Fretting fatigue and wear of mechanical joints: Literature study

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Abstract. Most mechanical connections are in one way or another exposed to some form of tear, wear, corrosion and fatigue, and likely to fail over time. If the contacting surfaces in a connection are exposed to tangential loading due to vibrations, small amplitude displacements called fretting can be induced at the surface, and might result in crack nucleation and possible propagation. The review and analysis reported herein are based on review of a wide range of studies reported in the literature during the last 25 years, which look into earlier studies around fretting fatigue in interference fit connections. In addition, a new method on how to obtain an interference fit is being mentioned as a possible way of increasing the joints fretting fatigue life. Previous investigations show clearly positive effects of finding and operating with the correct combinations of interference fit levels, palliative treatments and material choices to increase the fretting fatigue life.

1. Introduction

In most mechanical systems, there are needs for power transmission and connection techniques using various shapes and dimensions, and the most familiar transmission systems might be of electrical or mechanical type. Among those, spline, dovetail, riveted, interference fitted, pre-stressed and open-hole pin/bolt connections are the typical mechanical joint types [1].

In general, with an increasing transmitted power, the mechanical connections are exposed to increasing loads and stresses at contact areas, and the probability for damages at the contact areas is therefore increasing. Already early in the Nineteenth century, when the railway still had a very important role and position, it was known that repetitive loads caused failure in the axles and connected components. At the time, the number of axles in England was around 200 000, and in the middle of the 19th century, hundreds of people lost their lives in accidents all over Europe due to axle failures [2].

Many studies have been conducted during the last decades to analyse and increase the understanding and perception of the mechanisms that work in the contact areas and surfaces of different mechanical connections, like train wheels and axles (wheel seats, gear seats, brake disk seat) [3, 4]. The press-fitted parts on a railway vehicle are extremely important and critical because of the easily initiation of cracks in those areas and spots [2, 5, 6].

This literature study aims to look deeper into previous studies and investigations on the mechanisms of damages that occur in interference fitted connections of mechanical systems with relative movements between the connected parts. A special focus will be on fretting fatigue, what the causes are, and what can be done to prevent or to avoid factors that reduce the life of the component and the system. In addition, this review aims to have a critical approach to the previous studies and identify research issues.
and ways to approach problematics around these connection types. The review will focus on a few specific mechanical systems, but still mainly on interference fit challenges that could occur in mechanical systems with interference fitted couplings.

2. Mechanical connection techniques

There are a variety of different mechanical connections in use, depending on the type of industry, type of machine, equipment or joint, type and level of loads, materials involved, etc. Different connection types transfer forces and loads between different parts in the connection in different ways, and with an increasing power, the stress level increases, with damage and reduced fatigue life as a possible result. The damages in a contact surface can range from minimal surface or topographic changes to severe crack initiation, which again can lead to crack propagation if exposed to cyclic and/or dynamic forces. Such dynamic forces can originate from the type of operation and type of connection the system is designed for, or from external sources not within the original operational scope, like vibrations. It is well known that crack initiation at a contact surface, with crack propagation due to dynamic loading results easily in fretting fatigue and reduced fatigue life [3, 4, 7-10].

2.1. Interference fit connection

Interference fit, also known as press fit or friction fit, is a fastening method where two parts, typically circular cross section shape, are pushed together (one into the other) and kept in place due to the pressure between them. Typically, the inner part will have a nominal outer diameter slightly greater than the nominal inner diameter of the outer part, and when pushed or forced together the contact friction forces keep the parts from moving relative to each other (nominally). The level of interference depends on the negative difference in nominal diameters.

Figure 1 shows a principle sketch for an interference fit. The interference fit causes the bore to expand and induces the tensile tangential (tangent to the bore surface) stresses, i.e. Hoop pre-stresses at the bore edge. This increases the mean stress level but this pre-stress considerably reduces the magnitude of the local cyclic stress, meaning the alternating stress, which has a much more fatigue life reducing effect [11]. An advantage of this kind of connection is the superior level of possible torque transmission between two assembled parts, but the pressure distribution is the source responsible for fatigue failure.

![Figure 1](image)

**Figure 1.** Principle sketch of an interference fit

The classical analytical pressure in the connection, under the assumption of solid shaft, hollow hub, axis symmetry and plane stress, is given by [12]:

\[
p_f = \frac{E \delta_d}{2D_f} \left(1 - \left(\frac{D_f}{D_h}\right)^2\right)
\]

where \(p_f\) is interference pressure (MPa); \(E\) is the elasticity modulus (MPa); \(\delta_d\) is the interference fit level (mm); \(D_f\) is nominal shaft diameter and hub inner diameter (mm) and \(D_h\) hub outer diameter (mm).
There are other equations, known as Lame’s equations (elasticity theory) for thick-wall cylinder, commonly used to calculate stresses and deformations at interference fit connections [13-16]. Although the shapes typically used in Lame’s analysis could differ from the real shape of interference fit machine components, and they give approximate results, they are often used due to their practical applicability.

Lame’s equations are based on certain assumptions, among others:

- The thickness of the cylinder wall is constant.
- Thick-wall cylinder.
- Material of the cylinder is homogeneous and isotropic.
- The two mating parts (hub and cylinder) have the same axial length.
- Plane sections of the cylinder perpendicular to the longitudinal axis remain plane under the pressure.

The Lame’s equations indicate that Hoop stress and radial stress in an interference fit joint, and in addition axial stress in a closed cylinder, are subjected to a defined outer and inner pressure.

### 2.2. Shrink fitted connection

Shrink fit is an interference fit technique where typically the inner part is being cooled down (shrinks), or the inner surface of the outer part is being heated up, to make the fit possible. After assembly, the temperature-affected part will adjust its size back to original size, and there will be an interference fitted connection. The dimension-change of the temperature affected part will decide the final interference fit level, and contact pressure. Induction heating is a typical technique for heating and liquid nitrogen is often used for cooling.

The basic formula for calculating the required temperature (T) for the expansion of the metal is:

\[
T = \frac{d}{c\alpha}
\]

where \(d\) is the required radial expansion (of the radius), \(c\) is the nominal hub inner radius and \(\alpha\) is the coefficient of thermal expansion.

### 2.3. Open hole pin/bolt connection

A typically open-hole connection is a cylindrical pin in a joint with an operation tolerance equal to the installation tolerance, which means that the pin is “loose” within the bore and having the possibility to move relative to the bore during operation, as moveable joints in cranes or heavy machinery.

For instance, Bondura PIN technology (Figure 2 [17]) utilizes such open hole pin connection or expanding pin that is a form of an interference fit technique, where it is possible to expand and shrink the pin, mechanically, without need for any heating, cooling or axial force to push the pin into the bore, neither before nor during or after the expanding process. The pin has tapered ends, and end-sleeves with a conical inner surface that fits to the tapered pin. The sleeves are pushed into the pin by torquing the tightening end screws or nut and the sleeves climb the tapered pin ends, lock the pin to the bore as a wedge, and prevent any relative movement between the pin and the supports. The interference fit level depends on the torquing level of the tightening screws, and/or nut. By reversing the process, the complete expanding pin assembly can easily be removed, and the technique works well on all pin/hole sizes.

![Figure 2. Bondura PIN technology (a) Expanding pin solution (b) Expanding pin in a joint](image)
3. Fretting fatigue in different types of connections

3.1. Fatigue - general
The American Society for Testing and Materials (ASTM) defines the concept fatigue as [18]: “The process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations”.

It is well known and experienced during many years that many mechanical joints subjected to cyclical loads will develop fatigue cracks at the hole or bore where the bolt or pin is inserted. Many studies have been performed in the last decades to investigate problems with fatigue in mechanical connections [1, 3, 4, 7-9, 11, 13, 19, 20].

The process of fatigue involves three main stages:
1. An initial fatigue damage, which leads to a crack nucleation and possibly crack initiation.
2. Cyclic growth of a crack (propagation) until the remaining cross-section becomes too weak to withstand the loading.
3. A sudden fracture of the remaining cross section.

Among the various types of fatigue failure, the typical ones include: mechanical fatigue, creep fatigue, thermo-mechanical fatigue, corrosion fatigue, and fretting fatigue. Most of these fatigue forms and related failures are caused by cyclic loads combined with frictional sliding, or micro movements.

3.2. Fretting - general
Fretting as indicated by ASTM [21] is: “A small-amplitude oscillatory motion, usually tangential, between the solid surfaces in contact” and: “The process of crack formation at a fretting damage site, progressive crack growth, possibly culminating in complete fracture, occurring in a material subjected to concomitantly fretting and fluctuating stresses and strains”.

Another term related with fretting wear arises as a result of a combination of fretting and corrosion. This is a form of fretting wear in which different types of corrosion play a significant role and could reduce fretting fatigue life substantially [22-25]. The risk of fretting arises when two or more material surfaces are repeatedly moved against each other under load. Such loads can be cyclic loads from the normal operation, or maybe unwanted vibrations. The fretting process from first mechanical wear to a breakdown, Figure 3 (adapted from [26]), can be explained as: The loss of material due to fretting may not be so significant, but it might be enough to degrade the structural strength and to reduce the fatigue life. If the combination of amplitude and normal force is “right” the debris from the wear process could be trapped between the contact surfaces, and play an important role in the further wear process, and the topographies of the wear scars become complicated [24].

![Figure 3. The fretting process](image)

Fretting wear is one of the main reasons for failure of key components and can reduce the fatigue life up to 20 – 50% [27]. It is a type of wear damage induced by a short amplitude sliding motion between two loaded surfaces [24, 28]. It is a microscopic dynamic process involving deformed structures, cracks, oxidation process and subsequent of behaviour of oxide debris between contact surfaces [29-32].

In general, fretting can be treated as three interrelated problems: (1) Fretting wear, (2) fretting corrosion and (3) fretting fatigue. Fretting wear is typically wear damage due to a fretting problem, whose prediction is a critical aspect for prediction of fretting fatigue [33-38]. Fretting corrosion, on the
other hand, is a chemical reaction problem in combination with a fretting problem [22, 23, 28, 39-44], while fretting fatigue can occur when both fretting and fatigue conditions are working at the same time. Investigations have shown that by increasing the normal force, the fretting regime transforms from typically gross slip towards partial slip [24, 45, 46]. The main parameters affecting fretting wear normally include: Normal load, slip amplitude, cyclic frequency, surface roughness, material properties and contact geometry.

3.3. Contact surface zones and geometrical shapes
Different bodies in a joint will have different geometric shapes, and therefore often different contact surface shapes, and they could act differently under loading. Figure 4 [1] shows examples for different contact geometries. The contact zone will vary with loading, and the contact status can be defined as sticking, slip/sliding and opening area, as shown in Figure 5 [27]. The stick zone is the area with no relative movement between the two surfaces, and therefore wear will not occur. In the slip-zone, there will be relative movement between the surfaces, and fatigue and abrasive wear will occur. The fretting corrosion behaviour depends strongly on the fretting regime, being a microscopic dynamic process involving deformed structures, cracks, oxidation process and subsequent behaviour of oxide debris between contact surfaces [28-32].

![Figure 4. Different contact geometries](image)

![Figure 5. Stick, slip and open zone](image)

3.4. Fretting fatigue in railway interference fit connections, and aircraft fuselage connections
Fretting problems such as fretting wear, fretting corrosion and fretting fatigue have been studied for many years, with the latest studies adding new knowledge to previous knowledge. Fretting fatigue, which is a typical and frequently appearing type of fatigue, results from infinitesimal relative surface motion between two contact materials when cyclic loads are applied. In pressurized water reactors [23, 24] for instance, fretting fatigue is a common corrosion fatigue degradation phenomenon between the steam generator tubes and anti-vibration bars/tubes supports [22, 47, 48].

A number of studies have been performed to investigate more about the different fretting and fatigue problems that occur in different industries and mechanical systems. Some of the studies were aimed to find possible solutions to decrease the negative effects of fretting, and increase the parts’ and the systems’ fatigue life, among them, the following can be mentioned as examples: Railway axles with interference fit connections, aircraft structure and fuselage with riveted or pinned connections, steam generators in nuclear energy production environment, threaded tube connections, and high power excavator tracks.
3.4.1. Railway axles with interference fit connections

From a safety point of view, the axle with its connections is the most important component in railway vehicles. The axle, gear seats and wheel seats are joined by interference / press fit, and they are critical parts, due to the long-time exposure to crack initiation because of fretting fatigue [2, 5, 6]. Figure 6 [3] shows a typical interference fitted railway wheel axle with wheel hub and seat. Many actions have been taken and a number of investigations have been reported with an objective of reducing the problems related to fretting fatigue and improve the fretting fatigue life [5, 6, 49]. Examples can be; optimizing the contact pressure/interference level, surface treatments, stress relief grooves, strength, and more. For rotary bending axles the wear mechanism of fretting damage is typically combinations of abrasive wear, oxidative wear and delamination [50].

Figure 6. Railway axle (a) with hub and seat (b)

(a) Optimizing the contact pressure / interference level: Studies conducted to investigate the fretting fatigue life consequences of changing interference fit level, or contact pressure between the two contact surfaces shown that the transmission from high wear regime to low wear regime occurs when the contact pressure drops below a critical mean pressure of approx. 150 MPa (Figure 7 (a) [51]). As it is observed in the figure, the evolution of the wear kinetics as a function of the mean pressure identifies a critical pressure between mild and severe wear regimes.

These results are based on the fretting rig test (Figure 7 (b)) by imposing displacement independent of the normal force. As a result, one can read that with an imposed displacement combined with an increased normal pressure (> 150 MPa), the contact area will suffer severe wear. In many cases, and maybe in an interference fitted railway axle with hub and seat, it can be expected that there exists no relation between the normal force (interference fit level) and the actual displacement (relative movements between the hub and the axle). It could be expected that an increased normal force level would decrease the displacement, and therefore possibly decrease of the wear, or at least change the wear pattern.

Figure 7. (a) Evolution of the wear kinetics as a function of the mean pressure, and (b) schematic of the fretting rig test set-up.
(b) Surface treatment and fretting fatigue palliatives: One way to avoid fretting fatigue and its negative consequences is to avoid fretting fatigue contacts; though not always possible. There exist palliative mechanisms for fretting fatigue that could reduce the problem, including [1];
- reduction of friction (expected reduction of the tangential contact force) [52]
- introduction of residual compressive stresses (reduction of fretting wear) [7, 11, 53, 54]
- increasing surface hardness (by different peening processes) [55-61]
- altering surface chemistry and modifying the micro-topography [55]

(c) Stress relief grooves and fillets: For many years, it has been investigated on how to achieve important improvements of fatigue life [2, 3, 5, 62-64]. One way is to optimize the place, size and form of the stress relief grooves and fillets, to maximize their effect and increase the fatigue strength and life [62, 63]. The European Norm EN13104 [65] states the requirements for calculations for powered axles.

The other method is use of finite elements methods such as the one conducted by Zeng, et al. [3] who used the method for prediction of fretting fatigue crack initiation in a full-scale railway axle, powered railway axles used in China, taking into consideration the stress redistribution and surface change due to fretting wear. Thereafter, the influence of stress relief groove on the fretting wear and fatigue was investigated.

3.4.2. Aircraft structure and fuselage with riveted or pinned connections

The normal method how to connect skin plates, or fuselage, for an aircraft construction is by rivets, as shown in Figure 8 [1]. Fatigue of the pressurized fuselages of transport aircraft is a significant problem all designers of aircraft have to take into consideration for assuring a sufficient lifetime and safety. Such joints in a fuselage require holes that could easily weakens the strength, increase the risk of fatigue, and reduce lifetime. Due to the cyclic nature of the service loading of the joints in aircraft structures, fatigue failures are most common failure types. Both pins, bolts, and rivets are commonly used in these structures, often with an interference interface, or an open-hole connection, often cold expansion treated.

Cold expansion: Cold expansion does not include a cooling, or any other temperature dependent processes, so “cold” is referring to the absence of “introduction of heat” into the process, which is the normal way when forming metal. Cold expansion is a cold forming of the bore wall to make the material more resistant, before introducing a pin or bolt for operationally purposes [7, 11, 53, 54].

Interference fit: At the junction of the main load-bearing components in the aircraft, such as wing beams, fuselage strengthening frames, and other important structural connected parts, interference fit bolted joints are widely used to improve the structural fatigue performance. Connections like press-fit, shrink-fit and mechanical radial expansion can be seen as variations within the definition of interference fit.

![Figure 8. Riveted lap joints in a pressurized aircraft fuselage](image-url)
Iyer, et al [66] concluded in their study that an interference fit of 2% tended to inhibit fretting fatigue. In a related work Iver et al. [67] studied the influence of interference and clamping on fretting fatigue in single rivet-row lap joints, and the study was concerned with the determination of the three-dimensional contact stress and displacement fields in the panels of realistic riveted lap joints.

Moreover, Chakherlou, et al. [9] investigated both experimentally and numerically the effect of interference fit on holed plate with interference fit levels of 1%, 1.5%, 2% and 4%. The results showed that by increasing the interference fit level from 1% to 1.5% and further to 2%, the fatigue life also increased, but by increasing the level further up to 4%, it did not give any more increase in fatigue life.

To improve fatigue life of holed plates made of aluminum, in double shear lap joints, Chakherlou, et al. [11] conducted experimental and numerical studies of cold expansion (CE) and interference fit (IF) techniques. Both the cold expansion and the interference fit test levels were set to 1.5% and 4.7%. With increasing IF level, the amplitude of the alternating stress reduces, but the mean stress increases. At CE and IF level of 1.5%, the interference fit connection gives a longer fatigue life, and at 4.7% level the differences between cold expansion and interference fit are small.

Bi, et al. [68] have also performed experiments and FE analysis and concluded, in their case, that the maximum hoop tensile stress was at its minimum at an interference fit size of 1.5%. The interference fit size of 1.5% was therefore defined as the optimal value in aircraft interference assembly. Mirzajanzadeh, et al. [20] also conducted similar studies by considering different friction factors for different interference levels.

4. Discussions and outlooks

Fretting problems and challenges are well known and still be a continuous issue in many industries, although numerous investigations have been conducted for many years. Within the railway industry, especially when it comes to the axle/hub connections, many actions have been taken, and a number of investigations are conducted in order to reduce the problems related to fretting fatigue and improving the fretting fatigue life [5, 6, 49]. It has been focused on optimizing the contact pressure / interference level, palliatives, stress relief grooves and more, with the aim to prevent fretting related problems, and consequently prolong the fatigue life of the components and equipment. In general, the newer investigations are building their results on results from earlier investigations combined with new and often better techniques, test equipment and improved FE tools and methods, in addition to improved materials and palliatives / surface protection techniques.

When it comes to interference / press fit, and other treatments like cold expansion, it seems that all try to use similar techniques. An interference fit is made by forcing an axle axially into a hub, where the nominal axle diameter is slightly greater than the nominal hub diameter. The difference in nominal diameters defines the interference fit level. An alternative is to cool down the axle before inserting into the hub, and let it expand back towards nominal diameter, and create the interference fit level required.

The mechanical radial expansion, or expanding PIN technology [17] mentioned earlier, i.e. by companies like Bondura Technology and Expander, is not mentioned in any of the investigations found in this literature study. The mechanical radial expansion creates the interference fit slightly different from both the “normal” press fit and shrink fit techniques, and it is possible to control and adjust the fit level over time. The cold shrink energy issue is not present, neither the press force for reaching the fit level, nor the effects of temperature differences and friction between the connecting surfaces of the joint. This indicates future possibilities for improving press-fitted connection solutions of powered axles, typically like the axle/hub connection in a railway wheel. Further research and investigations will be necessary to clarify how efficient an expanding PIN solution can be, compared to existing solutions, like the traditional press-fit and shrink-fit.

Fatigue, in different forms, has caused many very serious accidents for many years, also within the aircraft and offshore oil & gas industries. A world-wide survey of aircraft accidents covering both fixed-wing aircraft and helicopters for the period 1934 – 1979, having metal fatigue as a related cause, showed 306 fatal accidents with 1803 fatalities [69]. Two-thirds of the accidents involved fixed-wing aircraft, with wing failure as the most common cause followed by engine failure. For the helicopter accidents, a
third were due to failure in the main-rotor system, and a quarter due to tail-rotor failure. Some of the most serious accidents at the Norwegian shelf would be the Alexander L. Kielland hotel platform fatal accident in March 1980, with 123 lost lives [70]. A hydrophone was fillet welded to a tube, and due to low mechanical strength combined with poor welding and high residual stresses, the fillet weld partially cracked, which again resulted in a fatigue fracture of the tube.

The Eurocopter AS332 Super Puma helicopter accident in the North-Sea in 1997, also called the Norne accident, had 13 fatalities. The official report [71] from 2001 stated that the initial and direct reason for the accident was due to fatigue in the spline-sleeve of the right gear box. The Eurocopter EC225 Super Puma helicopter had a fatal accident with 16 lives lost, close to Turøy (Norway) in 2016, when coming in from the North-Sea. The AIBN (Norwegian Accident Investigation Board) released their final report [72] in 2018 stating that the accident was a result of a fatigue fracture in a second stage planet gear in the main rotor gearbox which initiated from a surface micro-pit in the upper outer race of the bearing, propagating subsurface while producing a limited quantity of particles from spalling, before turning towards the gear teeth and fracturing the rim of the gear without being detected.

In general terms, the influence of fretting fatigue can be reduced or eliminated by means of the methods mentioned previously in this study; optimizing contact pressure, correct use of palliatives, correct use of stress relief grooves, improved test techniques, methods and numeric analysis tools and methods, and maybe also by investigating the use of expanding pin technology. The previously mentioned accidents [70-72] prove that the influence or consequence of fatigue can be fatal, and often a result of a highly complex chain of reactions. The investigation of the Turøy accident [72] has shown that the combination of material properties, surface treatment, design, operational loading environment and debris gave rise to a failure mode which was not previously anticipated or assessed. The investigators at the Norne accident [71] could not determine the exact cause why the fatigue fracture occurred, but it was discovered serious problems with the hard-metal coating of the spline-sleeve, with over-sized carbide grains and out-of-standard thickness variations of the coating, in combination with some undefined scratches on the coating surface from before the accident, which all together could be (partly) the reason for breakage. The Alexander L. Kielland platform accident investigation [70] revealed quality problems with material, weld, heat treatment and design. All these accidents could probably have been avoided, or had reduced consequences, with improved quality control of design and construction (platform), and of parts and materials (Norne and Turøy) and a higher general knowledge among the engineers and designers about the consequences of combinations of various individual fatigue-risk mechanisms (platform, Norne, Turøy).

5. Conclusion

Fretting problems and challenges are sources for concerns not only in most mechanical industries, but also in other industries that experience vibrations and micro movements relatively between adjacent material surfaces. In addition to continued investigations, it is imperative to improve material qualities, palliative methods, test techniques and the way of how to connect the parts of the joint. It is imperative to understand how combinations of mechanisms can result in fatigue problems, although each and one of them may not result in such problems. In practical life, minimizing the possible damage effects of a fatigue problem could be as important as avoiding having the fatigue problem itself. New methods, as the mechanical radial expansion technique have been in the marked for many years, but are possibly not well enough known among the researches. The mechanical radial expansion technique should be applied more in future investigations regarding how to reduce fretting fatigue and other related issues, in interference fitted joints. Its advantages when it comes to installation, retrieval, elimination of the need for heat/cold, and possibility to quickly adjust the interference fit level, makes this solution worth investigate further.
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