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WEAR IN FRICTION BRAKES

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Abstract

Parameters of friction systems decline in time by the process of wear. In friction brakes, the wear phenomenon is much more visible than in other friction systems. Wear itself is on one hand not desirable because of need for brake system parts replacement but sometimes is needed due to regeneration of the friction area which is damaged for example by temperature or aggressive ambient conditions. Wear can be fatal or catastrophic for the friction brake, leading to heavy damage or even to permanent loss of braking capability during operation. As the brake is one of the crucial safety systems in both aviation and road vehicles, it is necessary to know if and how wear will be present in friction brake system before the brake is allowed to be installed in the vehicle, especially one that carries people. Wear can be estimated via numerical methods for well-known brakes (i.e. materials) or it has to be tested using laboratory methods in order to check and prove or deny initial design assumptions. In this paper, the author describes the phenomenon of friction brake wear and laboratory-testing methods of friction materials wear using brake model test stand for aviation brake friction materials certification testing located in Institute of Aviation Landing Gear Laboratory. Author also presents sample data from aviation brakes materials testing in order to show how wear can affect friction brake performance and durability.

Keywords: *wear, wear testing, brakes, friction pair, friction material tests, full-scale brake tests*

1. Introduction

Wear and its observations are as old as friction brakes. Dating from ancient times when burning of wooden brakes was observed up to modern times when wear in high efficiency carbon brakes can be the cause of destruction of the whole brake and its surroundings.

Friction brake is a system, which requires as much friction as possible in order to efficiently dissipate kinetic energy of the movement (in other words transform kinetic energy to the heat). Wear in friction brakes is not desirable due to loss of material, which results in the necessity of replacing it during operation. However, some types of wear are allowed due to the phenomenon of regaining the properties of the friction surface (changed during friction).

In friction brakes, wear is also desirable in the first stage of brake operation. This process called bed-in generates mostly abrasive wear, and it is used in order to optimise brake efficiency by creating as big area of friction pair contact as possible.

Wear can be an inductor of normal friction operation (abrasive wear or fatigue wear) or can be catastrophic (explosive wear, thermal or mechanical shocks).

There are two definitions of the wear, which describe duality of the phenomenon:

- wear is the gradual loss of the friction material not causing major and rapid changes in the friction system,
- wear is the rapid loss or change in friction materials causing permanent loss or major change of the friction properties.

There are also several mechanisms of wear that in general are the same for all of the friction systems. In brakes, however, due to special properties, some of the wear mechanisms are different and some of the wear can became catastrophic. Main wear mechanisms are described in the next chapter.

2. Main wear mechanisms

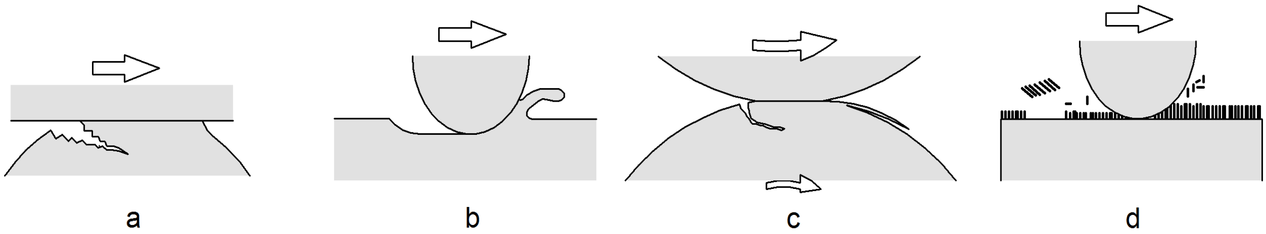

Fig. 1. Selected wear mechanisms (a – adhesive wear, b – abrasive wear, c – fatigue wear, d – corrosion wear) [5]

2.1. Adhesive wear (Fig. 1a)

Adhesive wear occurs where adhesive connections are made (sometimes called friction bridges) between friction pair materials and which are destroyed, due to the relative motion, resulting in material loss [3]. Adhesive wear is very common when metallic particles or materials are used because of their high cohesion. In order for adhesion to occur, it is necessary that the surfaces of the materials be close enough for successfully create friction connections. Those connections are strongest when surfaces are forced against each other with no relative motion. When motion starts, connections start to break resulting in less durable material particles peeling (even removing bigger parts of the material when base of the material is not strong enough to hold them – most often in composite materials where metallic particles are embedded in resin base). The strongest adhesion occurs on asperities' peaks when atomic forces are the highest. Adhesion also rises with purity of the contact surface. When oxidation covers contact surface, adhesion is quite low.

Adhesive wear is also connected with temperature rise (the higher temperature, the stronger adhesion).

The most common mechanisms of the adhesive wear:

- detaching of the particles from one material and attaching them to the other material as the new asperities (then abrasive or fatigue wear starts to occur in this area);
- detaching of the particles from one or both materials and holding loose particles in the friction area.

In the high temperature adhesive wear can be catastrophic due to very high atomic forces that can cause melting of the material and removing it from the surface layer and/or permanent joining of the friction pair that is not possible to separate (e.g. aviation brakes after rejected take off manoeuvre can be melted together).

2.2. Abrasive wear (Fig. 1b)

It is the most common type of wear. It occurs in every friction system dry or lubricated and demonstrates itself by the scratches or grooves.

Abrasive wear occurs when loss of material is caused by the local separation of particles of the material by the micro cutting, attrition or by separation of the surface inequalities. Abrasion occurs when there is abrasive material between surfaces of the friction pair (particles of friction products or external particles present in the friction zone) or when one of the friction pair's materials is harder than the other.

The most common mechanisms of the abrasive wear:

- Clowing – occurs when the groove is made in softer material, which is displaced to the sides by the particle of harder material without direct material removal or cutting it away. It happens when plowing particle has no sharp edges so it is unable to cut away removed material. Plowed material forms ridges (adjacent to the groves), which are often removed by subsequent passage of abrasive particles,

- Cutting or micro cutting – occurs when the groove is made in softer material by the particle of harder material and is removed or cut away by it. It happens when cutting particle has sharp edges and is acting as the cutting edge in conventional machining. Extracted particles can stay in friction area causing more wear or can be removed from the friction area as the friction products,
- Cutting of the asperities – process similar to the cutting but without grooving the material. It occurs when asperities of the friction materials meet and one of them is cut by the other due to the material hardness difference,
- Ripping of the asperities – it occurs when asperities of the friction materials meet and particles of one material are peeled off by the other. This mechanism is present when there is not enough hardness difference between materials or material is heterogeneous so the particles are not connected to the rest of the material strongly enough.

2.3. Fatigue wear (Fig. 1c)

This type of wear is connected to the fatigue processes occurring in the materials during operation. Fatigue can be described as stresses changing in time in the micro volumes of the material. During the friction process, fatigue is present in the contact areas of the friction pair as well as in the surface layer up to a certain depth (subsurface regions). Fatigue is caused by the cyclic load changes (tensile and compressive stresses) induced by the asperities on the friction pair material surface.

Fatigue in friction occurs when adhesion is not significant, but there are long term periodic changes, described earlier, in contact stresses occurring in the surface layers of the friction pair. Fatigue wear can be present both in the surface layer (sometimes called contact or surface fatigue) and in the deeper parts of the friction material (sometimes called volume fatigue).

Fatigue wear manifests itself at first as the micro cracks in areas where the stress change is highest; subsequently cracks become larger developing into macro cracks, which eventually cause the detachment of the portions of the material.

Fatigue wear is mostly caused by:

- uneven friction pair surface contact caused by the material roughness. Fatigue is higher when the roughness increases,
- periodic changes in load caused by machining or by bigger surface inequalities,
- temperature changes, which causes periodically changeable thermal stresses. In multi material or multiphase materials, stresses can be connected to the different thermal expansions of the material components.

There are several fatigue wear types described [10]:

- spalling – occurs in dry and not lubricated enough friction. It results in delamination of the material pieces (spalls) under changeable loads,
- pitting – occurs in the lubricated friction. Similar to the spalling, it results in separation of material pieces but its mechanism is more complicated. Mechanism of pitting wear is based on the presence of the lubricant that penetrates the material via fatigue cracks and separates the material pieces by applying the pressure in the crack,
- fretting – occurs only in the systems where the oscillating sliding motion is present causing surface fatigue similar to the corrosion. This type of fatigue wear is present mostly in pinhole configurations.

In friction brakes, fatigue wear occurs mostly as spalling (due to the lack of lubrication) and it is caused both by mechanical and thermal fatigue.

2.4. Corrosive wear (Fig. 1d)

Corrosive wear (sometimes called oxidation wear) is common to the metals and other corrosion susceptible materials. This type of wear occurs mostly on metallic iron based materials (steel, cast iron etc.). Surface of the material is covered by the corrosion layer, which has different properties than material itself. In most cases during friction process, the corrosive layer is removed quite quickly and friction properties return to required values. In some cases, the layer is not removed in the process so it is necessary to remove it prior to inducing friction in order to maintain desired properties.

Corrosive layer tends to build on surfaces, which are fresh and not used frequently. Due to the changes in the surface layer, the surface corrosion in friction brakes declines in time as friction surface becomes smooth and porosity of the materials becomes smaller.

There is also a second type of corrosion wear connected to the fatigue wear. This type occurs when corrosion penetrates material through cracks and causes detachment of the portions of the material.

2.5. Metallization

Metallization type of wear occurs when particles of metal from one friction material are transferred to its counterpart (most often resin based composite). In order for metallization to happen, there have to be a few conditions met:

- Friction surface temperature higher than resin destruction temperature,
- Plastic deformation, fatigue and defects on the metallic part,
- Destruction of oxidation layer on friction surface,
- Decarbonizing of the metallic part,
- Hardening of the metallic particles that will be transferred to the non-metallic material.

After meeting the conditions, metallization can occur in two mechanisms:

- Metallic particle removed from one of the materials is transferred to the counterpart. The particle is pressed into the counterpart and starts growing due to the transfer of other metallic particles sticking to it. During the process, there is a rise of the temperature of the metallic particle. It can cause more metal removal from metallic material or, when the base material around the particle is destroyed, previously transferred particles can stick back to the metallic material causing destruction of the non-metallic material by cutting it,
- Second mechanism is similar to the first one except that the initial metallic particle originates from loose particles occurring in friction zone instead of being removed from metal part of friction pair. Rest of the mechanism is as described above.

2.6. Pressure wear (explosion wear)

Pressure or explosion type of wear can be described as catastrophic type of wear. It can be induced by building up the pressure inside the friction material what results in momentary destruction when pressure reaches critical level [1]. Pressure wear can happen when gas or low evaporation temperature liquid penetrating porous friction material is present. For example cleaning resin based friction material with gasoline can cause material destruction when friction induced temperature rises before vapours of gasoline can evaporate. Another example is hydrogen that can accumulate in the material and its pressure can cause delamination of the material – this type of wear is also described as hydrogen or pressure wear.

In friction brakes, all of the described wear mechanisms occur except for pitting where lubrication fluid is necessary in order for wear to happen and fretting which occurs only in constant oscillating motion.

Summarizing, in friction brakes all of the wear mechanism are present (except these mentioned above) but their occurrence and magnitude varies with braking parameters change [8]:

- with small contact pressure and low temperature – mostly abrasive wear and mechanical destruction of the material (adhesive wear),

- as the braking time increases – abrasive wear and fatigue wear,
- further rise of the contact pressure, velocity and temperature – more of the fatigue wear (surface microcracks),
- high temperature rise along with more rise of the contact pressure – thermally induced fatigue wear, adhesive wear is dominant, and metallization occurs.

3. Wear testing methods

Wear testing is performed in many ways. Primary testing technique is the use of tribological machines (tribometers) in order to test material alone in fully controlled environment. Tribological machines are built in a number of variations and configurations. Testing interface of tribological machines changes due to the configuration and can be in form of a flat surface or a sharp pin (pin-on-disc configuration) (Fig. 2b), a round surface (ball-on-disc) (Fig. 2a) or a flat surface on a round surface (block-on-disc) (Fig. 2c). Tribometers in general can perform testing with constant speed and/or constant friction force applied to the friction material or pair.

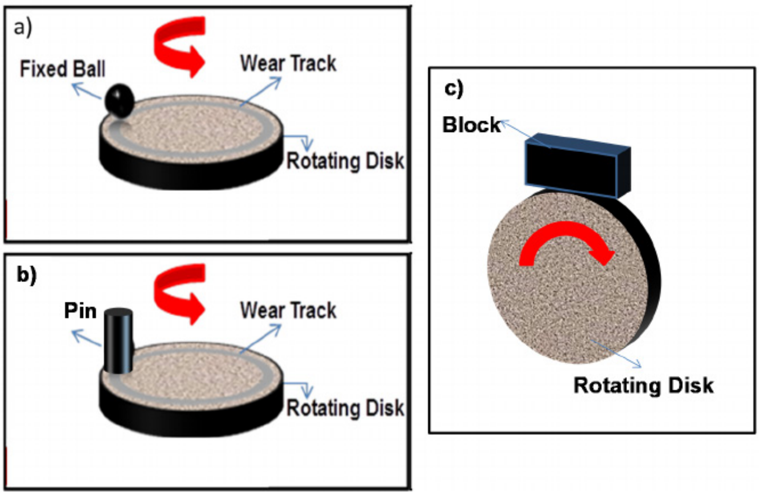

Fig. 2. Most common tribometer configurations [4]

In most cases, tribometers are not capable of performing tests using forces and speeds from the friction brake operation range so their use is limited to measuring general tribological properties of materials e.g. static and kinetic (dynamic) friction coefficient or general wear in required time of operation.

For brake material wear testing (as well as for general material performance testing) inertial type test stands are used on which the real time braking parameters can be set. These machines are built in two main configurations: one for material only testing (called model testing) and second configuration for full-scale brake testing.

Principle of operation is similar in both configurations. Inertial type test stand is a flywheel, which can be accelerated to desired speed and then stopped by the friction pair braking capability. Most often flywheel has adjustable inertia and speed in order to meet energy requirements of the test.

Model testing inertial type test stands are used to test only friction pair materials with stable and repeatable braking parameters independent from brake design and configuration. Tests made using model testing inertial type test stands are the best way of acquiring material data before using it in the brake or to test, the production samples of materials are in order to check if they meet the application requirements.

Full-scale inertial type test stands are used in order to check friction material in fully operational brake. Tests are carried out to be as close as possible to real braking conditions. Full-scale tests are intended to check brake efficiency, stability, mechanical properties, durability and wear. Full-scale wear testing is performed during brake certification and when the brake is recertified in desired periods in order to check if it meets, assumed parameters especially wear level.

Wear measurement is performed in many ways. On tribometers, there are special measurement systems that can measure loss of material in real time during the test. Loss of material is measured mainly by the changes in linear parameters such as material thickness. Wear types measurement (observation) is made mostly using optical methods such as cameras or microscopes. Most of the measurements in friction area are performed not during the test but after due to impossibility of direct observation.

In tests using inertial type test stands main wear parameter is loss of material thickness and its weight measured as difference between initial and final state of the material (before and after the test).

Some of the phenomena including wear products emission can be observed during the test using high-speed cameras or thermography (taking into account that wear products have much higher temperature comparing to ambient).

4. Example of friction brake wear testing

As an example of standard wear testing in friction brake, material Institute of Aviation Landing Gear Laboratory [9] tests are described.

Friction material model testing is carried out using IL-68 (Fig. 3, Tab. 1) inertial type test stand. IL-68 is designed for friction materials testing mainly for brake use. In normal test operation one test covers full braking from start velocity V_{max} to full stop ($V_{end} = 0$). Typical test campaign [2] consists of 5 to 8 bed-ins for establishing most efficient geometry of friction pair in contact zone and 10-qualification tests that are performed in order to evaluate various properties of braking process such as material friction coefficient, wear, temperature or braking time in designated conditions.

Methodology of the full-scale tests is similar [6] but much larger inertial type test stands are used and test campaign consists of 10 bed-ins and up to 100 qualification brakings of tested brake (equipped with wheel and sometimes with other parts of the landing gear or suspension). Example of technical parameters of M3T full-scale inertial type test stand used in Landing Gear Laboratory is shown in Tab. 1 and example of test set-up is shown in Fig. 4.

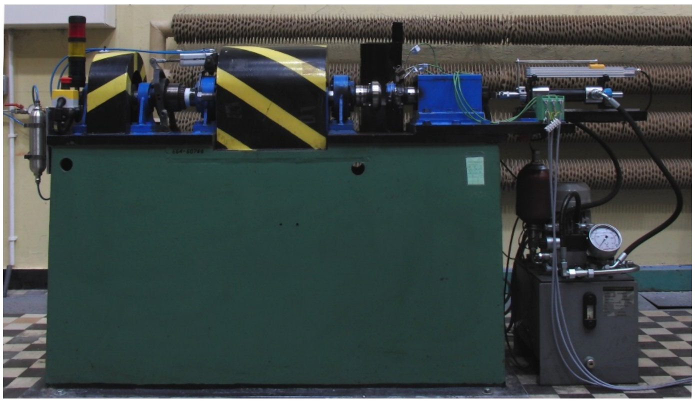

Fig. 3. IL-68 test stand side view

Fig. 4. Example of full scale brake test set-up

Tab. 1. Selected technical parameters of IL-68 and M3T test stand

Name	IL-68	M3T
Max. Rotational Speed	9000 rpm (150 rps)	800 rpm (13.3 rps)
Max. Torque	from 0.154 up to 1.54 kgm^2	from 294 up to 843 kgm^2
Max. Clamping Force	5.88 kN	varies with brake

In order to observe and estimate wear intensity during braking thermographic camera can be used to record emission of hot wear particles in test area [7]. Thermographic camera is the best way of wear observation due to particle size and short cooling time which makes them impossible (hard at best) to see with the naked eye or regular camera. Note that visual observation can only give rough estimation of the wear process and is not precise measurement method. Example of camera position during tests is shown in Fig. 5, and release of hot wear products is shown in Fig. 6.

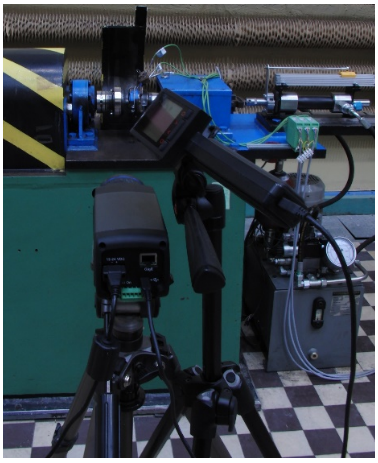

Fig. 5. Thermographic camera position during tests

Fig. 6. Image showing hot particles leaving friction area

In the IL-68 based tests, friction material wear is calculated as difference between initial and final thickness of the material (the thickness is measured before and after the tests). Examples of wear of selected materials are shown in Tab. 2. Sometimes, when the geometrical wear is significant, weight wear calculation is also used (difference between initial and final weight). Results from full-scale test are shown in Tab. 3.

Tab. 2. IL-68 wear tests results for various friction materials (average wear of single braking after 10 brakings, cast iron counter sample in all tests)

	Resin based composite	Resin based composite	Resin based composite	Caramic-metallic sinter	Resin based composite
Friction material wear [μm]	27	22	15	6.0	92
Counter sample wear [μm]	2	1	1.5	4.0	4
Friction material wear [g]					0.44
Counter sample wear [g]					0.37

Tab. 3. Results of full-scale test (M3T test stand)

	Name of brake assembly		
	Front	Middle	Rear
Average wear of single braking after 30 brakings [mm]	0.038	0.042	0.035

5. Summary

Wear is the phenomenon plays important role in all friction systems. In general, wear is not desirable due to the damages of friction pair materials. Engineers in most designs want to remove as much of wear as possible. One of the several mechanical systems where friction is needed is friction brake system. In this case, wear is also, to certain degree, necessary in order to allow friction surface to stay in optimal shape and to preserve friction coefficient in its nominal value – mostly by presence of the abrasive wear.

Unfortunately, not only positive aspects of wear are present in friction brakes. Most of the phenomena can lead to permanent change of the operating characteristics of the brake or even to fatal damages resulting in brake destruction by mechanical and thermal fatigue wear or thermal based adhesion wear. Even inappropriate maintenance can lead to wear or destruction of the brake by corrosion or pressure wear.

Nowadays there are several techniques of brake materials testing before application. Starting from tribometers and ending on inertial type test stands capable of matching brake parameters. Wear estimation in friction brakes are mainly based on geometry and weight changes of the friction pair. In addition, visualisation of the wear process via e.g. thermographic cameras can help to estimate and for better understand the wear in friction brakes.

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