of the S3 rail. After 8 months of service, their wear rates are 245.31%, 101.43%, and 86.05%, and the wear rate of the S1 rail is nearly three times that of the S3 rail, which demonstrates that the S1 rail suffers the most severe and fastest-occurring wear. Thus, rails with larger pearlite interlamellar spacing suffer more severe wear during service, while rails featuring smaller pearlite interlamellar spacing deliver superior wear resistance.

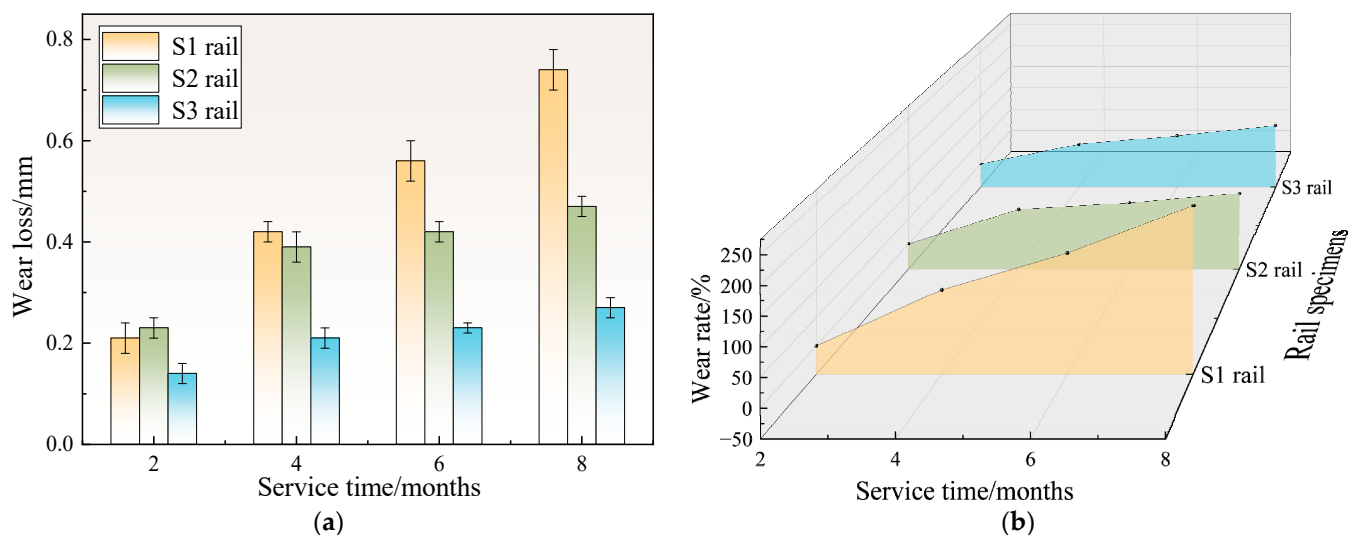


Figure 7. The wear measurement results of the rail specimens: (a) wear loss distribution; (b) wear rate curves.

Combining the results in Figures 6 and 7, it can be seen that tread hardness exerts a remarkable influence on wear loss: higher tread hardness corresponds to lower wear loss. It is generally accepted that the relationship between wear loss and material hardness conforms basically to the Archard wear equation, Equation (2) [43].

$$V = K \frac{Nd}{H} \quad (2)$$

where V represents the wear volume of material; K , N and d represent the wear coefficient, the normal load applied on the rail and the sliding distance, respectively. H represents the hardness of material. The rail specimens in this study were laid at the midsection of the curved track, so the service operating conditions for rails can be regarded as identical. According to the Archard wear equation, wear loss is linearly negatively correlated with material hardness, and the field service wear data acquired from rail specimens are in good agreement with this theoretical law. Pearlite interlamellar spacing directly determines the strength and hardness of rail steel. Rails with finer pearlite lamellae possess higher matrix hardness and superior wear resistance. Furthermore, such rails achieve a more intense degree of work hardening during service, which further improves the wear resistance.

3.3. RCF Performance

During rail service, the rail head surface is subjected to the coupling effect of rolling–sliding and tangential friction induced by train wheels. Sustained wheel–rail stress triggers plastic deformation in the contact zone. Once the plastic deformation accumulates to a certain extent, the plasticity of the deformed layer is exhausted, and the RCF cracks begin to initiate and propagate on the rail surface [44]. Figure 8 shows the statistical results for surface RCF cracks on rail specimens. Figure 8a presents the crack counts measured at different service times. Different evolutionary trends in crack number are observed for the three rail specimens with increasing service time. For the S1 rail, the crack number declines moderately and stabilizes gradually, with a final count of 8 cracks after 8 months of service. The crack number of the S2 rail remains nearly constant within the initial 4 service months before rising slowly from 6 months onward, reaching 24 cracks after 8 months of service. No RCF cracks are detected on the S3 rail within the first 2 months of service; however, abundant cracks initiate starting from 4 months and proliferate drastically, resulting in a total of 44 cracks after 8 months of service. Figure 8b shows the growth rate curves associated with the RCF crack numbers. The S3 rail presents the highest growth rate, with an obvious linearly increasing trend, reaching 61.73% after 8 months of service. The curve slope of the S2 rail is lower than that of the S3 rail, indicating a slightly slower crack quantity growth, yet still maintaining a linear rising trend, with a final growth rate of 30.91% at 8 months. Conversely, the growth rate of the S1 rail declines gradually and stabilizes at approximately -20% . Under identical track and operating conditions, the S3 rail develops far denser surface RCF cracks.

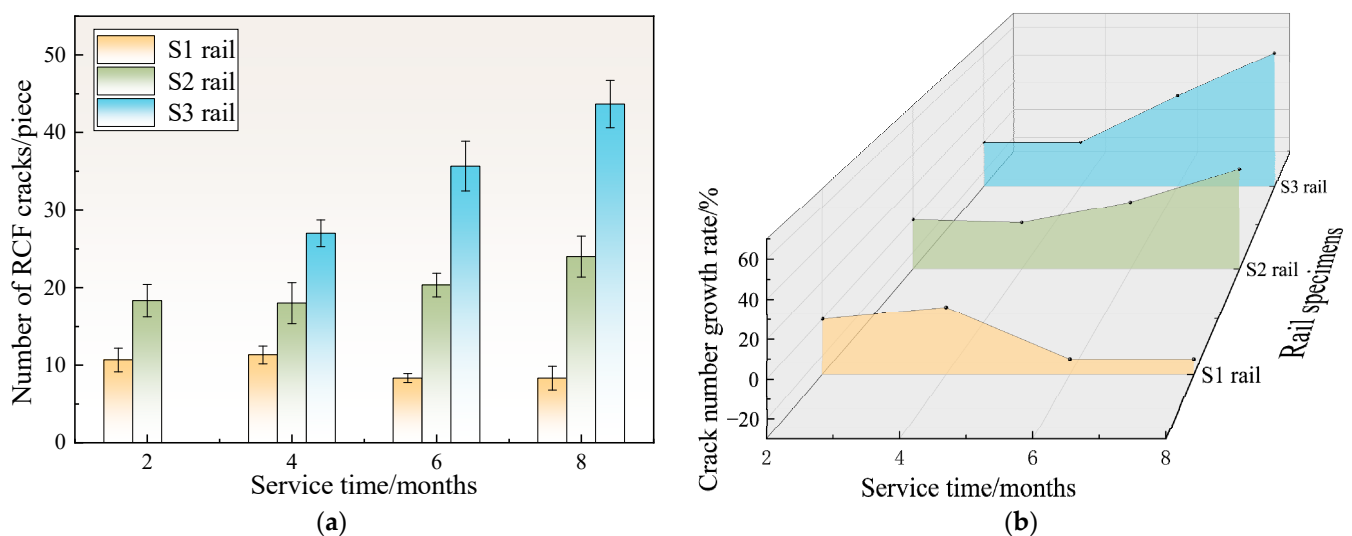


Figure 8. RCF crack number measurement results for the rail specimens: (a) RCF crack number distribution; (b) crack number growth rate curves.

The crack propagation length serves as another critical indicator for assessing the RCF performance of rails [45]. Figure 9a presents the measured total RCF crack lengths of rail specimens at different service times. The evolution tendency of the total RCF crack lengths basically matches that of the crack number with increasing service time. The total crack length of the S1 rail declines gradually to 64.3 mm after 8 months of service, and that of the S2 rail rises moderately and reaches 174.7 mm. In comparison, the total crack-length of the S3 rail surges sharply after 4 months of service and peaks at 616.9 mm after 8 months. Figure 9b shows the growth rate curves for total RCF crack lengths. The total crack-length growth rates of S1 and S2 rails fluctuate slightly before leveling off, with values of -60.44% and 28.26% at the 8-month service stage. By contrast, the total crack-length growth rate of the S3 rail increases linearly and significantly over service time, peaking at 323.70% after 8 months, verifying that the S3 rail possesses the fastest propagation rate of RCF crack length.

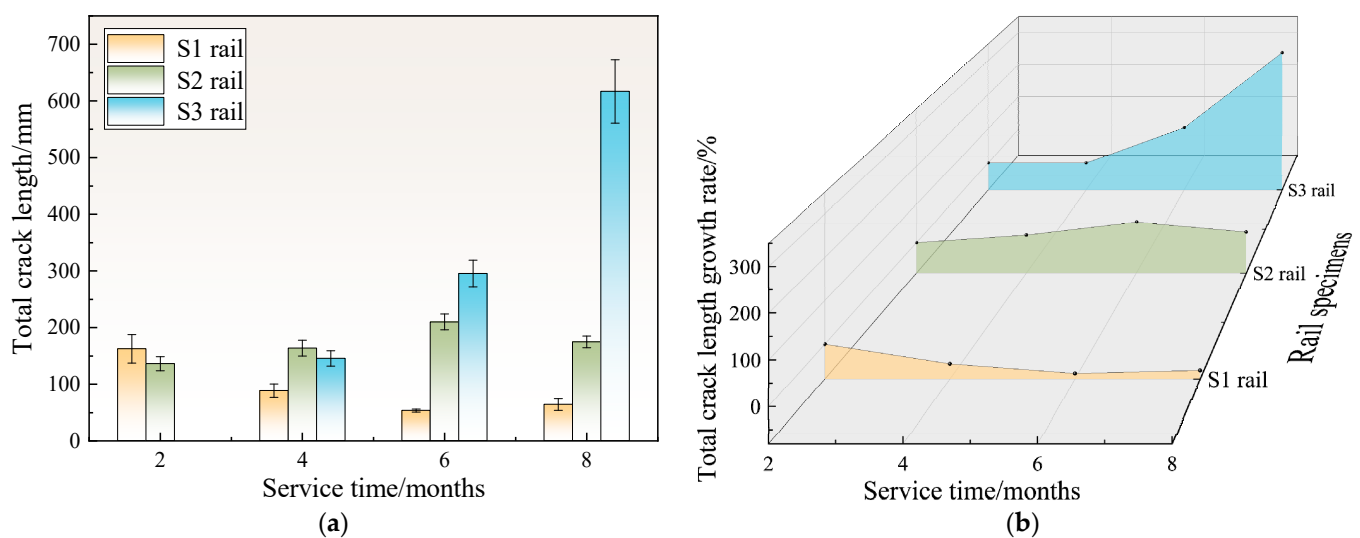


Figure 9. The total RCF crack-length measurement results of rail specimens: (a) the distribution of total RCF crack lengths; (b) growth rate curves of total crack length.

Total RCF crack length can only quantitatively evaluate the overall propagation scale of surface cracks and reflect the cumulative development of RCF damage. In order to further analyze the RCF crack propagation of rail specimens, Equation (3) was used to calculate the average lengths of RCF cracks under different service times.

$$L = \frac{P}{n} \quad (3)$$

where L represents the average length of RCF cracks; P represents the sum of the total length of RCF cracks measured; and n represents the sum of the number of RCF cracks measured.

The calculated results for the average RCF crack lengths of the rail specimens are shown in Table 5, and the growth rate curves of the average crack lengths are plotted in Figure 10. At the service checkpoint of 2 months, the S1 rail possesses the largest average crack length, which then drops sharply and gradually stabilizes within the range of 6–8 mm. The average crack length of the S2 rail varies moderately between 7 and 10 mm. For the S3 rail, the average crack length remains approximately 5 mm at the initial stage of crack initiation, yet its crack growth rate rises drastically afterward; the average crack length reaches 14.13 mm after 8 months of service. In summary, based on the evolution of the RCF crack numbers, total crack lengths, and average crack lengths of the rail specimens, it is

evident that although the RCF cracks of the S3 rail appear later, once cracks appear, the S3 rail exhibits remarkably higher crack density and faster crack development compared with the S1 rail and the S2 rail.

Table 5. The average length of RCF cracks of the rail specimens (mm).

Specimens	Service Time			
	2 Months	4 Months	6 Months	8 Months
S1	15.25	7.84	6.44	7.72
S2	7.43	9.10	10.33	7.28
S3	0.00	5.39	8.28	14.13

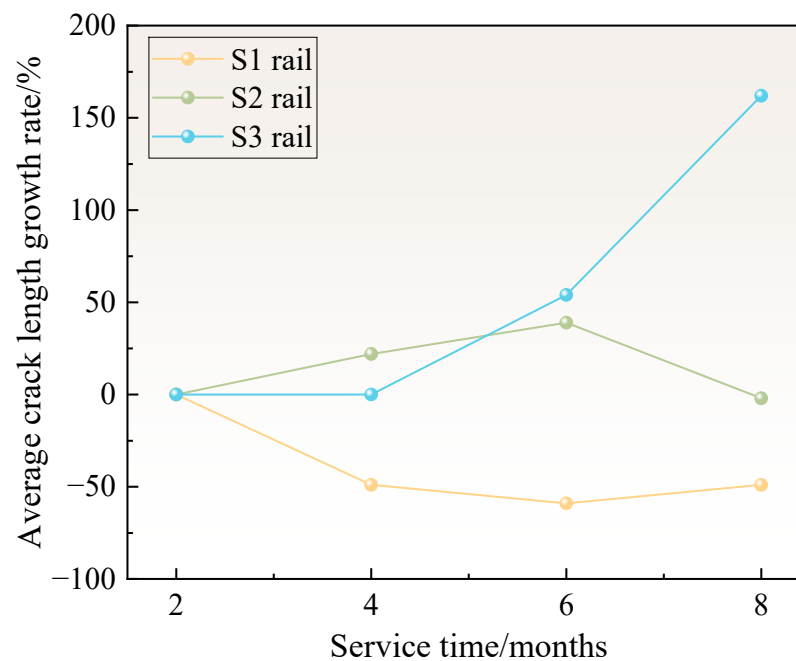


Figure 10. The growth rate curves for average RCF crack lengths of the rail specimens.

To analyze the development of RCF cracks more objectively and accurately, the lengths and number of all RCF cracks measured at different service times were statistically summarized, and the results are shown in Figure 11. In the early service stage, the crack lengths of the S1 rail span a wide range from 6 mm to 24 mm with scattered distribution, indicating the coexistence of crack initiation and rapid propagation accompanied by prominent dispersion in crack length. By contrast, the crack lengths of the S2 rail are distributed more compactly, mostly falling within 3–13 mm, as presented in Figure 11a. With increasing service duration, the distribution range of crack lengths of the S1 rail is narrowed markedly to 4–12 mm, with a much denser data distribution that complies well with the normal distribution law, indicating that the RCF crack propagation of the S1 rail gradually stabilizes, with limited fluctuations in crack number and crack length. The S2 rail exhibits a distribution characteristic similar to that of the S1 rail regarding crack lengths and crack number, as shown in Figure 11b,c. By contrast, the S3 rail presents an opposite evolutionary trend: the crack lengths are concentrated within 2–10 mm at the early service stage, while both crack numbers and crack lengths span wider ranges as service time increases. After 8 months of service, the crack-length distribution of the S3 rail expands to 6–24 mm, suggesting the rapid propagation of some RCF cracks, as illustrated in Figure 11d.

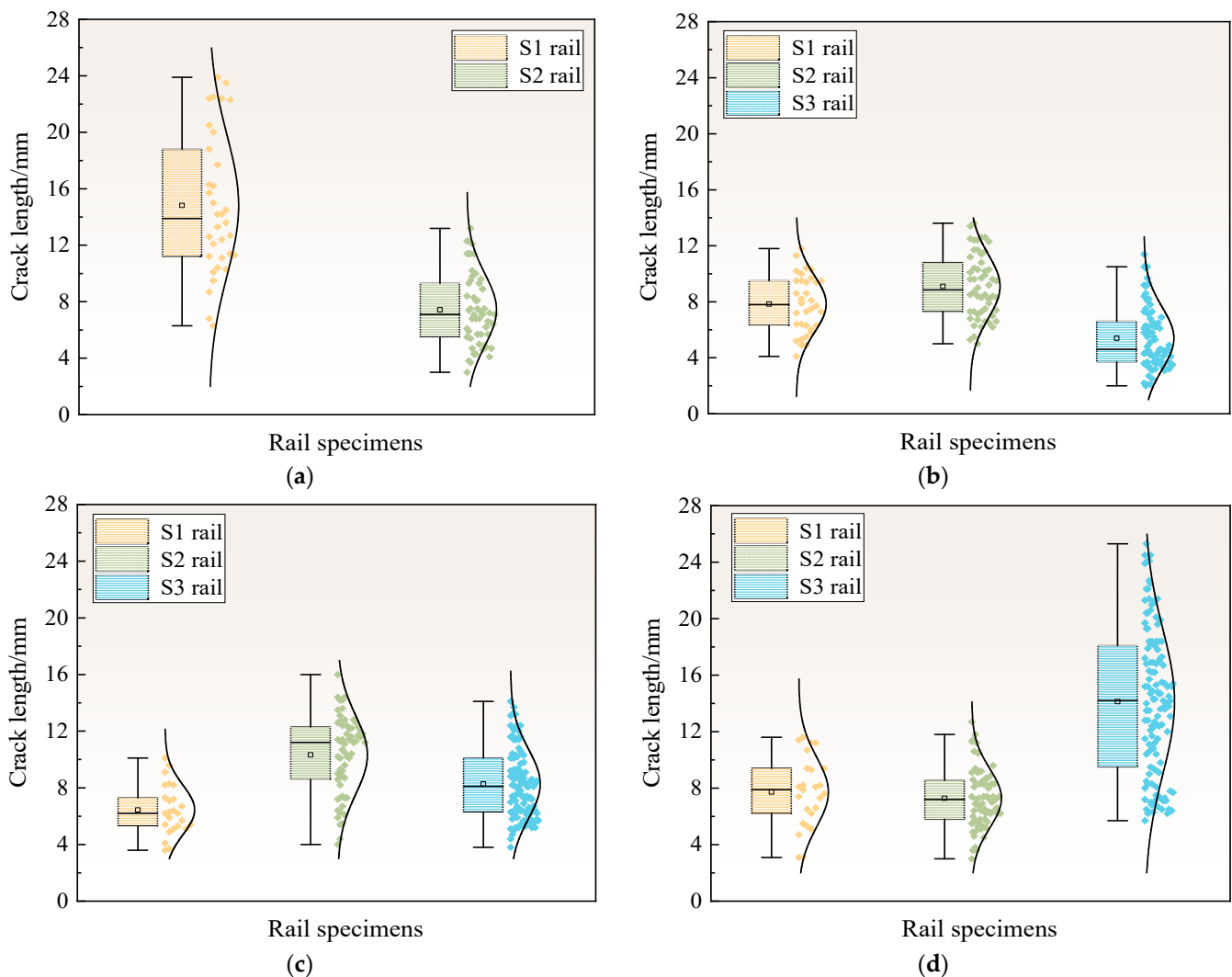


Figure 11. The statistical results of RCF cracks: (a) 2 months of service; (b) 4 months of service; (c) 6 months of service; and (d) 8 months of service.

Typical field observation photographs of RCF cracks on the rail specimens are shown in Figure 12. After the rail was laid on the curved track and run-in via repeated wheel rolling, the oxide scale and rust layer on the rail surface were removed, and the wheel–rail contact area was bright and smooth, as shown in Figure 12a–c. After 2 months of service, obvious RCF cracks emerge on the rail head surface of the S1 rail and the S2 rail. These cracks align in parallel at a certain angle relative to the train running direction. The cracks on the S1 rail are longer and sparsely distributed, while those on the S2 rail are relatively short, when comparing similar locations. In contrast, no RCF crack can be detected on the S3 rail, as presented in Figure 12d–f. Under the coupled effect of wheel–rail contact stress and tangential friction during service, a shear stress field is generated on the rail head surface. According to elastic stress theory, the plane of maximum shear stress forms an angle of approximately 45° with the principal stress plane [46]. Plastic slip preferentially initiates along the maximum shear stress plane for metallic material, triggering the nucleation and propagation of cracks. Accordingly, RCF cracks typically appear as inclined cracks oriented at a certain angle to the train’s running direction [47]. After 4 months of service, the crack lengths of the S1 rail decrease obviously, and the crack lengths of the S2 rail rise slightly, while no distinct variation is found in their crack numbers. Conversely, dense, fine RCF cracks emerge on the S3 rail. Although the individual crack lengths are shorter than those of the S1 rail and the

S2 rail, the S3 rail possesses a drastically higher crack distribution density, as shown in Figure 12g–i. After 6 months of service, both the crack length and crack number of the S1 rail further decline, presenting mild RCF damage. The crack morphology and crack number of the S2 rail remain roughly identical to those measured at the 4-month service stage. For the S3 rail, the crack lengths increase remarkably, accompanied by a much denser crack distribution, indicating continuous initiation of new cracks, together with rapid propagation of pre-existing cracks, as displayed in Figure 12j–l. After 8 months of service, the crack morphology and crack number of the S1 rail and the S2 rail stay nearly unchanged, whereas the S3 rail undergoes sharp increases in both crack length and crack number, with cracks propagating from the rail fillet toward the rail tread, as illustrated in Figure 12m–o.



Figure 12. *Cont.*

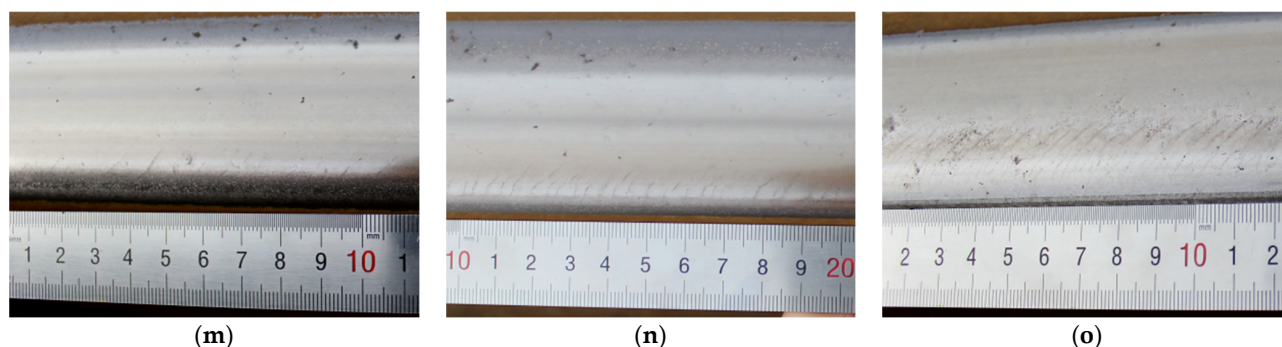


Figure 12. Typical field observation photographs of RCF cracks of the rail specimens: (a) S1 rail at 0 months; (b) S2 rail at 0 months; (c) S3 rail at 0 months; (d) S1 rail at 2 months; (e) S2 rail at 2 months; (f) S3 rail at 2 months; (g) S1 rail at 4 months; (h) S2 rail at 4 months; (i) S3 rail at 4 months; (j) S1 rail at 6 months; (k) S2 rail at 6 months; (l) S3 rail at 6 months; (m) S1 rail at 8 months; (n) S2 rail at 8 months; and (o) S3 rail at 8 months.

To visually characterize the evolutionary features of RCF crack morphology with increasing service time, manual extraction of crack outlines was performed using the images in Figure 12d–o. Each image was magnified, and crack outlines were manually traced to fit actual crack paths closely; these traced outlines were then merged to generate the characteristic RCF morphology diagrams shown in Figure 13.

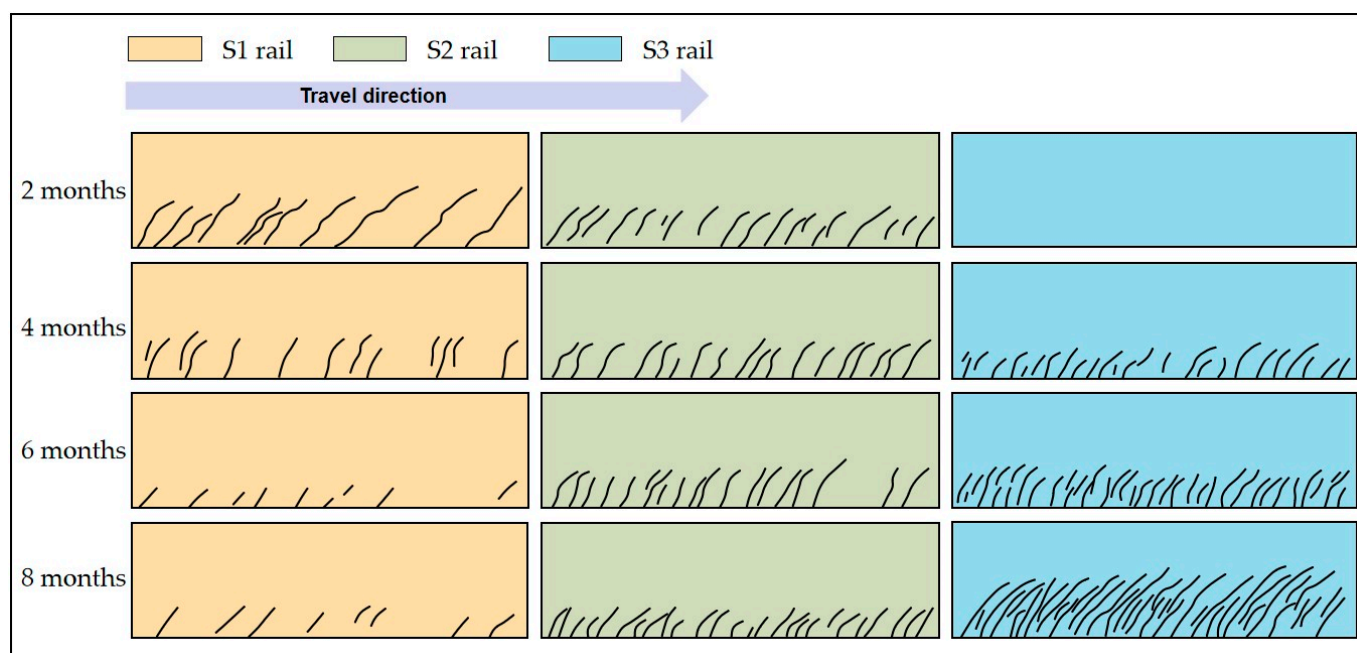


Figure 13. The characterization diagrams of RCF crack morphology.

Clear evolutionary patterns of RCF cracks can be summarized for the rail specimens: At the early service stage, cracks initiate and propagate most readily on the S1 rail, and manifest the longest crack lengths. Nevertheless, as service time increases, crack lengths reduce rapidly before crack evolution stabilizes, leaving only sporadic cracks scattered within the wheel–rail contact zone. The initial crack lengths of the S2 rail are smaller than those of the S1 rail, and its crack development remains steady throughout the service period, with minor fluctuations in crack number and length, placing it at an intermediate level among the three rail specimens. No RCF cracks form on the S3 rail at the initial service stage, yet dense, short cracks start to initiate after 4 months of service. Such rapid crack

propagation is accompanied by a significant increase in the crack number, implying severe deterioration of the RCF performance.

Given the complex field track-operating conditions, a manual measuring ruler was adopted to count the crack number and measure crack lengths in the field test. This manual data acquisition method relies heavily on visual judgment by operators, which suffers from low testing efficiency and insufficient measurement accuracy, making it difficult to realize highly precise quantitative evaluation of RCF damage. Nevertheless, all three groups of rails were measured under identical on-site environmental and operating conditions, so the comparative test data can still objectively reveal the intrinsic correlation between pearlite microstructure and rail service performance. For future research and practical on-site engineering inspection, our research team will carry out targeted studies using high-precision quantitative detection technologies to detect rail RCF cracks. An engineering-oriented intelligent detection system will be developed by combining deep learning and machine learning algorithms, one which can automatically identify, quantify, and characterize surface fatigue cracks on the rail tread with higher accuracy and efficiency.

4. Discussion

4.1. Influence of Pearlite Interlamellar Spacing on Wear and RCF

For pearlitic rails, pearlite interlamellar spacing acts as a critical parameter governing mechanical properties and directly dominates the service performance. To comprehensively and visually reveal how pearlite interlamellar spacing affects wear and RCF behaviors of rails, six evaluation indicators, namely, pearlite interlamellar spacing, average RCF crack length, RCF crack number, wear loss, tread hardness, and matrix strength, were selected to construct radar charts of rail performance at different service times, as given in Figure 14. As service time increases, the S1 rail, with coarse pearlite lamellae, exhibits continuous growth in wear loss, while its RCF crack lengths and crack numbers gradually decline and stabilize, and the performance coverage area gradually extends along the longitudinal direction and develops into a slender vertical strip shape, indicating that its service performance is mainly dominated by wear. By contrast, the S3 rail, with fine pearlite lamellae, shows negligible variation in wear loss, yet undergoes a sharp rise in both RCF crack length and RCF crack number; its radar region expands horizontally into a wide transverse band, indicating that its service performance is mainly dominated by RCF. Possessing a moderate pearlite interlamellar spacing, the S2 rail presents values intermediate in wear loss, crack length, and crack number among the three specimens. Its radar contour remains centrally distributed and approximates a regular hexagon, revealing a balanced development between wear and RCF.

Directly subjected to repeated rolling compression and friction from train wheels, the wheel–rail contact zone is always under severe service conditions featuring high contact stress, intensive frictional action, and cyclic loading. Surface material loss occurs owing to wear; meanwhile, fatigue cracks readily initiate and progressively propagate. Wear and RCF constitute the two primary failure modes of in-service rails. These two damage mechanisms coexist and interact on the rail surface over the full service life, presenting a competitive and restrictive relationship [48,49]. In detail, rails suffering severe wear generally exhibit mild RCF damage, whereas rails with low wear loss tend to develop serious RCF damage.

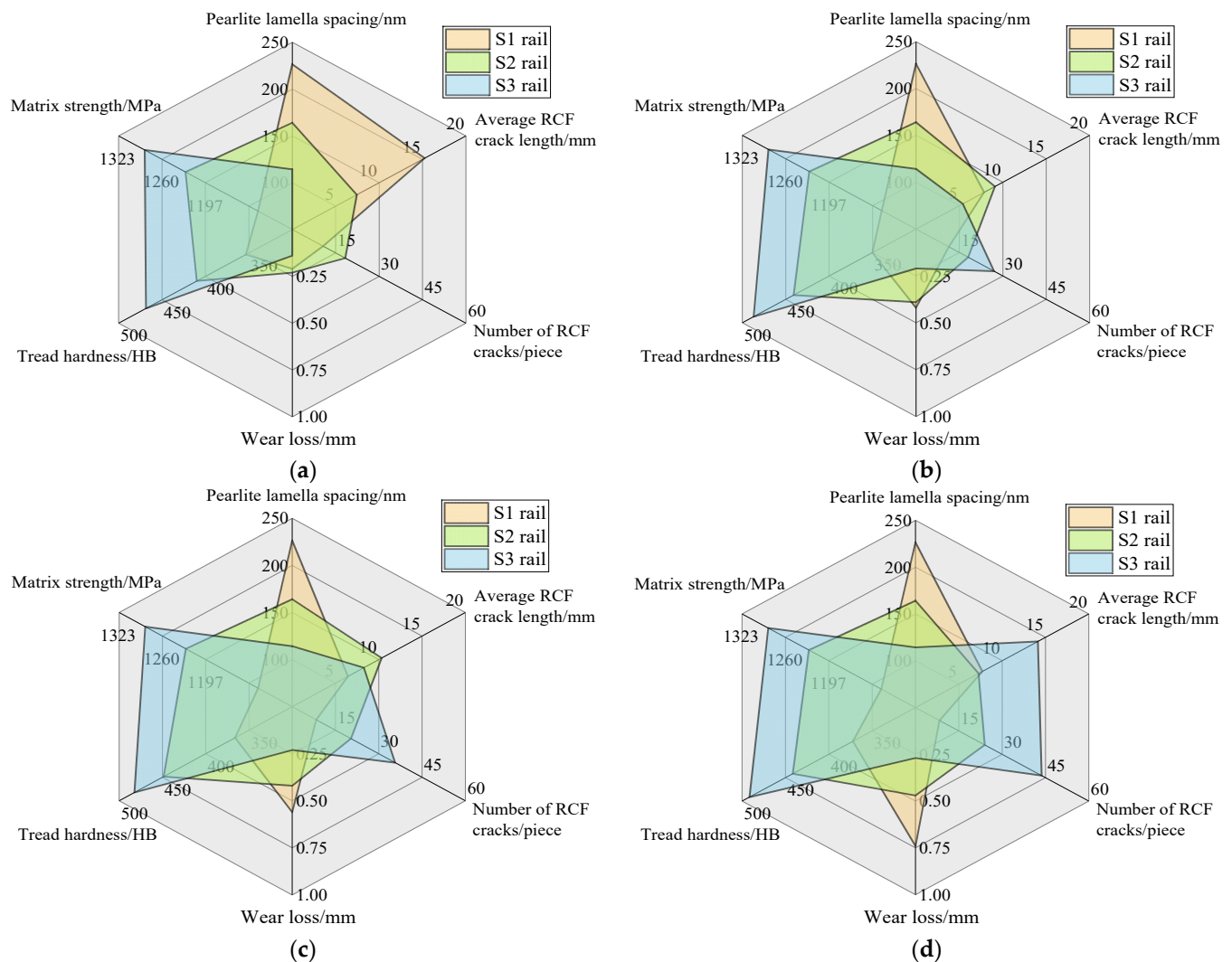


Figure 14. The radar charts of rail performance at different service times: (a) 2 months of service; (b) 4 months of service; (c) 6 months of service; and (d) 8 months of service.

The relationship curves for the wear life and the RCF life of field-service rails were plotted based on the existing literature [50], as shown in Figure 15. The two curves correspond to wear life and RCF life, where the horizontal axis denotes rail wear rate and the vertical axis represents service life. Wear life varies inversely with wear rate, while RCF life increases proportionally with wear rate. At an arbitrary wear rate, the practical service life of the rail is governed by the smaller value between wear life and RCF life. For instance, at wear rate A, the corresponding wear life is A1, and RCF life is A2, so the practical rail service life is A2. Similarly, the practical life is B2 at wear rate B. The intersection point of the two curves denotes the maximum achievable service life under balanced competition between wear and RCF, and the corresponding wear rate C is defined as the “magic wear rate” [51]. The left side of point C is the RCF failure area of the rail, and the right side of point C is the wear failure area. The red curve plotted in Figure 15 outlines the actual service life envelope covering the whole service cycle of rails.

It should be clarified that Figure 15 was plotted based on the overall evolutionary trends of rail wear and RCF damage, rather than measured data from a specific operating track. The schematic curves were designed to illustrate the competitive evolution trends of the two damage modes and introduce the theoretical concept of the “magic wear rate”, providing a theoretical reference for the coordinated control of the wear and RCF damage

to rails. In practical field service, however, the wear rates and RCF propagation rates of rails do not increase linearly. Both indices dynamically fluctuate with accumulated service mileage and variable wheel–rail contact conditions. For this reason, the critical threshold of the theoretical “magic wear rate” shifts continuously throughout service, making it impossible to calculate an accurate fixed value for the “magic wear rate” for the tested track based solely on the present field observation data. Given the competitive interaction between wear and RCF, the relationship between pearlite interlamellar spacing and rail service life is also applicable to the trend illustrated in Figure 15. After replacing the wear rate on the horizontal axis with the values for pearlite interlamellar spacing, the intersection point of the wear life curve and RCF life curve corresponds to the “magic pearlite lamellar spacing”. At this critical spacing, rail wear and RCF can theoretically achieve an optimal balance, allowing the rail to attain its maximum service life. Nevertheless, practical field service is governed by a multitude of complex influencing factors, including microstructure, track geometry, train operating conditions, and wheel–rail contact status, all of which alter rail wear and fatigue behaviors. Hence, it is extremely challenging to quantify the optimal pearlite interlamellar spacing for a specific operating railway track. The present work mainly focuses on the qualitative correlation between pearlite interlamellar spacing and rail service performance, and preliminarily verifies the feasibility of balancing wear and RCF from the microstructural modification of rail steel. The findings provide direct guidance for optimizing accelerated cooling processes and precise microstructural control during rail manufacturing. Reasonable tuning of pearlite interlamellar spacing can effectively balance wear and RCF, mitigate dominant service failures, and extend the overall service life of rails. Additionally, the coupled control mechanism of wear and RCF in this study can serve as a technical reference for railway track maintenance and regular inspection planning.

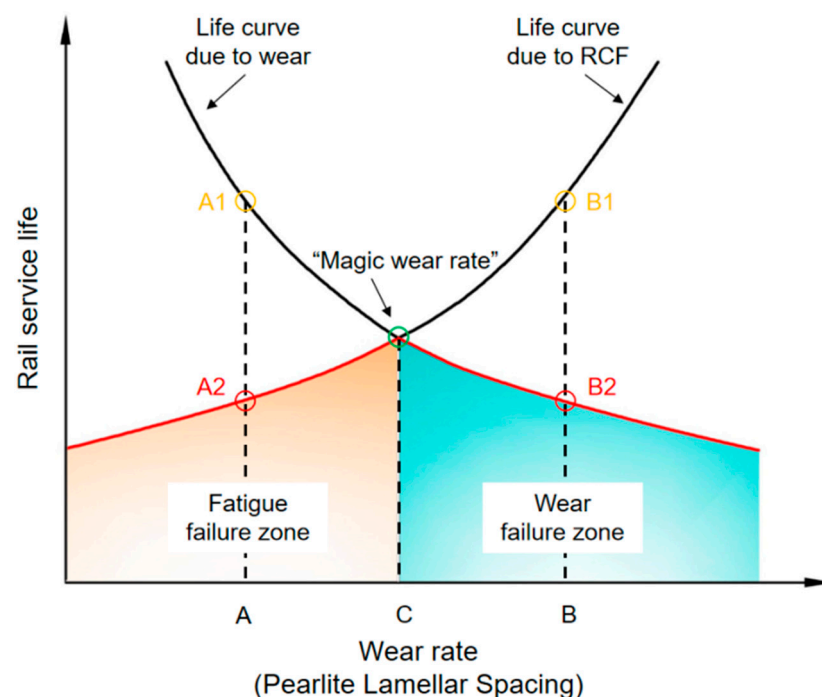


Figure 15. The relationship curves for rail wear life and RCF life.

4.2. Mechanisms of Wear and RCF Crack Evolution in Pearlitic Rails in Service

During service, the rail head surface material is continuously subjected to combined loads consisting of normal Hertzian contact pressure, tangential friction, and alternating shear stress imposed by train wheels. Grains are elongated and flattened along the running direction, and this is accompanied by plastic deformation, lattice distortion, and work

hardening of the surface material [2,52]. It is widely recognized that once the wheel–rail shear stress exceeds the yield limit of the rail material, lattice distortion occurs inside ferrite grains, dislocation slip initiates, and plastic deformation emerges throughout the matrix. Under repeated cyclic loads, plastic strain continuously accumulates on the surface of the rail head, exhausting the plastic capacity of the material and generating numerous micro-cracks within the surface plastic deformation layer [53]. Driven by persistent wheel–rail contact loads, these micro-cracks coalesce, propagate, and extend inward into the substrate, eventually developing into typical RCF cracks. Essentially, the evolution of RCF damage originates from continuous accumulation of micro-defects and gradual crack growth [54].

Pearlite comprises alternately stacked soft ferrite lamellae and hard cementite lamellae. Variations in interlamellar spacing greatly alter the mechanical properties and stress response of the matrix, thereby regulating the evolution behavior of RCF cracks. Rails with coarse pearlite lamellae exhibit low yield strength and weak resistance to plastic deformation. Under cyclic wheel–rail loads, dislocations inside ferrite move with low resistance across long distances, triggering widespread plastic flow. Such deformation creates severe mechanical mismatches at ferrite–cementite interfaces, leading to drastic stress concentrations. Consequently, micro-cracks preferentially nucleate and propagate along these phase boundaries and eventually evolve into RCF cracks [16]. By contrast, fine pearlite features smaller interlamellar spacing and denser phase boundaries, which significantly improve the yield strength and deformation resistance of the material. Densely distributed ferrite–cementite interfaces act as effective barriers to dislocation slip, shortening dislocation migration paths and preventing massive dislocation pile-up. Meanwhile, these densely arranged interfaces evenly distribute wheel–rail contact stress and remarkably alleviate stress concentration at phase boundaries [55]. In addition, the refined, uniformly distributed pearlite microstructure effectively restrains the fracture of cementite lamellae, further delaying the initiation and propagation of micro-cracks. At the early service stage, the S1 rail with the largest pearlite interlamellar spacing generated the longest RCF cracks, implying rapid nucleation and growth of fatigue cracks. No visible RCF cracks were detected on the S3 rail, the sample type with the finest lamellar structure, which verifies that fine pearlite effectively retards early micro-crack initiation. Nevertheless, with increasing service time, progressive accumulation of plastic deformation on the S3 rail eventually triggered crack nucleation. The dense ferrite–cementite interfaces with high dislocation density supply abundant preferential nucleation sites, leading to the dense RCF crack morphology observed on the S3 rail.

From the perspective of wear mechanisms, wear in pearlitic rails essentially originates from frictional spalling of surface material at the contact interface. Coarse pearlite lamellae exhibit poor shear resistance, and cementite lamellae tend to fracture and detach under frictional loading to accelerate material loss. Reduced interlamellar spacing increases the volume fraction of ferrite–cementite interfaces, which effectively hinders dislocation slip during plastic deformation. Continuous plastic strain leads to dislocation pile-up and multiplication, drastically elevating dislocation density and promoting work hardening, and consequently improving the wear resistance of the material [18,23,56]. Therefore, among the rail specimens in this study, the S3 rail, the sample type with the finest pearlite lamellae, possesses the highest initial matrix hardness and achieves the maximum tread hardening rate during field service, hence delivering superior wear resistance. By contrast, the S1 rail, the sample type with the coarsest pearlite lamellae, exhibits the lowest matrix hardness and the minimum tread hardening rate, resulting in the largest wear loss throughout service.

The service performance of rails can be categorized into two states: wear-dominated state and RCF-dominated state. In the wear-dominated state, continuous removal of surface material restrains the propagation of RCF cracks, while a large amount of material loss

occurs; in the RCF-dominated state, surface cracks expand rapidly and eventually evolve into severe RCF damage [48,57]. Figure 16 schematically illustrates the evolution of wear and RCF cracks during the service of rail specimens in this study.

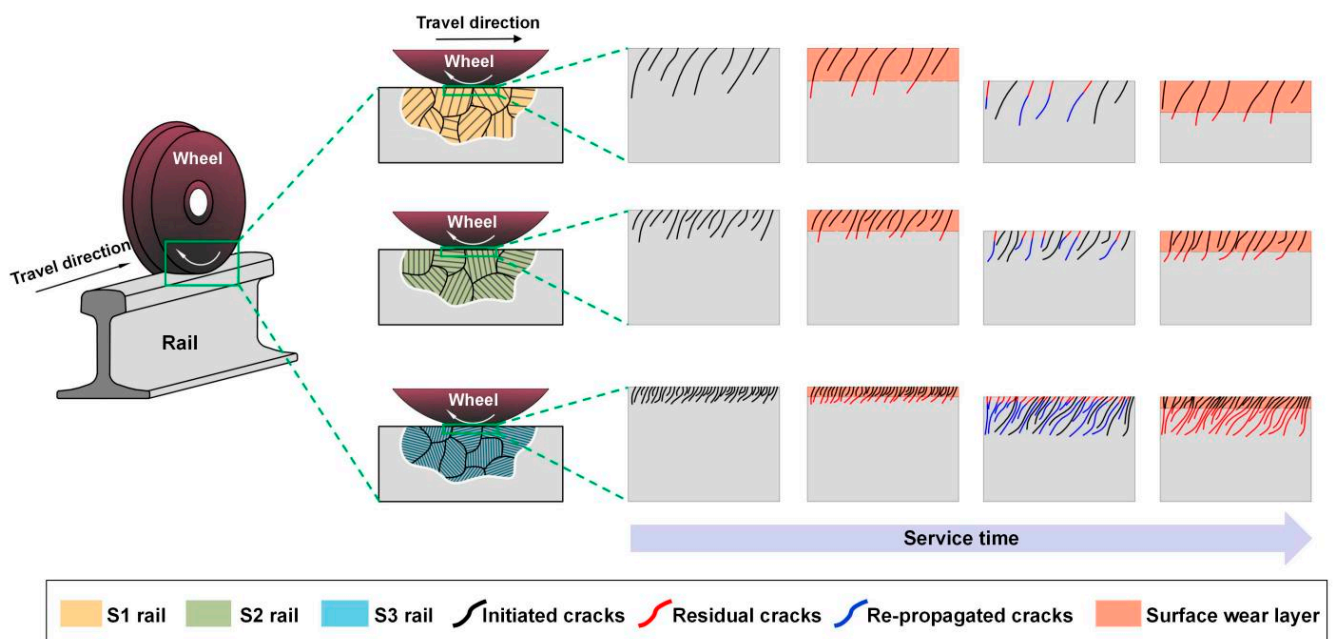


Figure 16. The schematic diagrams of wear and RCF crack development during the service of the rail specimens.

At the early service stage, RCF cracks initiate on the rail surface under cyclic wheel–rail contact loads. After initiation, the cracks propagate inward into the substrate and laterally across the rail head surface. Among all rail specimens, the S1 rail, the sample type with the coarsest pearlite lamellae, exhibits the earliest crack initiation and propagation, as well as the longest crack length. Meanwhile, wear takes place at the wheel–rail contact interface, leading to continuous material removal. The S1 rail suffers the largest wear loss, and most surface cracks are worn away, which greatly restrains RCF crack development. As service time increases, residual cracks keep expanding under cyclic stresses, and new micro-cracks continuously form on the fresh surface. Most newly formed cracks are then eliminated by wear, and this process repeats cyclically. Consequently, only short and sparse RCF cracks remain on the S1 rail surface, and its service performance is predominantly dominated by wear. For the S3 rail, the sample type with the finest pearlite lamellae, RCF cracks initiate at a later stage but exhibit fine and dense morphologies. Its low wear loss fails to effectively remove the cracked surface material, leaving numerous residual cracks that gradually grow longer with prolonged service. Eventually, massive slender and densely distributed RCF cracks appear on the surface of the S3 rail, so its service performance is dominated by RCF. The S2 rail possesses an intermediate pearlite interlamellar spacing. Surface wear removes most RCF cracks effectively, while the wear loss remains relatively low, guaranteeing satisfactory wear life. Therefore, the S2 rail maintains a favorable competitive balance between wear and RCF evolution during service.

5. Conclusions

In this study, the influences of pearlite interlamellar spacing on rail wear and RCF behaviors were investigated by continuous observation of the service performance of three rail specimens with different pearlite interlamellar spacing, on field tracks. The main conclusions are summarized as follows:

(1) Pearlite interlamellar spacing exerts a significant influence on the service performance of rails. The S1 rail, the sample type with a large pearlite interlamellar spacing, shows earlier initiation and propagation of RCF cracks and possesses the longest cracks at the early service stage. Meanwhile, it possesses the lowest tread hardening rate and the largest wear loss. As service proceeds, most RCF cracks on its surface are worn away, presenting a macroscopic morphology of short and sparse cracks. The service performance of the S1 rail is predominantly dominated by wear.

(2) The S3 rail, the sample type with a small pearlite interlamellar spacing, delivers the highest tread hardening rate and the minimum wear loss. It exhibits the best resistance to RCF and the latest-occurring crack initiation at the early service stage. As service time increases, numerous dense RCF cracks emerge and propagate rapidly, and the rail performance is eventually dominated by RCF.

(3) The S2 rail, the sample type with a medium pearlite interlamellar spacing, shows intermediate performance in terms of wear and RCF among the three rail specimens. Surface wear effectively eliminates most RCF cracks, with the relatively low wear loss accompanied by slight fluctuations in crack length and crack number. Overall, a well-balanced evolution between wear and RCF is maintained.

(4) Wear and RCF present a mutually competitive relationship during rail service. Under similar track conditions, appropriate regulation of pearlite interlamellar spacing can achieve a coupled balance between wear and RCF. For sharp radius curved tracks or heavy-haul lines dominated by severe wear, pearlitic rails with fine interlamellar spacing and high matrix strength are recommended for laying. For tangent tracks or passenger-dedicated lines where RCF acts as the dominant damage form, rails with relatively coarse pearlite lamellae are preferable. For tracks with moderate curve radii, pearlitic rails with medium interlamellar spacing should be prioritized, a type which can effectively balance the evolution of rail wear and RCF damage, thereby extending the comprehensive service life of field rails.

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