The friction surface destruction mechanism in a magnetic field

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Abstract. The paper considers the mechanism of forming and developing brittle (quasi-coarse) cracks in a sample of ferromagnetic material in a magnetized state. It is shown that the external magnetic field affecting friction surfaces has the most significant effect on the wear process if the cracks open perpendicular to the magnetization vector. The paper describes the criterion of spontaneous crack growth in brittle materials taking into account magnetostatic energy.

1. Introduction
Tribology researchers pay great attention to the search for promising methods of physicochemical and mechanical [1-7] effects on friction processes to purposefully change them in the desired direction. In particular, they try to stimulate the processes occurring in the frictional contact zone by an electromagnetic field, electric current, vibration, and a mechanical stress state [8, 9].

In recent decades, the interest in studying the effect of a magnetic field on friction and wear of materials with different properties and structures under different contact conditions of surfaces still exists [10-12]. Continuous studies have not given significant scientific results. It was not possible to establish reliable and well reproducible effects that occur when a magnetic field is applied to the friction zone. As a result, there is a lack of understanding the physical mechanism of friction processes in a magnetic field. The importance of studying tribomagnetic problems is also due to the fact that the design of many modern tribounits involves magnetic fields [13].

The destruction of friction surfaces of machine parts is often brittle or quasi-brittle and occurs as a result of fatigue wear. This type of wear is typical for rolling and sliding bearings, cam mechanisms, gears, etc. The first stage of fatigue wear in the surface layer of materials involves accumulation and displacement of dislocations accompanied by crack formation. At the second stage, the crack increases in size, which leads to separating of surface material particles.

Therefore, the purpose of the work was to study the role of magnetostatic energy in the forming and developing cracks in ferromagnetic materials that were in a brittle state.

2. A brittle crack physical model in a magnetic field
Let us consider how cracks form and develop based on the Griffith energy theory taking into account the magnetization of materials. We will study the formation of cracks in structural materials with high saturation magnetization (1–2 T), i.e. in materials based on ferromagnets - iron, nickel or cobalt.

We suppose there is a relatively large body in a uniform field of tensile stresses applied at infinity. Let the body have a straight crack with \( l \) width and unlimited length. There is no magnetic field. The critical values of \( l \), crack width and \( \sigma \), stress, at which the crack begins to expand spontaneously and
indefinitey, can be determined as follows. In the absence of a crack, a uniformly stretched body has accumulated elastic energy with a bulk density equal to \( \omega_{\sigma} = \frac{\sigma^2}{2E} \), where \( E \) is Young’s modulus.

After the crack occurrence, the elastic energy will drop in its surrounding area. We can roughly assume that such stress relaxation occurs in the \( l \) order region. The elastic energy stored in the body per unit length will decrease by a value proportional to the square of its width:

\[
\Omega_{\sigma} = \frac{\sigma^2}{2E} l^2.
\]

(1)

The crack opening is accompanied by an increase in surface energy due to forming a new phase interface with a specific area proportional to the doubled crack width:

\[
\Omega_{\gamma} = 2\gamma l,
\]

(2)

where \( \gamma \) is the specific surface energy.

If we ignore temperature changes, then the system free energy will consist of bulk elastic energy and crack surface energy. The value of free energy as a crack width function passes through a maximum. The maximum of free energy corresponds to a critical crack size that is equal to:

\[
l_c = \frac{2\gamma E}{\sigma^2}.
\]

(3)

A crack with a size larger than critical \( l_c \) is unstable and spontaneously increases its size, which leads to a fragile body destruction. A crack with a size smaller than the critical one seeks to reduce its size; however, this is not always possible in real conditions. It is easy to show that the real strength of a fragile body according to Griffiths is equal to:

\[
\sigma_c = \left( \frac{2\gamma E}{\pi l} \right)^{1/2}.
\]

(4)

Using more accurate calculations, Griffiths has found the exact critical stress value (\( \mu - \) Poisson’s ratio):

\[
\sigma_c = \left( \frac{2\gamma E}{\pi \left( 1 - \mu^2 \right) l} \right)^{1/2}.
\]

(5)

The possibilities of applying the theory of brittle fracture go far beyond that relatively narrow class of materials that are truly brittle (silicate glass, fused silica, and some others). Experimental studies have shown that during cracks formation, some materials, which behave as plastic ones during tensile tests, are destroyed so that plastic deformations are concentrated in a thin layer near the crack surface. The results of experiments with such materials confirm the Griffiths formula for critical stress. However, the determined magnitude of the effective surface energy is much bigger than the surface one. Similarly, we consider the case when a crack is formed and develops in a ferromagnetic body in a magnetized state. We will consider two extreme cases of a crack location with respect to a magnetizing field - parallel and perpendicular (Figure 1). The magnetizing field induction in a ferromagnet \( B_0 = \mu_0 H_0 \) (\( \mu_0 \) is a magnetic constant, \( H_0 \) is the magnetizing field strength) is usually two or three orders less than the magnetic field induction in a substance \( B_m \).
Figure 1. Magnetic field topography in the area of longitudinal (a) and transverse (b) cracks.

After a crack opens, a magnetic field appears in it, the bulk density of its magnetostatic energy is as follows:

$$\omega_B = \frac{BH}{2} = \frac{B^2}{2\mu_0},$$  \hspace{1cm} (6)

where $H$ and $B$ is the magnetic field intensity and induction in the crack cavity. It is taken into account that inside the crack it is $H = \frac{B}{\mu_0}$.

Volumetric energy in a uniformly magnetized substance:

$$\omega_{B_m} = \frac{B_m H_0}{2}.$$  \hspace{1cm} (7)

To calculate the total energy of the magnetic field in the crack cavity, it is necessary to know a characteristic transverse size of the crack. If the stresses relaxed in $l$ region, in accordance with the assumptions made, then according to Hooke's law, the crack characteristic transverse size $h$ can be written as follows: $h = \frac{\sigma l}{E}$. Then the magnetic field energy per crack unit length is equal to:

$$\Omega_B = \frac{B^2 l^2}{2\mu_0 E}.$$  \hspace{1cm} (8)

We express this energy through the magnetic field induction in a substance $B_m$ and the magnetizing field intensity $H_0$, i.e. through easily determined quantities. Since the crack is very narrow, then at its initial location in the direction of the magnetization vector, the magnetic field induction lines of force will bend around it. Magnetic field induction in the crack $B = \mu_0 H_0$, and, therefore, the field energy is equal to:

$$\Omega_{B_1} = \frac{\mu_0 H_0^2 l^2}{2 E}.$$  \hspace{1cm} (9)

In another case, when the crack is perpendicular to a magnetization vector, the lines of force pass through the crack, therefore, the field in it will be significantly higher: $B = B_{m}$. The magnetic field energy with this location of the crack is equal to:
The above equations suppose that the free magnetic energy of the body during a longitudinal crack formation slightly decreases, and with a transverse crack formation it increases significantly.

It is easy to show that the change in the magnetic field specific energy during a transverse crack formation is comparable to the surface energy, and much less than the latter in the case of a longitudinal one. Therefore, it is unlikely that the magnetic state of the material affects the dynamics of a crack located along the field.

After energy calculations of crack characteristics, taking into account the magnetic state of the body, we obtain the equation for the critical width of the crack:

$$ l_c \equiv \frac{2\gamma}{\sigma^2 - \frac{B_m^2}{E} \mu_0} \frac{\sigma l^2}{E} $$  \hspace{1cm} (11)

It is obvious that the greater the magnetic energy compared with elastic energy, the greater a critical width is. The critical stress in the presence of a magnetic field in a substance is approximately equal to:

$$ \sigma_c \equiv \left( \frac{2\gamma E}{l} + \frac{B_m^4}{4\mu_0} \right)^{1/2} $$  \hspace{1cm} (12)

The above expression shows that critical stresses increase in a magnetized material, and therefore it is more difficult to destroy a material in this state. It is difficult to assess the impact of a magnetic field on a critical field, since reliable data for an equilibrium crack length in various materials are not available.

If we consider the crack formation process from a force point of view, then the influence of a magnetic field is reduced to the fact that magnetic attraction between crack walls reduces the action of tensile mechanical stresses. The following equation helps approximately determine the specific magnetic force of attraction of walls (magnetic voltage):

$$ a_B \equiv \frac{B_m^2}{2\mu_0} $$  \hspace{1cm} (13)

3. Conclusion
After evaluative calculations of the crack length $l_c$ for various ferromagnetic materials, we can conclude that the magnetic field affects its critical value at a level no higher than 1–10% in the range of tensile stresses $10^6$–$10^7$ Pa.

The magnetostatic force $aB$ not only prevents fracture, but also contributes to crack collapsing when changing mechanical stresses. It follows from equation (13) that the magnitude order of the specific magnetostatic force in ferromagnetic materials can reach $10^6$ Pa. Therefore, magnetic forces can affect only the destruction of undurable materials or with some external effects on the surface. It should be added that when the crack is longitudinal, magnetic forces also contribute to closing the crack, but their magnitude is 2–3 orders smaller, so their role is also insignificant.

When a solid contacts a surface-active medium, the surface energy of the body decreases, and therefore the strength of the body decreases (Rehbinder effect). The strength of a solid can drop down to $10^6$–$10^7$ Pa, and then the role of a magnetic field in preventing body destruction can be very significant. In tribology, such case may well be observed when lubricating oil is applied to a friction surface or when a metal surface is coated with a thin fusible film formed after chemical interaction of additives with a surface material.
It is also known that under conditions of significant comprehensive hydrostatic pressure, the temporary strength of bodies increases. In particular, this is due to the fact that in the absence of resulting tensile stresses, the crack “collapses” and the material somewhat heals [14]. Magnetic forces affecting crack walls can likewise contribute to the restoration of the friction surface material strength. Such a mechanism of the magnetic field can fully manifest itself if an adsorption layer of environmental molecules has not yet formed on the inner crack surface.

It follows from the above that the magnetic state of a friction surface material most significantly affects the process of its brittle or quasibrittle fracture, if the cracks open perpendicular to a magnetization vector. In a magnetic field, the critical stress of spontaneous crack growth increases. The closer the material strength to $10^6$ Pa, the higher the effect is.

References

[1] Ryabov V V, Kniaziu T V, Mikhailov M S, Motovilina G D and Khuslova E I 2017 Structure and properties of new wear-resistant steels for agricultural machine building Inorganic Materials: Applied Research 7(8) 827–36

[2] Evgrafov A N, Karazin V I and Petrov G N 2019 Analysis of the self-braking effect of linkage mechanisms LNME 119–27

[3] Bashkarev A Y, Bukreev V V, Kuschenko A V and Stukach A V 2017 Adhesive bonding strength of polyamide coating on steel substrate in friction units of machines IREME 11(9) 673–6

[4] Platovskikh M J and Vetyukov M M 2017 Self-oscillations of machines and mechanism LNME 87–103

[5] Dorofeev V L, Golovanov V V and Gukasyan S G 2014 Modification of aircraft gears in order to reduce wear of the contact surface, modern mechanical engineering Science and Education 4 173–83

[6] Shabanov A Y, Galyshev Y V, Sidorov A A and Ivanovsky D K 2016 Research of efficiency of recovery of technical and economic characteristics of the worn-out engine with use of tribotechnical mixes of structures Proc. 5th Modern Mechanical Eng. Science and Education 583–96

[7] Bolotov A N and Gorlov I V 2002 Restoration of worn surfaces by plastic deformation, mechanics and physics of friction contact Inter-Univ. Collection of Papers 9 39–43

[8] Muju M and Ghosh A 1977 Model of adhesive wear in the presence of a magnetic field Wear 41(1) 103–16

[9] Bolotov A N, Novikov V V and Novikova O O 2013 Calculation and Optimization of Permanent Magnets for Special Bearing Supports (Tver: Tver State Technical University Press)

[10] Postnikov S N 1975 Electrical Phenomena in Friction and Cutting (Bitter) 280

[11] Baron Y M 1986 Magnetic Abrasive and Magnetic Machining of Articles and Cutting Tools (Leningrad: Mashinostroenie) 176

[12] Delyusto L G 2005 Foundations of Rolling Metals in Permanent Magnetic Fields (Moscow: Mashinostroenie)

[13] A Bolotov A N, Novikov V V and Novikova O O 2009 Magnetic oils of triboengineering assignment Physical and Chemical Aspects of Studying of Clusters, Nanostructures and Nanomaterials 1 5–9

[14] Bridgman P W 2010 Studies of Large Plastic Deformations and Fracture. The Influence of High Hydrostatic Pressure on the Mechanical Properties of Materials (Moscow: Librokom)