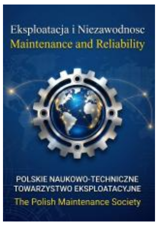

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Fretting-induced degradation of press-in connections during operation

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Abstract

This study analyses the degradation process of press-in connections operating under cyclic loading conditions, with particular emphasis on fretting wear. The aim of research was to identify the factors initiating damage and assess its influence on the service life of the connections. Experimental investigations conducted on shaft-sleeve models subjected to rotational bending revealed significant changes in the tribological properties within the contact zone, including an increase in the press-out force and the contact pressure and degradation of surface topography. A heterogeneous nature of fretting wear was observed, along with the presence of wear products in the form of iron oxides. It was found that fretting leads to the initiation of microcracks and a reduction in fatigue strength. The obtained results correspond to operational conditions similar to those encountered in rail vehicle wheel sets.

Keywords: *fretting wear, press-in connections, operation, wheel set*

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Highlights

- Fretting wear governs the degradation of press-in connections under cyclic bending.
- Wear develops heterogeneously, with severe damage concentrated near connection edges.
- Iron oxides accumulate within the contact zone and intensify abrasive interactions.
- Fretting wear promotes near-surface microcrack initiation and fatigue degradation.
- Press-out force and surface morphology provide indicators of progressive degradation.

1. Introduction

The degradation of press-in connections constitutes a significant operational problem, particularly in rail transport, directly affecting the reliability, durability, and safety of vehicle operation [1,2]. This issue is especially critical in the case of wheel sets, which are among the most heavily loaded structural components of rail vehicles and also perform a critical function from the perspective of traffic safety [3,4]. Damage initiated in the region of the press-in connection may lead to the deterioration of the interaction conditions between components, to a change of the stress distribution, and, in extreme cases, to serious failures such as axle fractures or loss of connection integrity [5,6].

Increasing operational demands, associated with higher travel speeds and greater axle loads, lead to intensified mechanical interactions within the wheel-axle system. Research indicates that real operational conditions involve the simultaneous action of vertical, lateral, and dynamic loads, which significantly complicates the analysis of connection durability [7,8]. Consequently, an increase in stress levels and an accelerated accumulation of fatigue damage occur, as confirmed by full-scale studies of rail axles, where crack initiation was observed as early as after a few million load cycles [9]. As a result of the increased stress, two types of damage are initiated: fretting wear and fretting cracks [10].

Figure 1 presents a sample diagram showing the loads acting on a rail vehicle wheel set. Vertical forces arise from the weight of the vehicle and constitute the primary component of the load transmitted by the wheel set. In addition, dynamic forces occur due to the interaction between the wheel and the track, resulting, among other factors, from track irregularities and vibrations within the vehicle–track system. Lateral forces also play a significant role, appearing during a ride along a curve as well as due to instability in wheel set dynamics. Under real operational conditions, these loads act simultaneously, leading to the development of a complex stress state in the region of the press-in connection. Particularly critical are transition zones, such as the wheel seat edge, where stress concentrations and damage initiation are commonly observed.

Press-in connections are widely used in industry for joining various components [11,12], including wheel sets, due to the connections' high load-carrying capacity and advantageous structural properties [13,14]. The operating principle of press-in connections is based on the use of frictional forces generated by contact pressure resulting from the geometric connection between mating components. However, as indicated by numerous studies, that region is especially susceptible to damage initiation due to the presence of high stress gradients and a complex loading state [15,16].

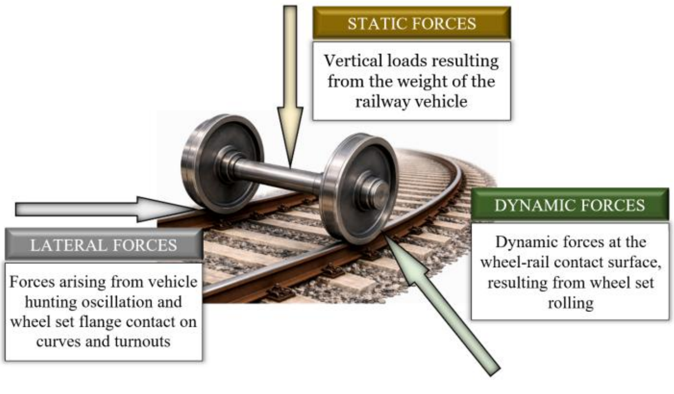


Figure 1. Diagram of loads acting on a rail vehicle wheel set.

An additional significant operational issue is the presence of geometric defects in the contact zone of mating components, such as scratches, microcavities, or surface deformations. Even minor discontinuities may lead to localised stress concentrations and to a significant reduction in the fatigue strength of the connection, as confirmed by experimental investigations of damage in press-in connections. The source of such defects is not limited to operational processes; defects may also arise as early as during the assembly stage. The press-in process, conducted under high contact pressures and significant friction forces, promotes the formation of localised plastic deformations and alterations in the material's surface layer. As a result of these phenomena, surface topography is modified and microirregularities are formed, which, during further operation, act as stress concentrators and may contribute to the initiation of fretting wear.

Despite numerous studies on the durability of press-in connections, the mechanisms responsible for the initiation and early stages of fretting wear under complex loading conditions representative of actual wheelset operation have not yet been fully clarified. Previous studies have primarily focused on fatigue life analysis or numerical modelling [17–19], whereas the number of experimental investigations enabling direct observation of changes in surface topography and the evolution of the near-surface layer as a function of the number of loading cycles remains limited.

In the present study, comprehensive experimental investigations were carried out on press-in connections operating under loading conditions representative of the actual service conditions of the wheel–axle system. The scope of the research included the analysis of changes in surface topography, the force characteristics of the connection, the chemical composition of wear products, and observations of the contact zone, which enabled a comprehensive assessment of the degradation process and the interrelationships between the tribological, mechanical, and material phenomena occurring within the connection.

The objective of this study was to identify the factors initiating and governing the development of fretting wear and to develop a degradation mechanism for a press-in connection based on the results of comprehensive experimental investigations. As a result of the conducted research, a six-stage mechanism describing the evolution of fretting wear was proposed, integrating changes in surface topography, the development of wear products, the evolution of contact conditions, and the initiation of fatigue damage into a coherent degradation model. In addition, indicators of progressive degradation were identified, and their potential significance for the diagnostics and condition assessment of press-in connections was determined.

2. Factors conducive to damage in press-in connections

An analysis of the operational conditions of press-in connections indicates that their degradation is of a multifactorial nature and results from the interaction of mechanical, material, and environmental influences. To systematize these relationships, the factors affecting the initiation and development of damage can be grouped into several fundamental categories, as schematically illustrated in Figure 2. The first group includes load-related factors. These comprise both vertical forces resulting from the applied weight and forces acting under specific conditions. In the case of wheels sets, those forces may include lateral and dynamic forces associated with wheel set motion. Their variable nature leads to the generation of cyclic stresses and microscopic relative displacements at the contact area. Particularly important in this context are vibrations and microdisplacements, which may initiate degradation processes in the surface layer of the material.

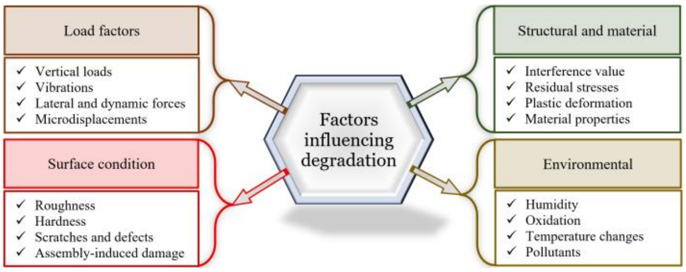


Figure 2. Factors conducive to damage in press-in connections.

The second group consists of factors resulting from the structural and material properties of the connection. A key parameter is the interference value, which determines the level of contact pressure. Both insufficient and excessive interference may lead to disadvantageous operational conditions of the connection. Additionally, residual stresses and the possibility of localised plastic deformation, particularly in regions of stress concentration, play a significant role.

Another group includes factors related to the surface condition of the mating components. These factors involve, among others, surface roughness, the directionality of machining marks, and the presence of defects such as microcavities or scratches. It should be emphasized that some of these defects may arise as early as at the assembly stage. The press-in process, carried out under high pressures and friction forces, leads to localised damage of the surface layer and to modifications of surface topography. As mentioned before, the geometric discontinuities formed in this manner act as stress concentrators and may initiate degradation processes during subsequent operation.

The last group consists of environmental factors that influence the operational conditions of the contact interface. The presence of moisture and oxygen promotes oxidation processes, leading to the formation of wear products with abrasive characteristics. Additionally, temperature changes may affect material properties and the stress state within the connection. As a result, friction conditions are modified and degradation processes are intensified.

The analysed factors act synergistically, creating a complex state of loading and contact conditions. The simultaneous occurrence of these factors leads to the localised intensification of tribological phenomena, promoting the initiation and development of fretting wear, which plays a key role in the degradation of press-in connections.

3. Fretting wear in press-in connections

Fretting wear is one of the primary mechanisms of degradation in press-in connections [20,21], particularly in components operating under variable service loads, such as rail vehicle wheel sets. The phenomenon is defined as a surface wear process occurring at the interface of components remaining in contact under normal load, while also subjected to cyclic relative displacements of small amplitude [22,23]. The development of fretting wear takes place under conditions of limited slip, which leads to a stress distribution conducive to fretting wear initiation and to characteristic degradation mechanisms of the material surface layer.

In press-in connections, the conditions conducive to fretting wear arise directly from the mode of operation of the connections [24]. Due to the press-in fit between mating components, high contact pressures are generated in the contact zone, while variable loads acting during operation induce localised microdisplacements of the surfaces. Consequently, gradual surface degradation occurs, which may lead to a significant reduction in the service life of the connection or to a loss of assembly contact pressure resulting in loosening of the connection.

Wear products accumulating in the contact zone plays a significant role in the fretting process [25,26]. These particles affect friction conditions and the distribution of contact stresses, acting both as a separating layer and as an abrasive factor that intensifies degradation [27,28]. The nature of the influence of those particles depends on operational conditions, including the presence of oxygen, moisture, and temperature.

One of the consequences of fretting wear is its effect on the initiation and propagation of fatigue damage. As a result of cyclic stresses and the presence of stress concentrators in the form of surface microdamage, cracks are initiated that may propagate deeper into the material [29]. It has been demonstrated that fretting leads to a significant reduction in the fatigue limit of the material, and crack initiation may occur at stress levels lower than those admissible for conventional fatigue [30].

In press-in connections of wheel set axles, cracks most frequently initiate in the region of the wheel seat edge, where the highest contact stresses occur [31,32]. Furthermore, crack propagation depends on localised contact conditions, which evolve over time due to progressive wear and changes in surface topography.

The intensity of fretting wear is influenced by a wide range of factors [33], including those discussed in the previous section. However, material hardness and the presence of geometric defects also play an important role.

In summary, it should be emphasized that fretting wear in press-in connections is a complex tribomechanical process governed by the interaction of mechanical, material and environmental factors. The occurrence of fretting wear leads to surface layer degradation, initiation of fatigue damage, and a gradual deterioration of the operational conditions of the connection. For this reason, efforts should be made to identify the mechanism governing the development of this kind of wear under specific operational conditions and to minimize the intensity of that mechanism both at the design stage of the connection and during subsequent operation.

4. Research methodology

To achieve the stated objective, experimental investigations were conducted to identify the nature of wear mechanisms constituting the fretting phenomenon and to assess their impact on the degradation process of press-in connections. The tests were conducted on sleeve-shaft type connections subjected to cyclic rotational bending. Analysed were the models of press-in shaft-sleeve connections designed to replicate the actual operational conditions of components loaded with cyclic rotational bending. The adopted geometry and assembly parameters correspond to typical engineering solutions, allowing the obtained results to be extrapolated to real structural systems.

To ensure repeatability of the results and to enable assessment of the influence of random variability on the development of fretting wear, the research programme was extended to include the analysis of a series of specimens with identical geometry and assembly parameters. A total of ten press-in connection specimens were prepared and tested, all made of the same material, i.e. C45 steel, whose chemical composition is specified by PN-EN 10083-2, and assembled with an identical interference value of 0.02 mm. Figure 3 presents the model of the press-in connection along with the basic parameters of the surface topography of the mating components.

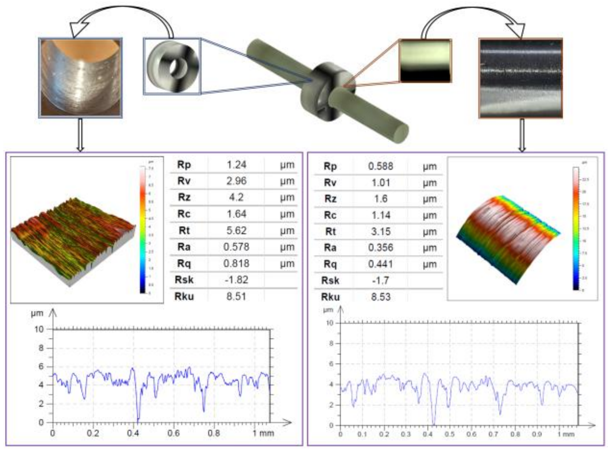


Figure 3. A model of the press-in connection and surface topography of the mating components.

On both surfaces, a distinct directional geometric structure is visible in the form of parallel machining marks. This type of morphology is characteristic of surfaces produced by turning processes and results directly from the kinematics of the cutting tool motion relative to the machined component. This structure manifests as regular ridges and valleys, whose orientation corresponds to the tool path. Surface roughness profiles confirm the periodic nature of the irregularities and the presence of distinct peaks and depressions. The occurrence of sharp peaks and deeper valleys indicates that the actual contact between the components is realized through a limited number of microcontacts located at the peaks of the irregularities.

Each specimen was subjected to identical fatigue loading conditions in the form of rotational bending, which enabled direct comparison of the obtained result [34,35]. Such an approach reduces the influence of random factors and increases the reliability of conclusions regarding the mechanisms of initiation and propagation of fretting wear cracks. Figure 3 presents the loading pattern of the test model under rotational bending conditions, along with the corresponding distributions of the bending moment and deflection along the shaft length.

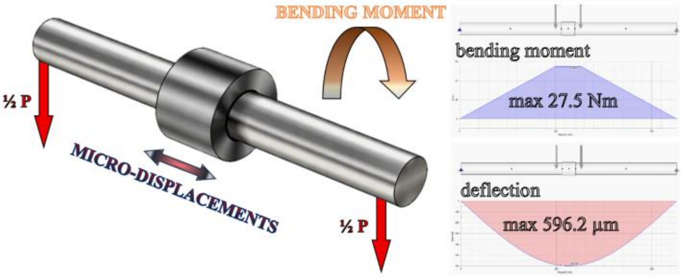


Figure 4. The loading method of the test model and maximum values of the bending moment and deflection.

The model was symmetrically loaded with two concentrated forces, with a total force value of 550 N. This loading configuration results in pure bending in the central part of the shaft, where the press-in connection is located. At the same time, during operation of the fatigue testing machine, the model is subjected to rotational motion, leading to cyclic changes in the direction of stresses. The distribution of the bending moment is linear, reaching its maximum in the central region of the specimen, i.e., in the area of the press-in connection. The maximum value of the bending moment is 27.5 Nm, indicating that the highest normal stresses responsible for the development of fatigue damage occur in this zone.

In contrast, the deflection distribution is curvilinear, with its maximum also located in the central part of the component. The maximum displacement amounts to 596.2 µm, indicating the greatest geometric deformation in the contact area between the shaft and the sleeve. In the same zone, both maximum bending stresses and relative microdisplacements at the contact interface occur at the same time. The tests were conducted until a total of 10^6 loading cycles was reached, corresponding to the high-cycle fatigue range.

After appropriate preparation of the test model, involving its cutting parallel to the shaft axis, observations and measurements were conducted to evaluate the development of fretting.

5. Test results

Initially, measurements of the press-in force and the force required to press the sleeve out of the shaft were conducted. Figure 5 presents the pattern of these forces as a function of displacement.

The press-in curve, obtained prior to the commencement of the tests, reflects the initial assembly conditions of the press-in connection. Its monotonic pattern indicates a gradual increase in contact pressures resulting from the matching of the components. The nature of this relationship is determined by the interference value, material properties, and surface topography.

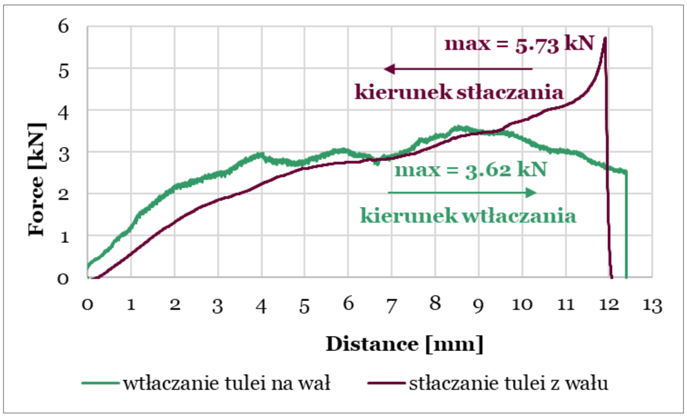


Figure 5. Force patterns relative to displacement during sleeve pressing-in onto the shaft and subsequent sleeve pressing-out.

In contrast, the curve corresponding to the press-out process, performed after 10^6 fatigue loading cycles, indicates a significant change in the tribological properties of the connection. The increased maximum force value and the non-linear nature of the pattern suggest a modification of the load transfer mechanism within the contact zone. This phenomenon should be associated with the development of fretting wear, leading to the generation and accumulation of wear products, their compaction, and localised plasticisation.

Additionally, the degradation of the surface layer and the development of geometric irregularities promote mechanical interlocking of the mating surfaces, resulting in increased resistance during the separation of the components. Consequently, the force-displacement characteristics of the connection after fatigue loading deviate from the initial state, reflecting changes occurring in the microstructure and surface topography.

It has previously been demonstrated that the press-out force is significantly influenced by changes occurring in the surface layer as a result of fretting wear development. To confirm this relationship, Figure 6 presents a fragment of the shaft surface after completion of fatigue testing, including a region of intensive fretting wear and an area with less pronounced wear traces.

In the region affected by fretting wear, complete degradation of the original surface topography is observed, manifested by the loss of directional machining marks and the formation of an irregular surface structure. This morphology results from cyclic tangential interactions leading to the fragmentation of the material, its displacement, and the accumulation of wear products. In contrast, areas not subjected to intensive fretting wear retain the characteristic features of machined surfaces, indicating the absence of significant changes in the surface layer.

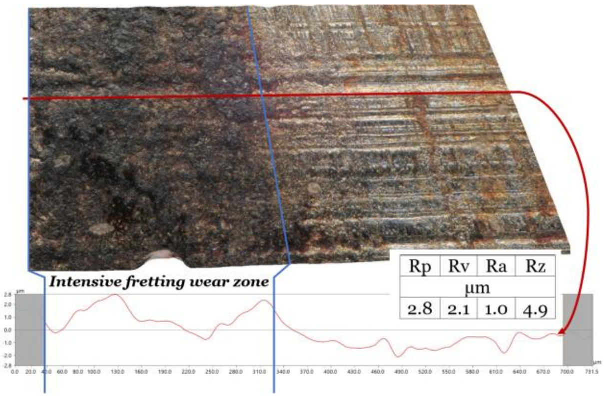


Figure 6. Surface roughness profile in the fretting wear zone.

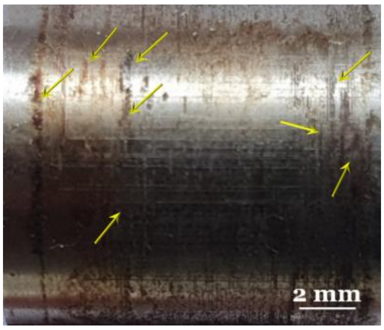


Figure 7. The macroscopic image of the shaft seat surface after wear testing (arrows indicate regions of fretting wear occurrence).

The roughness profile measured across the analysed region clearly confirms these morphological observations. Within the zone of intensive fretting wear, an elevated profile level and increased amplitude of surface irregularities are observed compared to other areas. This indicates an increase in effective surface roughness, resulting from the presence and compaction of wear products as well as localised plasticisation of the material.

The modification of surface topography leads to changes in load transfer conditions within the contact zone. The resulting geometric irregularities act as stress concentrators, promoting localised increases in both tangential and normal stresses. Consequently, resistance to relative motion increases, which is directly reflected in the observed increase in the press-out force after completion of fatigue testing.

Observations of the entire shaft seat surface reveal that fretting wear marks are present on both sides of that region (Figure 7); however, their distribution and morphological characteristics exhibit clear spatial diversity.

On the left side of the shaft seat, a well-developed, continuous wear zone is noted in the form of a ring approximately 4 mm wide, comprising the entire circumference of the shaft. That part of the surface was previously identified as the zone of intensive fretting wear. That area is distinguished by a homogeneous structure and the presence of wear products that cover the surface continuously. Such a distribution indicates stable operational conditions conducive to maintaining microdisplacements along the entire contact circumference.

On the right side of the shaft seat, fretting wear exhibits a discontinuous character, occurring in the form of localised, irregular areas of varying intensity. These traces appear as point-like or band-shaped clusters of wear products, distributed heterogeneously at the circumference. This type of wear indicates localised exceedance of the conditions required for fretting wear initiation, without the development of a continuous process.

The observed asymmetry in the wear distribution is directly related to the nature of the loading in the form of rotational bending. The time-varying distribution of normal stresses and the amplitude of microdisplacements lead to the formation of zones with different operational conditions: from regions where conditions for fully developed fretting wear are met, to areas where the process remains limited or at an initial stage.

In the zone of intensive fretting wear, dominant mechanisms include cyclic shearing of microirregularities, generation and transport of wear products, and their compaction within the contact zone. In localized regions, this process is limited to the formation of isolated wear sites without further spatial development. The resulting heterogeneity of the near-surface layer leads to diversity in localised mechanical properties and stress concentration, which promotes the initiation of microcracks and the development of fretting fatigue.

Continuing the macroscopic analysis, microscopic examinations of the shaft surface in the zone of intensive fretting wear were conducted (Figure 8), enabling identification of the dominant degradation mechanisms at the microstructural level.

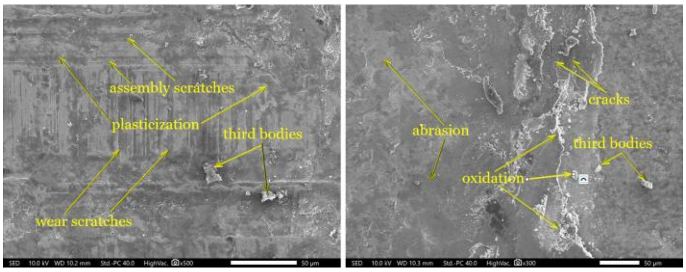


Figure 8. The microscopic image of the shaft surface in the zone of intensive fretting wear.

On the seat surface, the simultaneous occurrence of multiple wear forms characteristic of the fretting phenomenon is observed. In addition, parallel traces corresponding to the direction of relative displacement are visible, indicating the repetitive nature of tangential interactions. Within these regions, both assembly marks and service-induced traces have been identified, confirming the superposition of initial surface topography and wear processes.

Plastic deformation of the material is also evident in the analysed area, resulting from the cyclic action of tangential and normal stresses, which leads to localised material flow in the near-surface layer. This process promotes both the modification of the geometry of irregularities and the formation of zones with increased dislocation density, which constitute potential sites for damage initiation.

At the same time, numerous wear scratches and abrasive wear traces are present, indicating the involvement of solid particles in the degradation process. These particles are observed both as loose fragments and as compacted clusters within the surface.

The presented images also reveal regions where localised crack initiation occurs. These cracks develop within the near-surface layer, often in the vicinity of accumulated wear products or in regions of increased concentration of deformations. Their orientation indicates a dominant influence of tangential stresses and a complex stress state characteristic of fretting.

Localised cracks propagating within the near-surface layer were also observed. Their presence is particularly evident in areas of wear product accumulation and in regions of intense plastic deformation. These cracks represent an early stage in the development of fatigue damage typical of fretting fatigue.

The presence of oxidation products in the form of irregular, contrasting regions is also noted, confirming the involvement of tribochemical processes. These products are formed as a result of reactions between the material surface and the surrounding environment, and are subsequently introduced into the contact zone, where they participate in further wear processes. The presence of those products affects friction conditions and the localised stress distribution, contributing to further changes in the near-surface layer.

To complete the morphological observations, a localised chemical composition analysis of the wear products was performed using EDS microanalysis (Figure 9, Table 1). Point analysis was conducted in several representative areas of the shaft surface corresponding to different forms of wear products, enabling correlation of their chemical composition with the progression of tribological processes occurring within the contact zone.

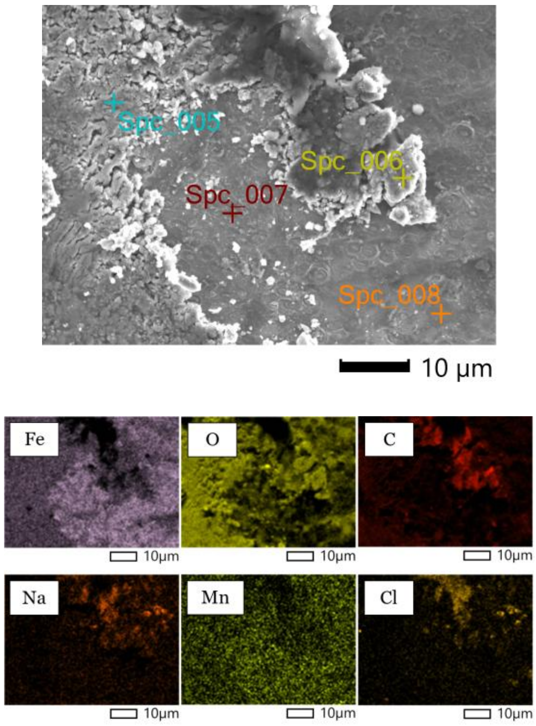


Figure 9. The chemical composition of wear products on the shaft surface.

Table 1. The chemical composition of wear products on the shaft surface.

	Spc_005		Spc_006		Spc_007		Spc_008	
	Mass %	Atom %	Mass %	Atom %	Mass %	Atom %	Mass %	Atom %
Fe	71.98	42.87	51.78	24.94	53.78	26.62	92.11	79.56
O	27.14	56.46	39.68	68.98	39.92	66.54	7.22	19.85
Na	-	-	3.73	4.39	3.79	4.39	-	-
Mn	0.88	0.67	1.17	0.43	0.87	0.49	0.67	0.59
Cl	-	-	3.64	1.26	1.64	1.96	-	-

The obtained results indicate a clear diversity in chemical composition depending on the location of analysis. In areas corresponding to compact and relatively homogeneous surface regions, iron is the dominant component, suggesting direct exposure of the native material or the presence of slightly transformed wear products. In these locations, the oxygen content is limited, indicating a low degree of material oxidation.

In contrast, in regions where an accumulation of wear products with a more developed structure is observed, the proportion of oxygen atoms increases significantly, accompanied by a reduction in iron content. Such a chemical composition distribution indicates the presence of iron oxides formed as a result of cyclic mechano-chemical interactions. This process is characteristic of fretting wear, where repeated microdisplacements lead to material fragmentation, followed by its oxidation under conditions allowing oxygen access to the contact zone.

The presence of sodium and chlorine atoms was also detected at selected points, which may indicate the influence of environmental contaminants or residues from technological processes. The presence of those atoms may affect the course of tribochemical reactions and modify the properties of the resulting wear products.

Elemental distribution maps confirm the heterogeneous nature of the analysed layer. Regions with an increased concentration of oxygen correspond to areas where wear products are present, whereas iron atoms dominate in less transformed regions. Such a distribution indicates the coexistence of different stages of surface degradation, ranging from the native material, through zones of initial wear, to areas with a well-developed layer of oxidized products. These observations are consistent with the fretting wear mechanism, in which material particles generated by the shearing of irregularities undergo oxidation and are subsequently reintroduced into the contact zone, and take part in the further wear process. As a consequence, an intermediate layer composed of oxidized wear products is formed, which modifies friction conditions and the localised stress distribution, creating favourable conditions for the initiation of microcracks and the development of fretting fatigue.

6. Observations of the contact surface of the sleeve-shaft connection

In order to formulate a fretting wear mechanism, it is necessary to identify the changes occurring within the contact zone of a press-in connection operating under rotational bending conditions. For this purpose, cross-sections of the interaction area between the components were analysed, enabling direct assessment of changes in the near-surface layer as well as the behaviour of wear products during operation (Figure 10).

The observed contact zones in the tested connection exhibit variability along the length of the connection, resulting from cyclic shaft deflection. This leads to a heterogeneous distribution of normal contact pressures and amplitudes of tangential displacements along the mating surfaces, which directly determines the conditions for the formation, transformation, and transport of wear products within the gap.

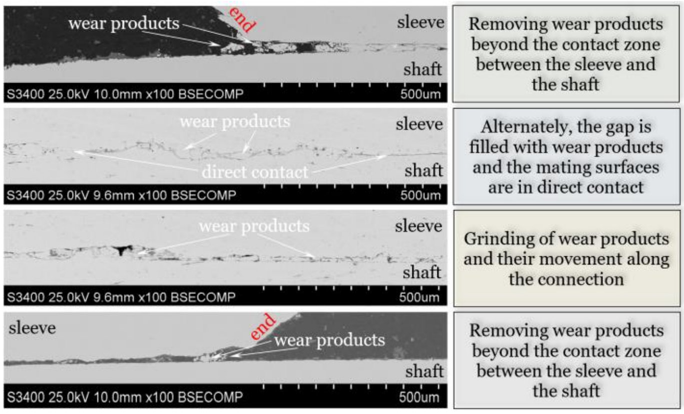


Figure 10. Microscopic images of the contact surfaces of the press-in connection.

In the edge areas of the connection, the domination of the phenomena associated with localised opening of the microcontact is noted. As a result of cyclic shaft deflection, normal contact pressures decrease in these areas, while the amplitude of tangential displacements increases. Consequently, wear products are removed beyond the contact zone. This process leads to the exposure of the material surface and the persistence of active adhesive and abrasive mechanisms. A characteristic effect of these interactions is the presence of intensive ring-shaped wear zones located near the edges of the connection.

Moving away from the edge toward the central region of the connection, a gradual change in operational conditions is observed. An increase in normal contact pressure and a reduction in the amplitude of microdisplacements are conducive to the retention of wear products within the contact zone. In these areas, wear particles accumulate and form an intermediate layer that partially separates the mating surfaces. Under such conditions, the load is largely transmitted through this layer, and its mechanical properties determine the localised course of tribological interactions.

In the central part of the connection, where contact pressures reach their highest values, the layer of wear products exhibits the greatest stability. Intensive fragmentation and tribochemical transformations of particles are also observed, leading to the formation of a fine-grained structure with an increased content of oxides. The presence of such products results in an increased contribution of abrasive mechanisms and further modification of the near-surface layer.

The spatial diversity of operational conditions leads to the formation of a system in which the processes of generation, transport, and removal of wear products occur simultaneously, but with different intensities depending on location. In the edge regions, the removal of wear products dominates, whereas in the central part their accumulation and stabilisation prevail. Such a distribution corresponds to the observed heterogeneous nature of fretting wear.

7. Mechanism of fretting wear development

In the available literature on fretting wear, no single, unambiguous mechanism for the development of this phenomenon in press-in connections has yet been established. This is due to the complex nature of fretting wear and its dependence on the factors discussed in Section 2. Consequently, the description of the fretting development mechanism should be related to the specific operating conditions of the connection under investigation.

Based on the experimental results presented in the article, together with observations of the surface and cross-sections of the contact zone, a mechanism of fretting wear development was proposed for a shaft–sleeve press-in connection subjected to cyclic rotational bending. This mechanism comprises a sequence of phenomena occurring simultaneously at the interface between the mating components and within the near-surface layer of the material, leading to the gradual degradation of surface topography, to changes in the interaction conditions of the connection components, and to the initiation of fatigue damage. The mechanism was described in six stages and presented in Table 2.

- In the initial state, the real contact between the shaft and sleeve surfaces occurs mainly at the asperity peaks left by machining. Under cyclic rotational bending, small relative tangential displacements arise within the interference zone, initiating the shearing and flattening of the asperity peaks. This is accompanied by local plastic deformation of the near-surface layer and the detachment of small material fragments, which constitute the first wear products. As a result, the original surface topography begins to undergo gradual degradation already at the early stage of the process (Stage I).
- With an increasing number of loading cycles, the generated wear particles are displaced along the contact gap, fragmented and oxidised. According to the results of the chemical analyses, they consist primarily of iron and oxygen, indicating the presence of iron oxides formed under combined mechanical and chemical interactions. Under the action of micro-displacements, the wear products become an active element of the tribological process. They may partly separate the mating surfaces, but at the same time, owing to their abrasive properties, they accelerate further material degradation and affect the local friction conditions and stress distribution within the contact zone (Stage II).
- At the edges of the connection, where the amplitude of micro-slip is greater and the local normal pressures are lower, wear products are removed from the contact zone. This leads to the exposure of the native material and the

persistence of intense adhesive–abrasive interactions. As a result, the most severe fretting wear zones develop precisely near the edges of the connection. Moving away from the edge towards the central part of the connection, the contact pressure increases while the amplitude of micro-slip decreases, which promotes the retention of wear products within the contact gap and the formation of a thin intermediate layer composed of fragmented and oxidised particles. Within the same contact region, areas filled with wear products may coexist with local zones of direct shaft–sleeve contact, where the contact gap remains very thin or disappears completely (Stage III, Stage IV).

- At a further stage of the process, progressive surface degradation leads to the accumulation of plastic strain, the development of scratches and wear grooves, and the initiation of microcracks in the near-surface layer. Their presence in regions of intense deformation and in the vicinity of accumulated wear products indicates that fretting in a press-in connection acts as a mechanism initiating fatigue degradation. As a result, the interaction conditions of the connection components deteriorate, the local stress distribution changes, and the fatigue resistance of the connection is reduced (Stage V).
- Ultimately, the development of fretting wear leads to the degradation of surface topography, to changes in load transfer conditions, and to a gradual weakening of connection integrity. This may be accompanied both by a local increase in resistance during disassembly, resulting from the compaction of wear products, and by local loosening of the contact caused by material loss and changes in the geometry of the contact layer (Stage VI).

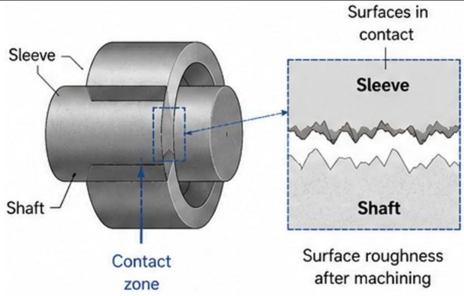
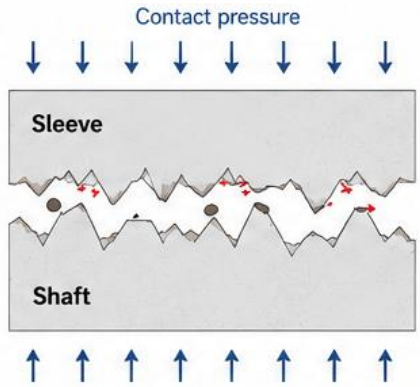
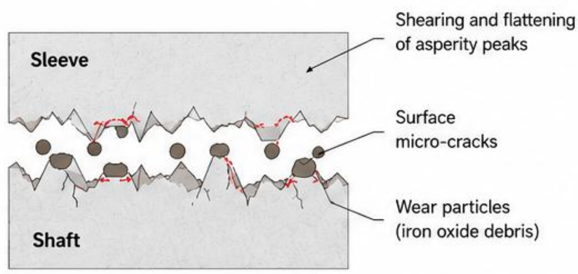
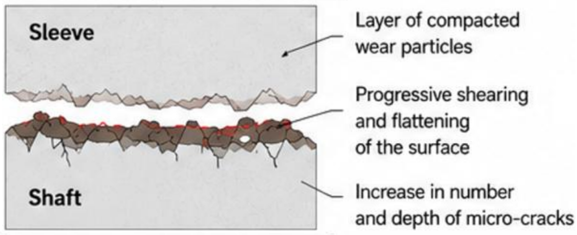
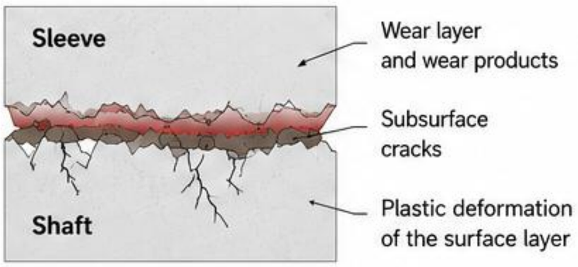
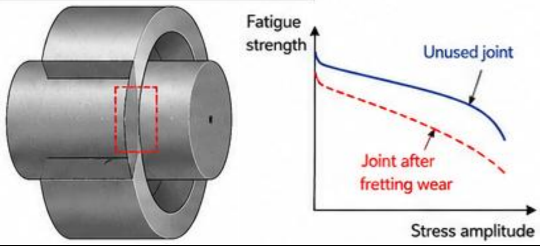
8. Practical implications for the operation of press-in connections

The obtained results provide a basis for translating the identified degradation mechanisms into practical implications for the operation, diagnostics, and maintenance of press-in connections. The conducted analyses demonstrated that fretting wear should be regarded as a process leading to gradual changes in the contact conditions, to the modification of the load transfer mechanism, and to a reduction in the fatigue resistance of the connection. Consequently, the development of fretting wear may result not only in damage to the mating surfaces but also in the progressive deterioration of the functional integrity of the connection and an increased risk of fatigue damage under prolonged cyclic loading. Therefore, fretting wear should be considered a phenomenon of considerable diagnostic and operational significance, and early identification of that kind of wear may play a key role in ensuring the durability and operational safety of press-in connections.

The regions near the edges of the press-in connection are of particular practical importance. The observations demonstrated that these regions are especially susceptible to the initiation and intensification of fretting wear due to the locally increased amplitude of relative micro-displacements and the removal of wear products from the contact zone. As a result, the native material becomes exposed and remains subject to active adhesive–abrasive interactions, which promote further surface degradation and crack initiation. The edge regions of the press-in connection should therefore be regarded as critical areas during in-service inspections, as they are the locations where the earliest signs of progressive degradation are most likely to appear. From a practical perspective, this indicates that inspection procedures should be focused on assessing the condition of the surfaces adjacent to the edges of the press-in connection, where the risk of stress concentration, microcrack development, and local loss of connection integrity is greatest.

The results also indicate that the degradation of the press-in connection is accompanied by measurable changes in its mechanical response. The observed increase in the press-out force after fatigue loading demonstrates that the development of fretting wear alters the load transfer conditions within the contact zone through the accumulation and compaction of wear products, material plasticisation, and the formation of surface irregularities that promote the mechanical interlocking of the mating components. Consequently, changes in the assembly and disassembly force characteristics may be interpreted as an indirect indicator of the progressive degradation of the contact layer. Although such measurements are not always feasible under in-service conditions, those measurements may provide valuable diagnostic information during maintenance, overhaul, or post-service connection examinations that are critical to the operational safety of the system. For components subjected to a high number of loading cycles, monitoring changes in the disassembly force may support the assessment of the degree of degradation and facilitate the identification of connections requiring more detailed inspection.

Table 2. Mechanism of fretting wear development.

No.	Description	Scheme
1	***Stage I:*** Assembly of the connection, Real contact between the mating components	
2	***Stage II:*** Cyclic loading induces micro-slip and the shearing of micro-asperities Formation of the first wear products, followed by their displacement and oxidation	
3	***Stage III:*** Accumulation of wear products Displacement of wear products along the connection and their partial removal beyond the contact zone	
4	***Stage IV:*** Accumulation of wear products and further degradation of the surface and near-surface layer through the development of microcracks	
5	***Stage V:*** Accumulation of plastic deformation and the development of scratches and wear grooves Further propagation of fatigue cracks	
6	***Stage VI:*** Increase in the force required to separate the connection components Reduction in fatigue strength Potential loss of connection integrity due to local loosening	

Another important practical finding is the observed non-uniform development of fretting wear. The fretting wear marks identified on the wheel seat surface of the shaft and in the cross-sections of the contact zone confirmed that this process does not develop uniformly along the entire length of the press-in connection. Within the same contact region, areas of severe wear, wear product accumulation, direct contact between the mating components, and microcrack initiation may coexist. Consequently, the assessment of the operational condition of a press-in connection should take into account both the global parameters and local examination of the contact surfaces, particularly in regions most susceptible to stress concentration and wear development. This highlights the need for targeted inspection of the most highly stressed regions, especially in components operating under bending or complex cyclic loading conditions. These relationships are illustrated in Fig. 11.

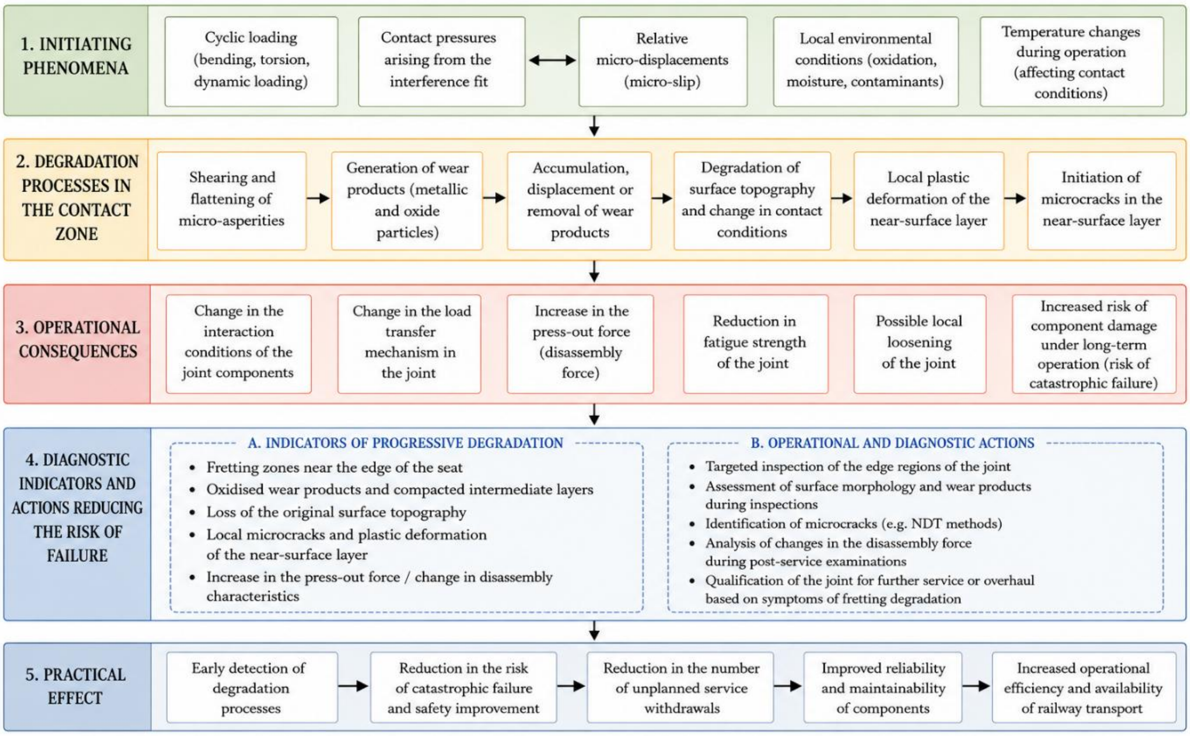


Figure 11. Block diagram of the operational implications of fretting wear in a press-in connection.

The identification of oxidised wear products in the form of iron oxides is also of considerable practical importance. Their presence confirms that oxidation is an integral component of the degradation process, while the wear products themselves play a detrimental role within the connection interface. Owing to their high hardness, they intensify abrasive interactions and modify the local stress state. Consequently, the accumulation of oxidised wear products within a press-in connection should be regarded as an indicator of advanced fretting wear development. In practical terms, the presence of oxidation products, local discolouration, compacted wear product layers, or characteristic ring-shaped wear zones may serve as important warning indicators of progressive degradation.

One of the most significant findings from the perspective of structural durability is the observed initiation of microcracks in regions affected by fretting wear. The results indicate that fretting wear in press-in connections acts as a precursor to fatigue damage, as local surface degradation, plastic deformation, and stress concentration associated with the presence of wear products create favourable conditions for crack initiation. Consequently, the operational significance of fretting wear extends beyond material loss alone and includes a direct contribution to the reduction in the fatigue life of the connection. In components subjected to repeated cyclic loading, localised surface damage may eventually develop into structurally significant cracks if not detected at an early stage.

The obtained results enabled the identification of indicators of progressive degradation in press-in connections that may be used to assess their operational condition. The most important of these indicators include the presence of ring-shaped or localised fretting wear zones near the edges of the press-fit connection, the loss of the original surface topography, the accumulation of oxidised wear products, changes in the assembly and disassembly force characteristics, and the occurrence of local microcracks and plastic deformation within the near-surface layer. The incorporation of these indicators into diagnostic procedures may facilitate the early detection of degradation processes, the assessment of the degree of connection deterioration, and the identification of components requiring repair or replacement before reaching a condition that could compromise operational safety. The principal practical implications derived from the present study are summarised in Table 3.

Table 3. Practical implications of the identified fretting wear mechanisms for the operation of press-in connections.

Observed phenomenon / research finding	**Operational significance**	**Diagnostic implications and practical recommendations**
Concentration of fretting wear in the edge regions of the press-in connection	Increased local stress concentration and a higher risk of microcrack initiation and fatigue damage	The edge regions of the connection should be regarded as critical areas during in-service inspections and post-service examinations.
Removal of wear products beyond the contact zone near the connection edges	Exposure of the native material and maintenance of intensive adhesive–abrasive interactions, promoting further surface degradation	Ring-shaped wear zones near the edges of the press-in connection may be regarded as an early indicator of progressing fretting wear.
Accumulation and compaction of wear products in the central region of the connection	Modification of load transfer conditions, increased abrasive interactions and changes in the local stress distribution	The presence of compacted wear products and oxidised intermediate layers should be considered an indicator of advanced fretting wear development.
Degradation of the original surface topography and development of surface irregularities	Deterioration of the interaction conditions between the mating components, increased local contact stresses and greater susceptibility to further damage	Assessment of the surface morphology may provide valuable information for evaluating the degree of degradation of the press-in connection.
Presence of wear products containing iron oxides	Confirmation of tribo-oxidation processes and the presence of abrasive particles contributing to the intensification of wear	Oxidation products, local discolouration and oxide-rich layers may be treated as warning indicators of active fretting wear development.
Initiation of microcracks in the near-surface layer	Onset of fatigue degradation and an increased risk of crack propagation leading to structural damage	The detection of microcracks in regions affected by fretting wear should be regarded as an indicator of an increased risk of further degradation during service.
Increase in the press-out force after fatigue loading	Modification of the load transfer mechanism within the contact zone caused by the compaction of wear products, local plastic deformation and mechanical interlocking of the mating surfaces	Changes in the force characteristics during connection disassembly may serve as an indirect indicator of the degradation of the contact layer.
Non-uniform development of fretting wear along the connection	Coexistence of regions exhibiting severe wear, wear product accumulation and local direct contact complicates the assessment of the connection condition	Diagnostic procedures should include targeted inspection of the most highly loaded regions rather than relying solely on the overall assessment of the connection.

The obtained results indicate that the effective mitigation of the failure risk in press-in connections requires the identification and monitoring of indicators of progressive degradation. Particular attention should be paid to fretting wear zones developing near the edges of the press-in connection, to the accumulation of wear products, to changes in surface topography, to local microcracks, and to changes in the force characteristics during connection disassembly. The incorporation of these indicators into diagnostic procedures enables the earlier detection of degradation processes, optimisation of maintenance strategies, and the reduction of the risk of fatigue damage leading to component failure.

From a broader operational perspective, the present findings indicate that the effective management of the service life of press-in connections requires consideration of the progressive and non-uniform nature of fretting wear. Diagnostic procedures should include targeted assessment of the edge regions of the press-in connection, analysis of surface morphology, identification of wear products, and evaluation of local damage within the near-surface layer. During post-service examinations, analysis of changes in the force characteristics during connection disassembly may also provide valuable complementary diagnostic information. Such an approach enables the earlier detection of degradation processes, more effective maintenance planning, and a reduction in the risk of fatigue damage that may ultimately lead to component failure.

The practical significance of the present findings is particularly evident in press-in connections operating under prolonged cyclic loading, such as those used in railway wheelsets. The application of the proposed diagnostic indicators may facilitate the earlier identification of degradation processes, reduce the number of unplanned service interruptions, minimise the risk of catastrophic failures, and contribute to improved reliability and maintenance efficiency of such systems.

9. Summary and conclusions

The conducted analysis of the degradation of press-in connections has shown that their service life is determined by the complex interaction of mechanical, material, and environmental factors. Particular importance is attributed to the nature of the loads acting on the system, including cyclic bending, variable contact forces, and microdisplacements within the contact zone. These conditions promote the initiation and development of fretting wear, which constitutes the dominant degradation mechanism in the connections under investigation,

Experimental investigations revealed significant changes in the tribological properties of the connection after cyclic loading. The observed increase in the press-out force and the change in its characteristics indicate modification of the material surface layer, resulting from the accumulation of wear products and localised plastic deformation. Surface topography analysis confirmed complete degradation of the original geometric structure in zones of intensive fretting wear, as well as an increase in effective surface roughness.

A pronounced spatial diversity of wear was also identified, associated with the distribution of stresses and microdisplacements resulting from the loading conditions. In the edge regions, the removal of wear products and active adhesive-abrasive mechanisms predominated, whereas in the central part the accumulation of those products and the formation of an intermediate layer with a significant influence on contact conditions were observed.

Microscopic investigations and chemical composition analysis confirmed that fretting comprises both mechanical surface damage and tribochemical processes leading to the formation of iron oxides. The coexistence of these mechanisms results in progressive degradation of the near-surface layer and a reduction in the fatigue resistance of the material.

Based on the presented research results and the conducted analysis, the following final conclusions can be formulated.

- The degradation of press-in connections is of a multifactorial nature and results from the coupled interaction of operational loads, material properties, and environmental conditions.
- Fretting wear constitutes the key mechanism responsible for the initiation and development of damage within the contact zone, leading to modifications of surface topography and deterioration of load transfer conditions.
- Cyclic loads induce microdisplacements that initiate degradation processes and promote the generation and accumulation of wear products.
- The distribution of fretting wear is heterogeneous and depends on localised contact conditions, resulting in the formation of zones with varying degrees of degradation.
- Wear products, particularly iron oxides, play a significant role in the degradation process by influencing friction conditions and the localised stress distribution.
- Fretting contributes to the initiation of microcracks in the near-surface layer, leading to a reduction in fatigue strength and potentially resulting in the development of fatigue-related damage.

In addition to their scientific value, the present findings also have considerable practical potential. The proposed mechanism of fretting wear development and the identified degradation indicators provide a basis for improving the assessment of the technical condition of press-in connections and for developing more effective diagnostic procedures aimed at the early detection of degradation processes. The findings may also support the development of condition-based maintenance strategies, enabling more efficient planning of inspections and overhaul activities while reducing the number of unplanned service interruptions. The implementation of the proposed approach has the potential to extend the service life of press-in connections, improve their operational reliability, and reduce the risk of fatigue damage leading to component failure. Furthermore, the identified relationships may provide a foundation for the development of service life prediction models and decision-support tools for maintenance management. Although the primary objective of the present study was to improve the understanding of the degradation mechanism rather than to quantify service life, the proposed approach provides a sound basis for future development of diagnostic criteria and maintenance strategies aimed at extending component life and reducing the probability of in-service failures. The proposed methodology may be particularly valuable for components operating under prolonged cyclic loading, such as railway wheelsets, where the early identification of degradation processes can contribute to improved operational safety, reduced maintenance costs, and more efficient life-cycle management.

References

1. Mohabeddine A, Correia J, Montenegro P A, De Jesus A, Castro J M, Calçada R, Berto F. An approach for predicting fatigue life of CFRP retrofitted metallic structural details. *International Journal of Fatigue* 2022; 154: 106557. https://doi.org/10.1016/j.ijfatigue.2021.106557.
2. Zeng D, Meng Y, Dong Y, Zhang X, Zou L, Lu L. Fretting fatigue analysis and residual strength evaluation of railway axles containing defects of natural crack and micro-sinking. *Engineering Fracture Mechanics* 2025; 313: 110678. https://doi.org/10.1016/j.engfracmech.2024.110678.
3. Helal W M K, Wang G X, Su Y P. Orthogonal Simulation Test for Evaluating Fretting Wear in Low-Speed Diesel Engine Connecting Rods. *International Journal of Engineering Research in Africa* 2025; 74: 101-114. https://doi.org/10.4028/p-Ua0q6f.
4. Le Falher M, Fouvry S, Arnaud P, Maurel V, Antoni N. Fretting-fatigue of shrink fit lug-bush assemblies: Interference-fit effect. *Tribology International* 2023; 186: 108581. https://doi.org/10.1016/j.triboint.2023.108581.
5. Szkoda M., Michnej M. A method of fretting wear reduction in an automatic wheel set gauge change system. *Engineering Failure Analysis* 2014; 45: 363-375. https://doi.org/10.1016/j.engfailanal.2014.07.009.
6. Wang Z, Wang Z, Bai X, Zhang X, Wang Y. Effect of interference fit on dynamic characteristics of spindle rotor system. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 2022; 44: 316. https://doi.org/10.1007/s40430-022-03545-4.
7. Ren Y, Cao J, Tang P, Yang P, Li M, Li Z, Peng J, Shen H, Fan X, Zhu M. Probing fretting wear behavior of gauge-changeable spline axle under rotational bending loads. *Engineering Failure Analysis* 2024; 166: 108846. https://doi.org/10.1016/j.engfailanal.2024.108846.
8. Li T, Jiang C, Gong S, Song T, Zhang Y. The Influence of Structural Design Parameters on the Retention Force and Interference-Fit Reliability of Connecting Rod Bushings. *Applied Science* 2026; 16: 1843. https://doi.org/10.3390/app16041843.
9. Zou L, Lu L, Li Y, Yang K, Zhao H, Dong Y, Zeng D. Experimental and numerical study on press-fitted railway axles: Fretting fatigue behaviour in the very high cycle regime. *International Journal of Fatigue* 2023; 166: 107243. https://doi.org/10.1016/j.ijfatigue.2022.107243.
10. Zou L, Zeng D, Li Y, Yang K, Lu L, Yuan C. Experimental and numerical study on fretting wear and fatigue of full-scale railway axles. *Railway Engineering Science* 2020; 28(4): 365–381. https://doi.org/10.1007/s40534-020-00224-9.
11. Shu Y, Yang G, Liu Z, Dong L. High-speed train axle fretting fatigue scaling experiment research and damage analysis. *Engineering Failure Analysis* 2024; 162: 108317. https://doi.org/10.1016/j.engfailanal.2024.108317.
12. Wang H, Zhang L, Zhang W, Li H, Chi H, Yang K, Zhou J, Ai L. Research on node-improved energy dissipation wear model for fretting fatigue prediction in railway press-fit shaft. *Wear* 2025; 574-575: 206104. https://doi.org/10.1016/j.wear.2025.206104.
13. Zhang Q, Zuo Y, Hu Z, Xu Y, Liu X. Advances and Challenges in Interference-Fit Technology for Enhancing the Mechanical Performance of Joints. *Journal of Materials Engineering and Performance* 2025; 34: 3585–3607. https://doi.org/10.1007/s11665-024-10418-5.
14. Pan A-X, Wen C, Wan H, Shi P, Bi Q, Jia X, Tao P, Liu X, Gong Y, Yang Z-G. Premature Fatigue Failure Analysis of Axle in Permanent Magnet Direct-Drive Electric Locomotive. *Materials* 2025; 18: 3747. https://doi.org/10.3390/ma18163747.
15. Zeng D, Dong Y, Zhao H, Guan M, Ren M, Li X, Zhang J, Lu L. Investigation on fretting fatigue crack initiation of scale press-fitted railway axle containing axial defects. *Tribology International* 2026; 216: 111581. https://doi.org/10.1016/j.triboint.2025.111581.
16. Shu Y, Liu Z, Yang G. Finite element simulation of fretting wear on railway axle press-fit specimens. *Tribology International* 2023; 178A: 108024. https://doi.org/10.1016/j.triboint.2022.108024.
17. Kowalski S. Application of dimensional analysis in the fretting wear studies. *Journal of the Balkan Tribological Association* 2016; 22(4-

I): 3823–3835.

18. Xu T, Lu L, Zeng D, Zou L. Fretting fatigue crack growth simulation and residual life assessment of railway press-fitted axle. *Engineering Fracture Mechanics* 2023; 286: 109290. https://doi.org/10.1016/j.engfracmech.2023.109290.
19. Dong Y, Zeng D, Zhao H, Wu P, Song Y, Li X, Lu L. Fretting fatigue strength evaluation of scaled press-fitted railway axle containing a circumferential groove defect. *International Journal of Fatigue* 2025; 194: 108824. https://doi.org/10.1016/j.ijfatigue.2025.108824.
20. Haragâș S, Buiga O, Tudose L. Experimantal validation of the new theoretical model of interference fits. *Acta Technica Napocensis Series-Applied Mathematics Mechanics and Engineering* 2023; 66 (II). 175-182.
21. Zhang H, Liu Y, Dai S, Li F, Dong G. Optimization of boundary slip region on bearing sliders to improve tribological performance. *Tribology International* 2022; 168: 107446. https://doi.org/10.1016/j.triboint.2022.107446.
22. Izmailov V V, Novoselova M V. On Some Criteria Defining Fretting. *Journal of Friction and Wear* 2024;45: 267–273. https://doi.org/10.3103/S1068366624700405.
23. Shu Y, Yang G, Liu Z. Experimental study on fretting damage in the interference fit area of high-speed train wheels and axles based on specimen. *Engineering Failure Analysis* 2022; 141: 106619. https://doi.org/10.1016/j.engfailanal.2022.106619.
24. Suo H, Wei Z, Luo B, Wang L, Hang K, Liang B, Deng Cheng H. Interfacial wear damage mechanism between Ti-alloy and Al-alloy in interference-fit joint and influence of surface coatings: Experimental and numerical study. *Engineering Failure Analysis* 2023; 143B: 106931. https://doi.org/10.1016/j.engfailanal.2022.106931.
25. Peng G, Huang X, Zhou L, Zhou G, Zhou H. Solid-liquid two-phase flow and wear analysis in a large-scale centrifugal slurry pump. *Engineering Failure Analysis* 2020; 114: 104602. https://doi.org/10.1016/j.engfailanal.2020.104602.
26. Bian X, Wei C, Liu Y. Research on the fretting contact fatigue strength of interference fit in high speed rail traction motor shafts. *Engineering Failure Analysis* 2024; 157: 107875. https://doi.org/10.1016/j.engfailanal.2023.107875.
27. Chen X, Wang J, Lu L, Zou L, Xu T, Dong Y, Zhao H, Zeng D. Effect of interference magnitude on fretting wear and fatigue strength of scaled press-fitted railway axles. *Wear* 2024; 546-547: 205347. https://doi.org/10.1016/j.wear.2024.205347.
28. Li Y, Xie G, Sun X, Jingcao C, Wu X, Zhang Y, Yu C, Du P. A review on fretting wear/fatigue behavior, protective measures, and application examples of typical alloy materials. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 2025; 239(10): 1261-1290. https://doi.org/10.1177/13506501241313249.
29. Kowalski S. The Use of PVD Coatings for Anti-Wear Protection of the Press-In Connection Elements. *Coatings* 2024; 14(4): 432. https://doi.org/10.3390/coatings14040432.
30. Irena K A, Lemu H G, Kedir Y A. Effect of Interference Size on Contact Pressure Distribution of Railway Wheel Axle Press Fitting. *Designs* 2023; 7: 119. https://doi.org/10.3390/designs7050119.
31. Okamura Y, Ikoma K, Nagatomo T. Preventive measures of fretting wear in railway axle bearings: Combined effect of grooving and amorphous carbon coating towards their backing rings. *Engineering Failure Analysis* 2022; 137: 106356. https://doi.org/10.1016/j.engfailanal.2022.106356.
32. Xu G, Li X, Zhu Y. Support stiffness effects on damage behavior of thin-walled composite interference-fit joints in the installation. *Engineering Failure Analysis* 2024; 156: 107841. https://doi.org/10.1016/j.engfailanal.2023.107841.
33. Michej M., Guzowski S. Fretting wear simulation in a clamped joint based on the example of a rail vehicle wheel set. *Wear* 2019; 438-439: 102654. https://doi.org/10.1016/j.wear.2018.12.083.
34. K C G, V K, M S, R R, Panda R. Evaluating the effectiveness of interference fit connections in automotive transmission component design. *Mechanics Based Design of Structures and Machines* 2026; 54(1). https://doi.org/10.1080/15397734.2025.2517876.
35. Ren Y, Cai Z, Nie H, Dong Y, Shen H, Xu X, Zhu M. Fretting wear behavior of different surface modified layers of a tight fit spline used for a gauge-changeable railway Vehicle. *Tribology International* 2024; 193: 109359. https://doi.org/10.1016/j.triboint.2024.109359.