Frictional Vibration of Anodic Alumina-based Ceramic Friction Pairs and Brake Pads (Effects of hardness, deformation and porosity)

Maksim Kireitseu, Sergey Yerakhavets, M. Istomin
Department of Mechanics and Tribology
Institute of Machine Reliability (INDMASH), National Academy of Sciences of Belarus
Lesnoe 19 - 62, Minsk 223052, Belarus e-mail: indmash@rambler.ru

This paper presents a new view on frictional vibration observed in friction pairs and brake pads or brakes, considering hardness, deformation and porosity characteristics of anodic alumina based ceramic material to be used as friction resistant layers. A stability criterion is derived on the assumption that vibrations in two directions, tangential and normal, are coupled. In comparison with experimental results, it is confirmed that the criterion can predict the stability limit more accurately than the conventional one, which does not consider deformation of friction material and depends only on the gradient of friction coefficient to sliding velocity. Based on the criterion, influences of material properties on stability to frictional vibration are discussed.

For more information, contact:
Dr. Maksim V. Kireitseu
Department of Mechanics and Tribology
Institute of Machine Reliability (INDMASH)
Lesnoe 19 - 62, Minsk 223052,
Belarus
Email: indmash@rambler.ru

Introduction

Brake pads usually operate in strong conditions of complex load, thermal and mechanical stresses, few are less forgiving in the event of a failure. Thus, one of the considerations in the design of an automotive brake system is the reliable work and durability of the brake pad system.

For many years the automotive brake systems has been manufactured from low-carbon steel. On the other hand, an advantage that aluminum has over steel is high corrosion resistance, low weight as well as the manufacturing cost. For many companies this means looking for better alternative in technologies that are used to coat aluminum with hard alumina layer, a coating technique is under increasing pressure of an environmental-protection standpoint.

Alumina is one or more superficial coatings applied to improve wear and corrosion resistance, load rating and thermal stability of aluminum parts.[6] Although coating composition has changed in the best mode since the original anodized alumina layer to modern hard alumina formed by microplasmic or micro arc oxidizing process,[1-3] coating application remain a problem. In particular, this paper will consider the aspects in application of the alumina coatings in brake pad systems, where dynamic forces actively influence on balance of the disk.

Friction affects several aspects important to the design of kinematic couplings, in particular, that is based on composite oxide ceramic coatings. In fact, the ability to reach centered position is fundamental to reach performance and durability of friction units that depends on deposited protective coating on contact surfaces[1]. Usually, it becomes centered when contacting surfaces are fully seated even though a small uncertainty may exist about the exact center where potential energy is a minimum value.

For many applications, centering ability is a good indicator for optimizing the coupling design. Typically, the coupling design process has been largely heuristic based on a few guidelines.[5] Several simple kinematic couplings (for example, a symmetric three-point coupling that is friction disk and three pads sliding on frictional surface) are compared for centering ability using closed-form equations. More general configurations lacking obvious symmetries are difficult to model in this way in the break disk with alumina-based composites.

Problem overview

Kinematic couplings serve many applications that require: 1) separation and repeatable engagement, and/or 2) minimum influence that an imprecise or unstable foundation has on the stability of a precision component. An object that is rigid, relatively speaking, requires six independent constraints to exactly constrain six rigid-body degrees of freedom. This paper deals only with six-constraint alumina-based couplings supported through local surfaces and held in contact by a consistent nesting force. Quite often the nesting force is the weight of the object being supported, or it may result from a spring or other force device. Ideally, the nesting force causes all surfaces to engage freely and with uniform loading.

Figures 1 and 2 show the type of kinematic couplings that are particularly used in motorcycle brake systems. In general, the symmetry of the brake pad offers several advantages: more uniform contact stresses and corresponding loads, thermal expansion about a central point and reduced manufacturing costs due to identical features. Conversely, the cone offers a natural pivot point for angular adjustments.

In order to the work of the brake pad system the satellites interact with opposite contact surface in multipoint contact, in which the contact pressure is distributed in different magnitudes on contact points. In a whole, the coefficient of uniformity in pressure distributed on the contact surfaces depends on the accuracy and rigidity of geometric sizes in the system as well as on opposite position of contact points in the system.

The local contact areas typical of these kinematic couplings are small and require a Hertzian analysis to ensure a robust design. In some cases, greater durability is achieved by curvature matching such as a pad against a concave surface and/or by using ceramic materials such as alumina. It is expected that designs based on line contact rather than point contact offer a significant increase in load capability. Alternatively, in view of geometrical design the three-tooth coupling is based on three theoretical lines of contact formed between cylindrical and flat teeth. Each line constrains two degrees of freedom giving a total of six constraints. Manufactured with three identical cuts directly into each coupling half, the teeth must be straight along the lines of contact but other tolerances can be relatively loose. In this paper, the term kinematic coupling refers to any connection device based on pairs of contacting surfaces that provide six constraints in an ideal sense.

The objective of the paper is to consider dynamic of kinematic coupling as basis for application alumina-based ceramic coatings to be used on.

Experimental technique

Technological process to produce the alumina coating consists of micro arc oxidizing processing of the contacted surface to decrease the roughness and modify surface structure of aluminum into hard alumina layer. The treated part is fixed in the special steel-polymer unit protecting the rest surface from oxidizing in the bath. To produce the layer applied current density was between 10-15 A/dm^2 and voltage between U = 420-440V during 45-50 min.

Usually, aluminum parts deepen and oxidized into electrolyte is coated with alumina layer in all surfaces. To form alumina layer on the working surface of brake pads specialized protective unit (see fig. 1 ref.1) was developed.

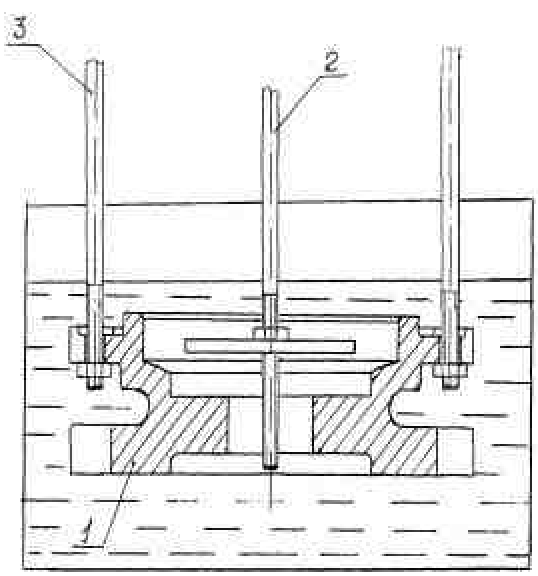

Figure 1. Brake disk unit in the bath.

In the figure 1 number 1 is the main body of the brake disk unit, number 2 is the electrode that provides charge to the surface, number 3 is electrode that connects the part with power block of micro arc oxidizing equipment.

In the system on fig. 2 the intensive friction forces appear on the interacting satellites 7 and the bronze parts 9, inside surface of satellite 7 that interacts in sliding contact with part 6, wheel element 1, inside surfaces of the body 3 and the aluminum part 11. The sliding velocity of the system is about 3 m/s, whereas contact pressure reaches up to 20 MPa and more. Basically it increase temperature and could lead to localized failure due to misbalanced load during stopping.

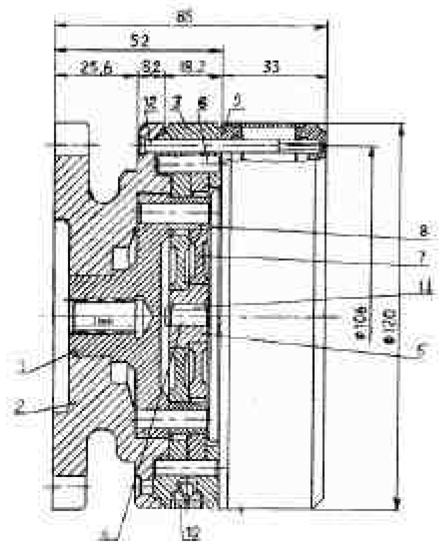

Figure 2. Brake disk in detailed view.

Results & Discussion

Friction affects at least four important characteristics of a kinematic coupling as indicated by order-of-magnitude estimates[3,4] that all include the coefficient of friction ì in the frictional couple as alumina vs. steel.

1) Repeatability
$$\frac{f}{k} \approx m\left(\frac{2}{2R}\right)^{1/3} \cdot \left(\frac{P}{E}\right)^{2/3} \quad (1)$$

2) Kinematic support $$|f_t| \le m\cdot f_n \quad (2)$$

3) Stiffness $$k_t = k_n \frac{2-2n}{2-n}\left(1-\frac{f_t}{m\cdot f_n}\right)^{1/3} \approx R\,k_n \quad (3)$$

4) Centering ability $$\frac{f_c}{f_n} \approx 0.5-1.3m \quad (4)$$

where P is applied load, E is Young modulus, í is Poisson coefficient of alumina, R is radius of the disk. Tangential friction forces at the contacting surfaces may vary in direction and magnitude depending how the coupling comes into engagement. This affects the repeatability of the coupling and the kinematic support of the precision component. The estimate for repeatability is the unreleased frictional force multiplied by the coupling's compliance. The estimate is derived as if the coupling's compliance in all directions is equal to a single Hertzian contact carrying a load P and having a relative radius R and elastic modulus E. The frictional force acts to hold the coupling off center in proportion to the compliance. This estimate will underestimate the repeatability if the structure of the coupling is relatively compliant compared to the contacting surfaces.

Kinematic support is important for stability of shape of the precision component and the composite structure. The estimate for kinematic support simply gives a bound on the magnitude of friction force acting at any contact surface coated by alumina layer. A sensitivity analysis of the precision component will determine a tolerable level of friction that the coupling can have. This may drive the design to include flexure elements and/or procedures to release stored energy. On the other hand, if repeatable engagement is not so important, then constraints using rolling-element bearings offer very low friction.

In some cases frictional overconstraint is valuable for increasing the overall system stiffness, especially by using alumina-based units that provide coefficient of friction above 1 under dry contact. Provided the tangential force is well below what would initiate sliding, the tangential stiffness of a Hertz contact is comparable to the normal stiffness.[4]

Centering ability can be expressed as the ratio of centering force to nesting force and the estimate shown is typical. A larger ratio means the coupling is better at centering in the presents of friction. Later, it is convenient to express centering ability as the coefficient of friction where the ratio goes to zero. For the estimate, it was accepted that the limiting coefficient of friction is 0.3/1.5 = 0.2 to provide erective breaking in machine. In general, the coupling will center if the real coefficient of friction is less than the limiting value.

The contacting surfaces of alumina-based kinematic coupling come into engagement sequentially unless it is placed precisely at the exact center. The path to center is constrained by the surfaces already in contact. For example, four surfaces in contact constrain the coupling to slide along a well-defined path. Four surfaces in contact allow motion over a two-dimensional surface of paths and so forth. Although there are infinitely many paths to center, only the limiting case is of practical interest for determining centering ability. Further, it is reasonable to expect the limiting case to be one of six possible paths that have four surfaces in contact. The point is demonstrated in view of design aspects and mechanical properties of alumina using the alumina-based break pads.

For any given path to center, the centering force that results from the nesting force may be derived using Static and the Coulomb law of friction.

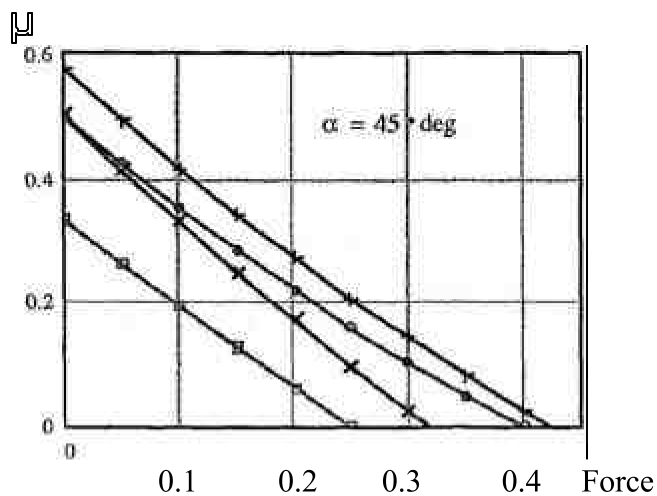

Figure 4. Centering dynamic force vs. coefficient of friction.

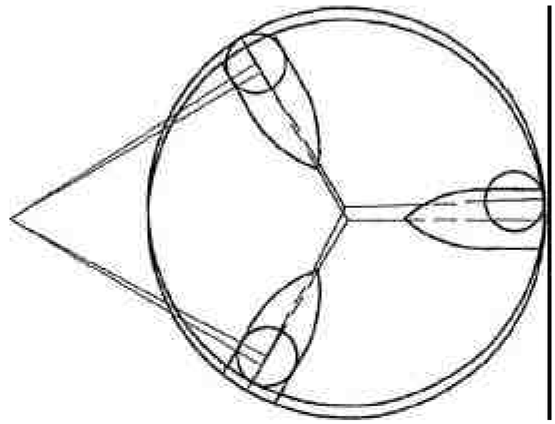

Figure 5. The limiting case for centering occurs when three steel break pads contact the alumina surface of the disk.

The three-point coupling slides on four surfaces producing rotation about its instant center in an idealized case.

Figure 4 shows examples of centering force (per unit nesting force) plotted versus the coefficient of friction that is based on semi empirical relations derived from investigated porosity, hardness and structure of the alumina coating[6,7]. These curves were generated from closed-form equations yet to be published in detail. Although the curves look simple, the equations are rather tedious to develop even when the coupling has simple geometry and the load is symmetrical. Compound this with the possible number of paths to center and it becomes obvious that a systematic, computer-based approach is essential for designing more general configurations of alumina-based couplings.

Figure 5 shows a symmetric three-point coupling rotating about its instant center to reach the center position. This path has four surfaces in contact and is the limiting case along with four other symmetrically identical paths. Equation 5 provides the centering force for this path assuming the nesting force is uniformly carried by three pads. Note, the sides of the contact points are an angle a with respect to the plane of the three pads. In addition, there are two sets of symmetrically identical paths having four surfaces in contact.

$$\frac{f_c}{f_n} = \frac{\sin a - m \cdot \cos a}{2(\cos a + m \cdot \sin a)} - \frac{\sqrt{3}m}{3 \cdot \cos a} \tag{5}$$

$$\frac{f_c}{f_n} = \frac{\sin a - m \cdot \cos a}{2(\cos a + m \cdot \sin a)} - \frac{\sqrt{3}m}{3 \cdot \cos a} - \frac{m}{3} \tag{6}$$

$$\frac{f_c}{f_n} = \frac{\sqrt{4 - \tan^2 a} \cdot \sin a - 4m}{2(\sqrt{4 - \tan^2 a} \cdot \cos a + m \tan a)} \tag{7}$$

This example shows that the path with four surfaces in contact has less centering force than either path with four surfaces in contact. This may not be universally true for a general kinematic coupling. That is, a path with four surfaces in contact may have greater centering force than another path with four surfaces in contact. However as the coupling continues toward center, the centering force cannot increase as it picks up the fifth contact surface. Thus, we need only look at paths with four surfaces in contact to determine the limiting case.

It is also useful to compare the centering forces for the other types of kinematic couplings. Figure 5 shows the cone-point-flat coupling translating along its point. This path is underdetermined for a conical socket but is representative of the limiting case. It was chosen to simplify the expression for centering force given in Equation 6. Referring back to Figure 3, it may come as a surprise that the cone-point-flat coupling has the least centering ability of the three types. However, significantly improvement is possible by carrying more loads with the cone and by increasing the cone angle.

Equation 7 gives the centering force for the three-tooth coupling as it translates on four surfaces. The centering force with four surfaces in contact is very difficult to model in closed form but behaves similarly to the limiting case for the three-point coupling. For example, the limiting coefficient of friction for the three-points coupling is 0.317 at á = 45° or 0.364 at á = 60°.

Conclusion

Design of alumina-based kinematic break couplings have been discussed in view of dynamic forces affecting on coefficient of friction and balance of the system. The equations for three-points contact of steel pads vs. alumina surface is found to be effectively used while design of the break couplings.

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