NEW INVESTIGATIONS AND APPROACHES TO EXPLAIN STANDSTILL MARKS ON ROLLER BEARINGS (FALSE BRINELLING)

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Abstract

On (seemingly) motionless roller bearings, minute movement through oscillation or vibration-induced elastic deformation can produce standstill marks on the runway. The subsequent overrolling of the marks in operation results in an uneven run and later in premature failure. Such minute movement can be induced by machine or aggregate oscillation but also by the dynamic effects of the road and rail transport. These marks are called false brinelling marks. Brinelling or true brinelling, is a surface damage caused by overload and plastic yield, similar to the damage caused by the Brinell hardness test. Contrary to this, false brinelling is a damage caused by fretting corrosion and other not completely understood mechanism. It causes a similar-looking damage due to completely different tribological mechanisms.

This paper shows the latest results of experimental tests on a special designed test rig at the Competence Centre for Tribology of the Mannheim University of Applied Sciences. For the first time, knowledge from "fretting"-research was connected directly to the effects in a false brinelling contact. This new approach can be the basis for further computer simulations.

Key words

false brinelling, roller bearings, standstill marks, vibrations, lubricating greases, fretting

Introduction

False brinelling is a quite old wear problem of roller bearings; however, it is still not completely understood and solved. First time, false brinelling was mentioned in the 1930s. It is reported that new automobiles that were transported by ship or train for delivery showed severe wheel bearing damage when unloaded. On further inspection, it turned out that many wheel bearings showed periodical marks in the raceways. The damage was probably traced to rocking of the cars by the vibrations of the large Diesel engines on the ships or the regular impact every time a railroad car wheel passed a track joint. These conditions led to the first false brinelling research work of ALMEN at General Motors (1).

Although the auto-delivery problem has been solved, there are many contemporary examples. For example, generators or pumps may fail or need service, so it is common to have a nearby spare unit which is left off most of the time but brought into service when needed. Surprisingly, however, vibration from the operating unit can cause bearing failure in the unit which is switched off. When that unit is turned on, the bearings may be noisy due to damage, and may fail completely within a few days or weeks even though the unit and its bearings are otherwise new.

***Fig. 1** Axial ball bearing with advanced damage*

Another big area where problems are reported, is that of the pitch bearings of wind turbines and transmission gear bearings. Because of the growing economic importance of wind turbines, the rising power size and new off shore techniques, the topic will gain in importance.

***Fig. 2** Big off-shore wind park (source: it-material.de; Siemens AG)*

Grease is usually used in the referred applications. The greases are optimized for operating conditions that result in the dynamic stresses of highly loaded roller bearings, particularly for the operating conditions that are characterized by continuous rotating movements with an elasto-hydrodynamic lubricant film formation. They are often not suitable to prevent wear under micro movements caused by vibrations or very small pivoting angles. In practice, there are several testing methods for investigating false brinelling (e.g. ASTM D 4170 / Fafnir, SNR-FEB 2, HRE-IME vibration tester), but the results do not correlate with the individual test methods in general, neither with each other, nor with the experience from practice. Often, these tests provide different results when using the same lubricant.

Unfortunately, there is a relatively limited number of literature sources on the specific subject of false brinelling. The investigations of ALMEN at General Motors (1), the publication of EISELE (2) and a very extensive publication of PITTROFF (3) are nearly the only published contributions that really treat the special case of standstill effects at roller bearings.

The most obvious cause of false brinelling is when lubricant is pushed out of the highly loaded region. But a detailed inspection of the problem shows that complex physical-mechanical processes occur in the contact zone of a false brinelling contact and that a single mechanism is unlikely to be responsible for the observed surface damage. In the contact area, all four main wear mechanisms appear: Abrasion, adhesion, tribochemical reaction and disruption. Depending of the load parameters, one or another mechanism becomes dominant. New research results within my dissertation thesis show strong destruction of the surface due to cracks even after a few thousand cycles (4). The resulting wear debris oxidizes to form an abrasive compound which further accelerates wear.

One of the most important sources of information is the very extensive theoretical and experimental work of PITTROFF (3) at the SKF roller bearing company. Despite the age of this paper, the experimental results are very interesting and most of the relations found can be confirmed by the study presented. After PITTROFF’s project at SKF, the false brinelling topic was neglected for several years. Research concentrated on fretting conditions.

Mathematic evaluation and solutions originate from the early work of MINDLIN et al. (5). Current results of this project show that a part of the false brinelling contact is exposed to fretting conditions, but other areas are affected by mechanical maximum stress. Important publications of the last two decades are those of ÖDFALK and VINGSBO et al. (6, 7), FOUVRY et al. (8) and SUNG-HOON et al. (9).

Experimental Methods

A big problem is that the term “false brinelling” covers a wide variety of damage symptoms, which are partly caused by different mechanisms. The wear symptoms in tests with micro-oscillation differ significantly from the tests with relatively wide oscillation movements in the range of above 1°, as in the normal laboratory testing methods, such as the Fafnir test according ASTM-D 4170 or the worldwide laboratory test developed by the French ball bearing company, SNR. Such macroscopic oscillation movement of +/-6° in the Fafnir test or +/-3° in the SNR test lead to “real” bearing processes and not to the micro movements which occur and are particularly problematic with seemingly motionless bearings.

Better, and for the false brinelling problem more practically relevant, test methods are used in some companies and institutes e.g. the SKF Vibration Tester, the HRE-IME-groove tester at the University RWTH Aachen or the FAG vibration tester with original hub units.

For the investigations within this dissertation, the special false brinelling tester of the Competence Centre for Tribology at the University of Applied Sciences in Mannheim was used (Figure 3). The design is based on the SNR test but it has been improved in different points. The test method and first results have already been presented at different tribology conferences, for example at the annual conference of the German association for Tribology (4). The standardized test parameters in Mannheim are an oscillating angle of +/- 0.5° and a load of 750 N/ball (C_0/P = 5.2). These parameters are suitable to simulate real standstill effects. This test is the basis of all comparative investigations.

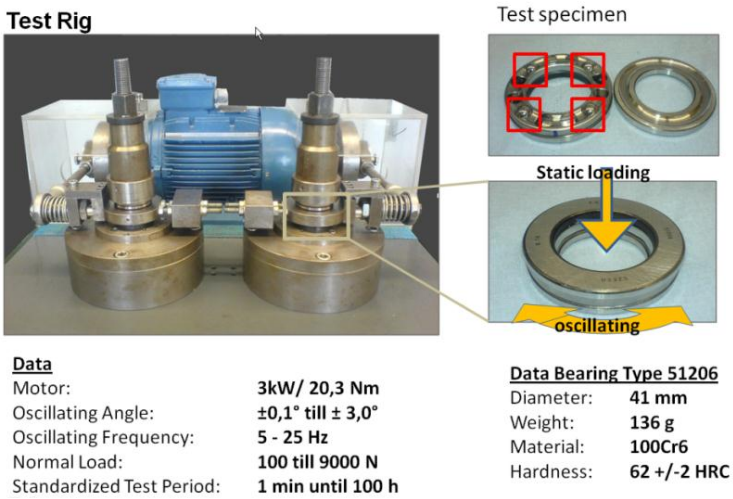

Fig. 3 *Test rig with standard test parameters*

Experimental results and discussion

All tests conducted so far show that the contact zone can be divided into different zones, some of them optically discernible (Figure 4). Clearly visible are the undamaged adhesion zone in the centre of the marks (inner ellipse) and the damaged micro glide zone (between the inner and middle ellipse). At closer observation, one can discern an outer zone, known as the influence zone. The size of this outer ellipse correlates with the calculated Hertz contact surface. There is no relative movement in the centre of the elliptical mark. Both the base body and counter body adhere well. On the edge, however, there are micro slip movements and local tension peaks which are caused by elastic deformation, bearing movements or shifting of the pressure centre, and these can cause extensive surface damage.

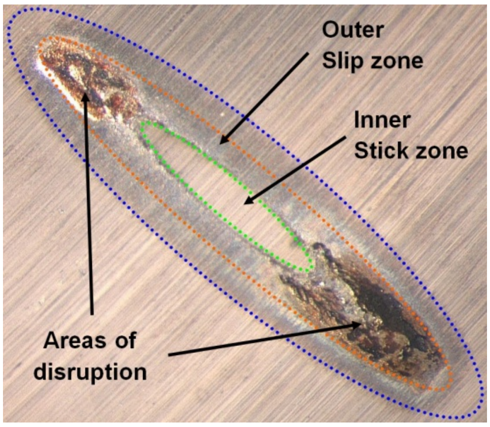

Fig. 4 *Division of the marks in different contact zones like stick zone, partial slip zone with micro sliding and affected zone (from the inside outwards)*

The pictures clearly reveal the correlation of several wear mechanisms. The outer end of the elliptical wear marks shows tribochemical reactions and surface disruption. The middle ellipse zone in the centre of the runway track only shows tribochemical reactions. There are no visible changes in the centre of the ellipse. The original grinding marks of the race are completely preserved. Even high resolution inspection methods can detect no topographic changes. The deep indentations often observed in practical application are caused by pollution with abrasive wear particles and reaction products or by a total lack of lubricant at the friction point

In order to measure the depth of the visible cracks of the outer zone, the Robert Bosch GmbH company produced some focused ion beam cuts (FIB). The FIB cuts were taken from the outer glide zone (Figure 5). Four out of five examinations of different samples revealed cracks. The FIB cut images clearly show in-depth transcrystalline cracks (Figure 6). Subsequent overrolling of the cracks in normal bearing operation will relatively quickly lead to particle break-off and bearing failure. A fact which causes concern is that, at closer inspection, there is severe damage when using the grease which has so far achieved the best test results. This would indicate that such damage may never be fully avoided, but can only be reduced. There is however still a potential in the testing of other "lubricant-formula-variations".

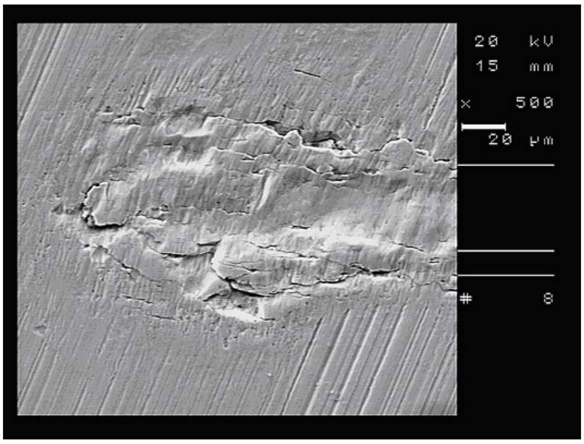

Fig. 5 *SEM picture of the outer end of the elliptic false brinelling mark of a high (!) reference grease after just 1000 load cycles*

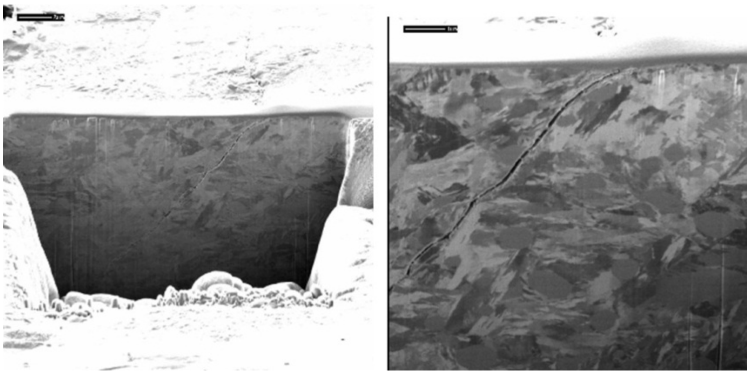

Fig. 6 *FIB/XB-Investigations at the outer end of the elliptic wear mark (width of the complete cut is about 20 µm, the visible depth is about 10 µm)*

The tribological tests at the false brinelling test rig and the study of literature reveals that complex physical-mechanical processes occur in the contact zone of a false brinelling contact and that a single mechanism is unlikely to be responsible for the observed surface damage. In the contact area all four main wear mechanisms appear. Depending of the load parameters one or another mechanism becomes dominate.

The mentioned damage mechanisms described above cause the production of wear particles and reaction products, which are not pushed out of the friction area due to a lack of "real" relative movement and thus have a strong abrasive effect. This phenomenon correlates with the formation of fretting corrosion (tribo-chemical corrosion) and normally leads to the damage progression and deep indentations which cover the traces of the original damage mechanism. In further damage progression and bearing rotation, there are additional wear mechanisms (in particular abrasion and surface disruption), which overlap and add to the covering of the real cause of damage. Depending on the predominance of one or several of the mechanisms described above, there are different types of standstill marks. The predominance of one mechanism depends on the load conditions – and within those mainly from the oscillation angle. Another damage factor with strong influence is the lubricant used. Unfortunately, main parts of this project part were sponsored by lubricant industry and are accordingly confidential. An exemplary result of unsuitable barium grease is shown in Figure 7.

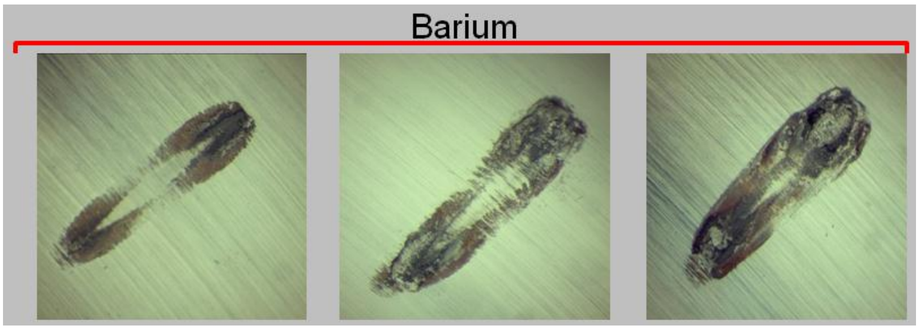

***Fig. 7** Marks after 1 min., 6 min. and 80 min. with a barium soap grease*

Owing to their better flow properties, oils are in general more effective than greases in preventing damage due to lack of lubrication. For the same reason, oils may also be more suitable when it comes to preventing tribo-chemical corrosion, as oils achieve more reliable surface wetting and thus prevent the formation of dry friction oxides (Fe_2O_3), which, due to their abrasiveness, lead to quickly progressing damages. Results of an extensive test series about the influence of the base oils can be found in the presentation of the annual tribology conference of the German Association for Tribology in Göttingen (Germany) (10).

The research project involved a wide range of tests to examine the effect of certain parameters on false brinelling damage. In the first project phase, all the main values of the load collective were varied separately. This revealed that normal force is only of secondary importance. Damage increases with increased normal force, but not as much as one may expect. The effect of oscillation frequency is also less marked than expected. The damage increase observed when the frequency increases may also partly originate from higher mass changing forces. These frequencies are normally not high, such as those occurring with electromagnetic stimulation. This is a field that we have not been able to examine as the test bench only allows a maximum frequency of 25 Hz. With decreasing temperature, the damage increases with most of the tested lubricants. There were, however, also a few greases which showed opposite effects. A very important factor is the size of the pivoting angle. A change of the pivoting angle does not simply increase the damage but has an effect on the wear mechanisms. Small pivoting angles produce similar effects to fretting corrosion. The friction point is never fully exposed. This nearly completely impedes the entry of new lubricant. Wear and reaction products cannot move from the wear point. An adhesive zone develops in the centre of the contact area, while microscopic sliding movement takes place at the edge of the contact area. This state of discontinuity leads to the high internal tension and fast crack initiation, beginning on the surface. With increasing pivoting angles, the friction point is exposed. In such cases, the flow characteristics of the lubricant play an essential role. The predominant features are wear mechanisms known from oscillatory sliding friction. As the lubricant industry is aware of this feature, it has developed highly suitable greases for this situation. This is not the case with the development of lubricants for scenarios with small pivoting angles, like those observed under vibration loading, which is still at an early stage. This has been confirmed by all experiments conducted to date. This conrtibution, therefore, puts another main focus on the research and development of suitable greases. All components, such as base oils, thickeners and additives were varied. The final analysis shows that simple greases with a mineral oil base and with lithium soap thickener provide the best results. There is no clear demonstrable proof of the effect of standard wear protection additives or high pressure additives. Grease lubricants help for a very short period, but are soon worn away from the friction point. Greases with low base oil viscosity and a low NLGI class offer advantages, but the effect observed is not homogeneous.

Apart from the analysis of the load collective and lubricant composition, we conducted some tests on the bearing design. The effect of the material used could not unfortunately be fully analysed because there were not enough suitable bearings. Tests with hybrid bearings, i.e. with ceramic balls, now show outstanding results even though this material results in a clear reduction of the adhesive component. The effect of the raceway roughness could be proven with hand-prepared bearings. In these tests, rougher raceways showed advantages, which could be explained by the better lubrication conditions. The deeper roughness valleys can store the lubricants better and can provide more lubricant where necessary. The higher local compression at the roughness peaks may also have a positive effect on partial sliding. Random tests were conducted to examine the effect of different coatings. Carbon nitride coatings could not withstand the applied load. A DLC coating however showed excellent results. This feature certainly means a large potential for development. The drawbacks are the high cost and the fact that the coatings have to be sufficiently wear-resistant in normal operations.

Another focus was on extensive literature research and the theoretical explanation of the results and effects obtained. The literature research however showed that little research has been conducted on the subject. Apart from a project at the SKF company at the end of the 1960s, there are practically no studies.

Based on the observation that there are stick and sliding zones within the false brinelling contact, literature research was extended to the field of fretting research. This proved to be a wise move as many effects could be described and explained on the basis of these research results (see Figure 8). The work of MINDLIN and the studies conducted by VINGSBO/SÖDERBERG are particularly helpful when trying to understand the extremely damaging effect of small pivoting angles. Contact mechanics served as a basis to explain the effect of the stress forces, but it is still not possible to produce computer calculations of these forces for a specific bearing and lubricant. There are too many boundary conditions yet to be considered. Even though the understanding of the forces and stress applied was achieved, the findings are only partially useful when developing suitable lubricants. This is also confirmed by the results observed with some prototype samples of a leading grease manufacturer.

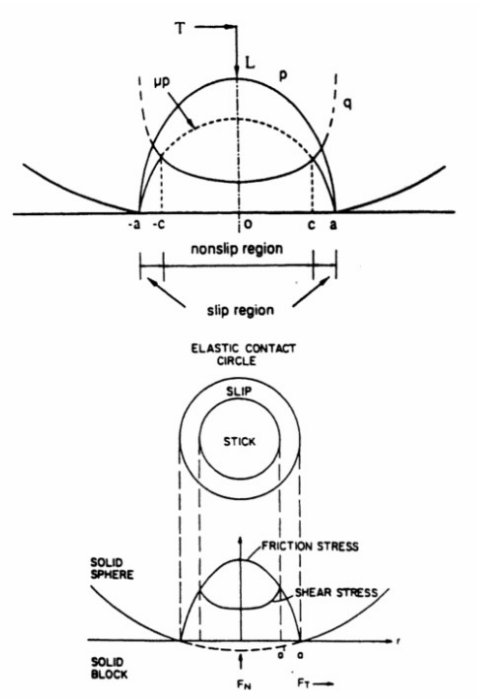

Fig. 8 *Microslip in a point contact with acting tangential force (1)*

Conclusion

All tests conducted so far and the bibliography confirm the hypothesis that standstill marks develop due to various mechanisms:

- The lubricant is literally pushed out of the friction area by micro movement and high local pressure. This leads to a lack of lubricant and the typical wear mechanisms of abrasion and adhesion (”galling“).
- The micro movement activates the surface energy (in particular the microcontacts on the surface roughness peaks). This leads to tribochemical reactions down to a depth of several nanometres.
- Another important factor which is often not considered and can hardly be detected on superficial inspection is the microcracks caused by tangential forces due to the load changing on the surface (Contact mechanical theory of MINDLIN). When exposed to further load, these cracks result in more extensive and deeper particle break-off.

The three damage mechanisms described above cause the production of wear particles and reaction products, which are not pushed out of the friction area due to the lack of “real” relative movement and thus have a strong abrasive effect. This phenomenon correlates with the formation of fretting corrosion (tribochemical corrosion) and normally leads to the damage progression and deep indentations which cover the traces of the original damage mechanism. In further damage progression and bearing rotation, there are additional wear mechanisms (in particular abrasion and surface disruption) which overlap and add to the covering of the real cause of damage. Depending on the predominance of one or several of the mechanisms described above, there are different types of standstill marks.

The predominance of one mechanism depends on the load conditions – and within those mainly from the oscillation angle. Another damage factor with strong influence is the lubricant used. Due to their better flow properties, oils are in general more effective than greases in preventing damage which is due to lack of lubrication. Oils may also be more suitable when it comes to preventing tribochemical corrosion, as oils achieve more reliable surface wetting and thus prevent the formation of dry friction oxides (Fe_2O_3), which, due to their abrasiveness, lead to quickly progressing damages.

A big problem is that the term “false brinelling” covers a wide variety of damage symptoms, which are partly caused by different mechanisms. The wear symptoms in tests with micro-oscillation differ significantly from the tests with relatively wide oscillation movements in the range of above 1°, as in the normal laboratory testing methods, such as the Fafnir or SNR test (Fafnir: +/-6°; SNR test: +/-3°). Such macroscopic oscillation movement leads to “real” bearing processes and not to the micro movements which occur and are particularly problematic with seemingly motionless bearings.

An important result of this project is that false brinelling marks are not to be considered as an optical or fatigue problem that only occurs towards the end of the estimated life cycle, but indicate critical early damage, which rapidly progresses from the first cracks and particles. False brinelling tests performed so far, such as the SNR test, require testing times of several days and thus load cycle numbers of more than 4.5 million cycles. The false brinelling effect was therefore often associated with a life cycle problem. The current tests, though, show that with critical parameters, there is severe damage on the contact zone after only a few minutes. In terms of strain cycling, this comprises a time period of only a few thousand load cycles.

We succeeded to increase the basic knowledge about the processes acting in the highly loaded contact area between roller and raceway in the case of vibrational or oscillating stress. The influence of the main tribological parameters like load, frequency, temperature, tilting angle and contact geometry on the formation and the manifestation of false brinelling damages could be determined. Also it was possible to detect the basic mode of action of the main components of greases (base oil, thickener and additives). However, it was not possible to develop unrestricted suitable grease, for false brinelling affected bearings yet. In cooperation with different lubricant developers, some model greases were tested, but no one was able to prevent false brinelling completely. But at least some could decrease the speed of the damage progress.

For the first time knowledge from “fretting”-research was connected directly to the effects in a false brinelling contact. The division of the contact area in a stick and micro slip zone based on the theories of MINDLIN (5) and CATTANEO (11) has been already adopted by other scientists. These approaches combined with current theories of contact mechanics (e.g. of JOHNSON (12)) also helped to build up theories about the acting stresses and the resulting cracking of the surface after just some hundreds of load cycles. Based on contact mechanical theories, it will be possible to calculate the stresses in the tribological contact. These theories can help to explain why only a little load changing cycles with loading far beyond the critical value can cause such massive damage. We will soon conduct computer simulations and FEM calculations to investigate the influencing parameters.

Modern microscopic and analytic methods like REM and FIB/XB helped to visualize the extremely negative effect graphically. This microcracking is a complete new wear mechanism that was overlooked due the long test periods and large oscillating angles of the known old standard laboratory test methods like Fafnir or SNR-test. The development of a new standardized test procedure was a very important intermediate step to reach the ambitious goals of this project. It is now possible to test possible improvements under realistic test parameters.

Future test bench setups will be designed to either confirm or disprove the existing hypotheses. Furthermore, the project members developing lubricant formula are working on concepts for improvement. But at this point of time, we do not know yet if lubricants have an influence on the wear mechanism in surface disruption.

The research conducted so far shows the complexity of wear damage due to the overlapping of all four main wear mechanisms. It is thus extremely difficult to find suitable lubricants for damage prevention. All in all, it was possible by many lectures and publications to enhance the sensitivity for the topic „false brinelling“ in several industrial sectors. Numerous inquiries of companies and very interesting discussions confirm this success.

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