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MEASUREMENT OF METAL TEMPERATURE IN ABRASIVE WEAR

Key words: abrasive wear, heating, fixed wear particles, temperature measurement.

Abstract: Publications from the last several years concerning friction and abrasive wear are reviewed in this paper. The scarcity of studies addressing temperature growth of solids at the time of abrasive friction is notable. Methods are discussed of the author's research to obtain information about the heating of friction elements in the process of abrasive wear of selected metals. An abrasive disk serves as a counter-sample. Thermal measurements at the time of friction helped to determine the heating of specimens, the degree of their heating as dependent on the distance from a friction surface and, to some extent, heating of the counter-sample. The method allowed for a macroscopic temperature measurement. The temperature at friction microcontacts could not be measured. Causes of varied heating of different materials are determined.

Pomiar temperatury metali podczas zużywania ściernego

Słowa kluczowe: zużywanie ścierne, nagrzewanie się, utwierdzone cząstki zużycia, pomiar temperatury.

Streszczenie: W pracy przeprowadzono przegląd publikacji z ostatnich kilku lat poruszających zagadnienie tarcia i zużywania ściernego. Zauważono niewielką liczbę prac zajmujących się badaniem wzrostu temperatury ciał podczas zużycia ściernego. Opisano sposób przeprowadzenia badań własnych mających na celu uzyskanie informacji o nagrzewaniu się elementów trących w procesie zużywania ściernego wybranych metali. Jako przeciwpróbkę dobrano tarczę ścierną. Pomiary termowizyjne podczas tarcia umożliwiły określenie stopnia nagrzania się próbek, stopnia nagrzania się ich w zależności od odległości od powierzchni tarcia oraz w pewnym zakresie także nagrzewania się przeciwpróbki. Zastosowana metoda pozwoliła na makroskopowy pomiar temperatury. Uzyskanie pomiarów temperatury w mikrostykach tarcia nie było możliwe do osiągnięcia. Określono przyczyny zróżnicowanego nagrzewania się różnych materiałów.

Introduction

Abrasive wear plays an important role in human activity. It can be observed in the operation of various machinery and equipment, in manufacturing processes in farming, construction, mining, and other industries. It can occur at room temperature and at elevated temperatures (often associated other types of wear). Abrasion itself is dominated by mechanical effects, with normally negligible chemical and thermal effects. Materials in friction become heated, which does have a substantial impact on friction pair material on the macroscopic level. Temperature may rise in a top layer, which may result in alloy tempering or softening of plastics. Such changes can affect magnitudes like friction resistances or the intensity of wear. Exploration of thermal effects in abrasive wear could answer the question: Does heating of friction elements influence processes of friction and wear and, if so, to what extent?

1. Processes of abrasion in light of current research

A number of publications addressing various aspects of friction and abrasive wear appear globally. These studies can roughly be grouped according to areas of scientific focus.

A wide range of studies analyse individual friction couples using specific materials and co-working parameters [1–29]. Diverse types of materials may be taken into consideration (plastics, composites, coatings, and metal alloys). Wear mechanisms in particular tests are commonly observed and described. These investigations frequently apply to concrete machine parts, and abrasive or cutting tools. They are often of purely practical significance for individual cases of actual equipment. This research is only representative for very narrow ranges of friction conditions (friction couple materials, their thermal, plastic or other treatment, load, the rate of friction, coatings applied, types of pairs, e.g. fixed particles or loose abrasive material and their particular characteristics, etc. These descriptions are commonly of use only for particular engineering solutions and not easily conducive to generalisations. They most often focus on describing wear intensity in selected conditions and occasional attempts are made to define wear mechanisms in place.

Researchers also analyse friction and the wear of single abrasive grains [30–38]. Attempts are undertaken at describing the impact of abrasive grains' shapes on stresses, deformations and displacements of materials in micro-machining zones. Displacements of materials in micro-machining zones are modelled. Abrasion is studied on the nanoscale as well.

Current literature describes effects associated with friction. Modelling of wear and the durability of abrasive tools, the modelling of abrasive grain loading, and spalling are attempted. Precise numerical modelling of abrasive wear of hot forging dies encounters difficulties, because the forecasted wear results diverge from experimental results. Scientists also try do describe the effect of abrading materials attaching to abrasive tools and the significance of this phenomenon for the abrasion of two or three solids. Attempts at linking size, the feed rate, and the shape of sand grains to the progress of abrasive wear can also be encountered in such publications [39–42].

New methods are being developed to evaluate friction or wear characteristics (e.g., the abrasive resistance of specific parts of farming machinery). Studies are also conducted to determine dependences between treatment conditions and the durability of elements required for the purposes of such treatment [43–46].

A large number of publications are devoted to the development of test methods or test stands. Laboratory conditions are produced that resemble conditions in actual machinery and equipment. Research potential is enhanced by building stands that address the maximum possible number of factors present in the process of friction (e.g., volumes of abrasive materials). For fragile and hard metals or ceramics, methods of determining abrasion and crack resistance have been proposed. The possibility of reusing abrasive materials in tribological testing is explored [47–56].

New methods of surface treatment are described that can have positive effects on processes of friction and wear [57].

There are few descriptions of energy effects associated with friction [58, 59]. Some authors describe heating of elements exposed to abrasion [60–64].

One publication describes nanoscale testing of abrasive wear and refers the results to the existing Rabinowicz model [65].

One publication [66] introduces a new tribological tester that provides for a constant abrasion couple subject to abrasive wear. This is important, because stationary and recurrent test conditions can be obtained.

Specific cases of friction and conclusions regarding very restricted friction conditions are most commonly addressed in the literature, whereas attempts at characterising friction and wear in broader (more general) contexts are few and far between. This is due to difficulties with theoretical descriptions of even relatively minor changes of friction conditions. Construction of functional models of friction and wear and energetic descriptions of these phenomena continue to pose a major challenge.

Heating of a friction pair is an aspect of wear that is ignored by a great majority of authors. The impact of temperature growth on the process is normally assumed to be negligible in the case of this wear mechanism (absence of heating effects like deformation, partial melting, triggering, or acceleration of chemical reactions). Only a few studies discuss thermal aspects of frictional wear without exhausting the issue of possible heating in real friction couples. Conditions and results of testing that allow for temperature measurements of elements in friction as part of the abrasive wear process are presented in this paper.

2. Test conditions

These experiments were designed to generate information on the heating of selected metals in the process of wear involving an abrasive disc. Temperature was measured with an infra-red camera. Similar methods of temperature measurement of elements in friction; however, other than abrasive materials, are available in [67].

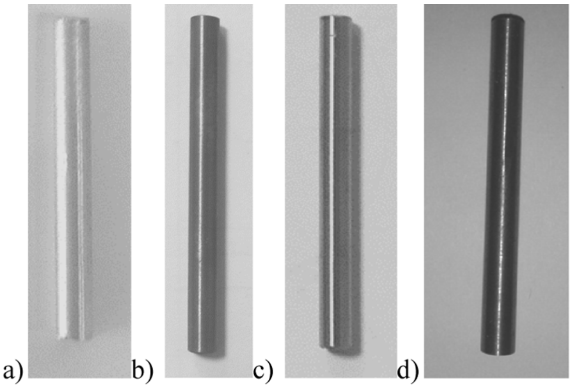


Fig. 1. Metal samples for tribological testing: a) aluminium, b) copper, c) Armco iron, d) wolfram

T-01M was used. Wear of four metals was examined: vacuum refined Armco iron, copper, aluminium, and wolfram. The material samples, shown in Figure 1, were 50mm long rollers with diameters of 5 mm. An abrasive disk was mounted on the revolving table of the T-01M tester to adapt its head to testing of abrasive wear. Depending on the disk type, wear was either non-uniform and highly intensive or non-measurable, as a result of which spaces among grains were filled with metal, causing the “levelling” of the disk. Several tests were carried out to select a disk that would provide for recurrence and reproducibility. A 125x13x20 disk, designated as 34C4880J9 (carborundum, grain 80, hardness – J, structure 9), was finally installed. The test stand including the abrasive disk, a sample, and an infra-red camera as illustrated in Figure 2. The condition of the disk surface reproduces itself as grains of the abrasive material chip off at the time of testing. In addition, the abrasive material adequately models the properties of soil (sand, stones) in which metal tools are operated. Rubbing speed of 0.9 m/s was established as part of the study.

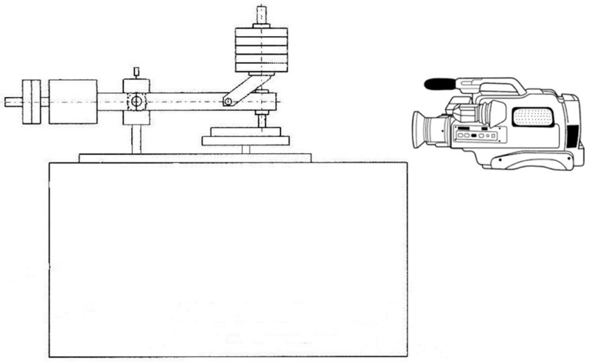


Fig. 2. Diagram of a test stand for measurement of sample temperature in friction against a rotating abrasive disk

The rate of friction adopted is close to the actual rates at the time of road, mining, or agricultural operations. For instance, TBM (Tunnel Boring Machine) Anna that bored the 2nd underground line in Warsaw, reached a linear machining speed of 0.65 m/s. The speeds attained in field farming may be in excess of 2 to 3 m/s. The tester in question is not capable of operation at such high velocities. The contact load was 2.45 N, which meant a unit loading of 0.125 MPa. The ambient temperature in the lab was 21°C, the relative humidity 40 to 50%. Temperature was measured prior to and at the time of each test by means of Thermo Tracer NEC H2640 infra-red camera. Its thermal sensitivity is 0.03°C up to 30°C, it operates in real time, and its frequency of image refresh is 30Hz – 30 frames a second. An emissivity of ε = 0.86 was adopted following trials. Photographs taken were then analysed using Thermography Studio software. The measurements enabled the observation of temperature variations in the sample and counter-sample. Maximum temperatures were noted near the surfaces, in the vicinity of the friction zone. It should be remembered, however, the temperature of the top layer is defined as the temperature of the superficial layer of materials in friction. Metal samples, with their relatively high thermal conductivity, rapidly absorb heat from friction micro-areas. Therefore, the measurements produce general results for the temperature of rubbing objects [64]. Unfortunately, the method is incapable of measuring temperature directly in micro-areas of elements in friction. This problem encounters enormous difficulties and has not been solved satisfactorily. A view of the friction couple used in the testing is presented in Figure 3.

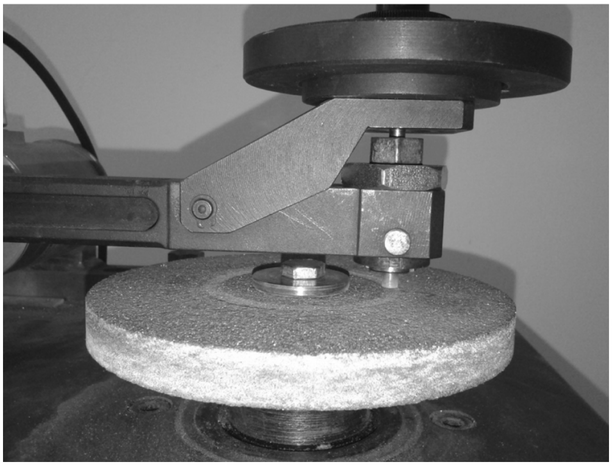


Fig. 3. A view of a friction pair on T-01M modified to test abrasive wear of metals

3. Results

The infra-red photographs of friction couples helped to record temperatures of the materials tested. The maximum temperatures measured are listed in Table 1. The table also characterises selected properties of the materials. The temperature of the disk friction path was not observed to increase for the couplings of copper and wolfram. In the case of aluminium and iron, parts of the disk heated to 22.3ºC and 22.4ºC, respectively.

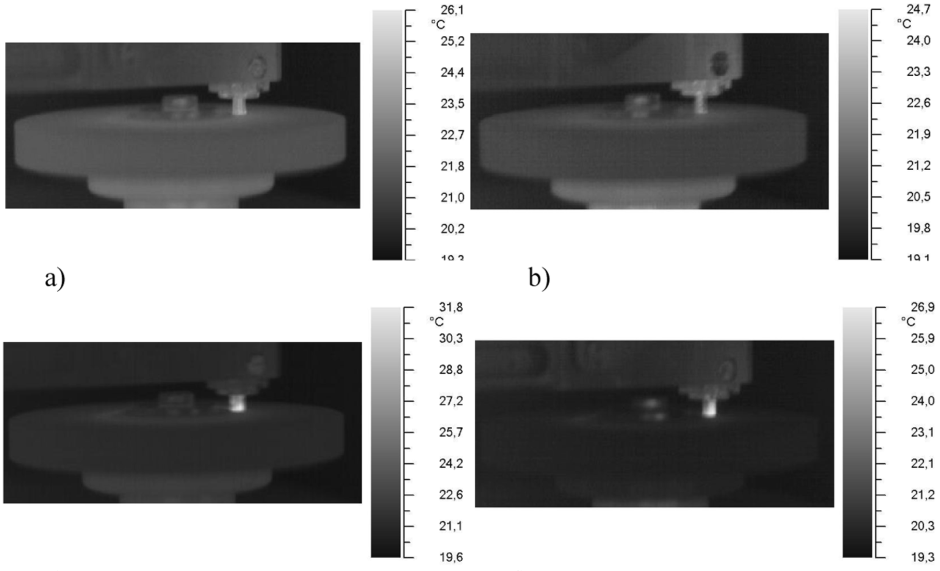
Figure 4 contains infrared images of the samples produced during tribological tests of the materials.

Figures 5, 6, and 7 show temperature diagrams for some lines plotted along the samples. This helped to illustrate variations of sample temperature depending on the distance from the friction surface. The elements tested protruded only 6 mm out of the grippers holding them. This gave rise to difficulties noting temperature distribution across the samples. In the case of copper with the minimum temperature increment, a result demonstrating temperature reduction with the growing distance from the friction surface could not be obtained.

Table 1. Temperatures of selected materials at the time of the tribological testing and selected properties of sample materials [64]

Material	Aluminium	Copper	Iron	Wolfram
Temperature [ºC]	24.1	22.7	31.8	26.9
Temperature growth [ºC]	3.1	1.7	10.8	5.9
Density [g/cm^3]	2.7	8.96	7.86	19.3
Specific heat capacity [J/g·K]	0.9	0.385	0.449	0.13
Thermal conductivity [W/m·K]	237.0	401.0	80.2	174.0

That could be affected by a limited area of the sample subject to temperature measurement coupled with a low temperature growth. The copper sample could have heated more uniformly than others due to its low thermal conductivity.



a) b)

c) d)

Fig. 4. Infrared photographs of the stand while testing samples of a) aluminium, b) copper, c) iron, d) wolfram [64]

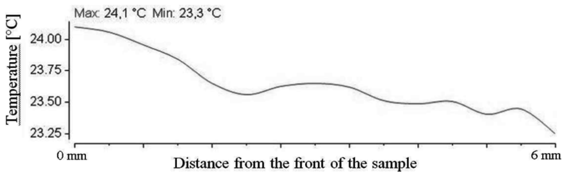


Fig. 5. Temperature distribution across the top layer of the aluminium sample along a measurement line parallel to the sample axis [64]

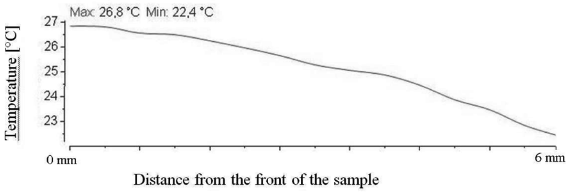


Fig. 6. Temperature distribution across the top layer of the wolfram sample along a measurement line parallel to the sample axis [64]

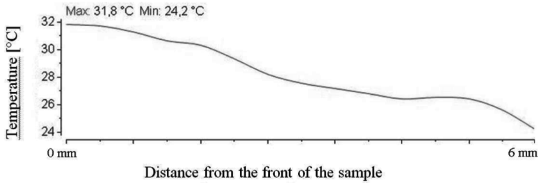


Fig. 7. Temperature distribution across the top layer of the iron sample along a measurement line parallel to the sample axis [64]

Conclusions

The author's investigation helped to evaluate the degree of heating of test samples during friction. In some cases, heating of the counter sample (abrasive disk) was observable as well. Figure 8 shows the friction path along the disk with an increasing temperature of the aluminium coupling. With the exception of copper, the results indicated temperatures falling away from friction zones in spite of the relatively small distances from the friction surfaces – below 6 mm.

The maximum heating of the elements in friction, below 32ºC, indicates no macroscopic impact on wear of thermal transformations associated with partial melting or phase shifts caused by sufficient heating of a material. High temperature increments may be suspected; however, in friction micro-areas, sources of heat were provided to sample volumes. Temperature could not be established directly in friction micro-areas, and neither could its possible effect be established on transformations (e.g., tempering) as part of the testing.

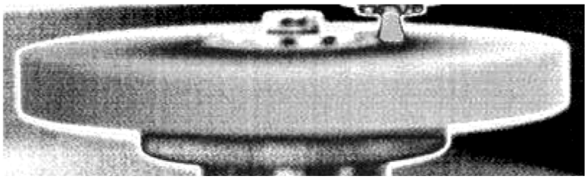


Fig. 8. A clear, dark area on the disk surface, corresponding to an area of elevated temperature – the aluminium test

Sample materials became heated to highly varied degrees. A minimum temperature growth of merely 1.7ºC was noted for copper, with the maximum of 10.8ºC in the case of iron. The divergences among the materials result from a number of factors. Properties such as density, specific heat capacity, and conductivity are the most important. Depositing of the materials on the abrasive disk was an additional influence on the heating of the samples. This was most distinct in this respect with aluminium, where shiny areas of the deposited sample material could be seen along the friction path on the disk. This applied to copper to a lesser extent. Transfer of a material to the counter sample changes the nature of friction which, in the case of aluminium, began to resemble friction of a metal – metal pair. In farming, mining or roadwork practice, the problem of a tool material transferring to a material under treatment (earth, rock, road surface) is basically negligible in view of the properties of materials used which are constantly in friction with new surfaces, and this relates to a great intensity of treatment of materials like soil or rock. The intensity of the disk's wear was not comparable at the time of testing. Heating of the disk surface in the case of aluminium was a result of the sample material deposited on to the disk, while the increasing temperature of the disk's friction path working with the iron sample was connected to the relatively substantial heating of the sample itself.

The testing and measurements allowed the assessment of the degree of material heating at the time of abrasive wear. Regrettably, the method is incapable of establishing mirocontact temperature. This information would be highly useful, because thermal effects in the vicinity of a contact itself could be evaluated. Observations using metallographic microscopy of wear particles could indicate whether any significant thermal effects have taken place in a sample material. However, such observations were beyond the planned scope of this study. In order to arrive at more universal results of temperature measurements, it would be advisable to undertake testing across broader ranges of speeds and unit pressures that correspond to real cases of frictional wear at the time of farming, mining, or roadwork operations. For instance, ploughing rates can be three times as fast as the rate applied in this testing. Sample movement along the same path over the counter sample limits the representation of real friction couples. Although the surface of a friction disk wears and is reproduced, this does not fully correspond to tool movements across soil or rock.

Rather moderate temperature increments of the elements in friction were observed. This can have grave consequences in special cases of real contacts, for instance, in the case of wearing plastics, whose properties change at moderate temperatures. In the circumstances, the growth of temperature may lead to softening or the degradation of a plastic. Abrasion at elevated temperatures is another possible example. Temperature in a frictional couple operated at great temperatures may exceed the limit of phase transitions or trigger chemical reactions affecting friction, wear, or other properties of a rubbing element.

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