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MECHANICAL PROPERTIES OF MATERIALS AND THEIR EROSIVE WEAR

WŁAŚCIWOŚCI MECHANICZNE MATERIAŁÓW A ICH ZUŻYCIE EROZYJNE

Key words:
erosion speed, proper strain energy, wear

Słowa kluczowe:
prędkość erozji, właściwa energia odkształcenia, zużycie

Abstract
In this paper, the authors analyse the impact of selected mechanical properties of materials on their erosive wear caused by a steady stream of solid particles. A wear process is a function of the material properties of two materials that interact with each other in a given environment, i.e. the construction material and the particles that cause erosion. Erosive losses occur upon reaching a critical condition of damaging an element of the material’s surface under the influence of kinetic energy that result from incident particles of an abrasive

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material. It is proposed that the critical condition that accompanies the formation of erosion losses should be represented by the toughness (U) and the specific work of the deformation of the sample in the tensile strength test (W). The study involved the following materials: NC6, 42CrMo4, 20MnCr5, and S235JR.

**INTRODUCTION**

The manner in which a stream of solid particles affects the surface of a given medium causes the process of erosion occurring in this medium. Machine constructors or users select materials satisfying specific conditions, e.g., endurance, corrosion, technological aspects, and resistance to erosion. The problem of erosion is a tribological issue and is associated with occurring losses on the surface of an element and not in its total volume. There remains an open question as to how to diagnose the critical stage of the material and which of its properties determine the speed of erosion [L. 1–4].

Historically, one of such parameters is hardness. There exists a common perception that the harder the material, the less prone to erosion it becomes [L. 5, 6]. However, there appears a problem with plastic and fragile materials. The paper [L. 7] analyses the process of corrosion as resulting from the activity of the elements of a stream of particular energy in a static and normal direction towards the surface. Each direction is assigned specific material constants. Also knowing them in particular conditions of the process, i.e. the familiar speed of the stream and the angle of its inclination to the surface, one can calculate the speed of erosion. Hatchings [L. 8] defines a dimensionless coefficient dependent on density, the limit of material plasticity, and the speed of the stream. This constitutes a basis for a comparative table of speeds of the erosion of various materials. Pogodajew [L. 9], describes a critical intensity of the energy of the stream that is characteristic of a given material.

The impact of the particles of the stream leads to the development of defects, creating a surface layer [L. 10]. Upon the incubation period $t_{ink}$, a surface layer of the depth $h_a$ is formed (Fig. 1). The moment of creating this layer unequivocally means reaching the critical condition. Further influence of the particles of the stream leads to removing the particles of the material from the surface and it is subsequently rebuilt. This also explains why, in specific conditions of the process, the speed of erosion is constant. This constitutes stage III of the erosion curve (Fig. 1).

If the element works with its entire volume, the estimation of its damage is easier in comparison to the assessment of the surface layer only. The particles of the material are ruptured once the critical condition of the damage is reached. This is accompanied by a change of its properties. This may concern, e.g., plastic, magnetic properties, and the properties of acoustic emission. These are changeable in the surface layer at the depth of several μm. The change in the
endurance and plastic properties in the layer \( h_u \) is possible indirectly, e.g., through measuring micro-hardness [L. 10]. A specified level of micro-hardness does not mean the critical condition.

![Image](image.png)

**Fig. 1.** Scheme surface layer on the background of the erosion curve. I – incubation period, II – transition period, III – period of erosion [L. 11]


Erosive losses in the material result from rupturing its particles from the surface layer. While creating the surface layer, plastic deformations occur. This is followed by deformative hardening, where: hardness increases. The impact of subsequent particles of the stream causes further plastic deformations until critical values on the surface of the material are reached, causing losses of its fragments. Reaching such a condition is associated with the specific work of the deformation of a friable material. Hence, this may lead to some comparisons of this process to stretching (compressing) the sample.

In his paper [L. 12], Żochowski defines the coefficient \( D_w \), called damage, in order to compare the level of damage to various materials with the following formula:

\[
D_w = \frac{W - W_s}{W} = 1 - \frac{W_s}{W} \tag{1.1}
\]

where: \( W \) and \( W_s \) – specific work of deformation to rupture of the sample, respectively from the unloaded and deformed material, which becomes damaged and undergoes a permanent plastic deformation \( \varepsilon_p \) (Fig. 2).
This leads to a question about whether specific work of deformation to the rupture of the sample $W$ can measure the material’s resistance to a dynamic erosive impact of the particles of the stream. Still, the work needed to break the sample and referred to a unit intersection is a measure for the toughness $U$ of a given material. These two values characterise the material in its total volume, and how they influence the speed of erosion remains unknown.

![Diagram](image)

**Fig. 2. Comparison of specific work of deformation to rupture of the sample $W$ and having the initial plastic deformation of $W_s$.** [L. 12]

Rys. 2. Porównanie pracy właściwej $W$ – odkształcenia do zerwania próbki i $W_s$ – posiadającej wstępne odkształcenie plastyczne [L. 12]

The paper aims at verifying the possibility of determining the speed of the erosion of a given material based on the knowledge of its specific work of deformation to rupture ($W$) in a tensile strength test and toughness ($U$).

**EXPERIMENTAL TESTS**

In order to achieve its objective of the paper, the authors selected only such materials that can be used in appliances working in erosion conditions. These are steadily NC6, 40CrMo4, 20MnCr5, and S235JR. Erosion tests were conducted on a test stand whose scheme is presented in **Fig. 3**.

The incident angle of the particles was 30°, 60° and 90° at an air pressure in the stream of 5 MPa. Erosive particles were made of quartz sand of granulation shown in **Table 1**. The samples had a shape of a cylinder 50 mm in diameter and 5 mm thick with a two-sided ground surface. The erosion tests were conducted on both surfaces. The loss in the mass of the samples was a measure for their erosive wear. The samples were weighed with an accuracy of 0.001g at every 30 s of the process. Due to the steady speed of the wear, the total time of the trial was limited to 2.5 min.
Fig. 3. A scheme of the test stand: 1 – supply of compressed air, 2 – manometer, 3 – pressure pipe, 4 – stop valve, 5 – guide ring of 6 mm in diameter and 120 mm long, 6 – sand stream, 7 – sample, 8 – fasting grip, 9 – ventilation pipe, 10 – working chamber, 11 – sand container, l = 15 mm – sample distance to outlet of sand stream, \( \alpha = 90^\circ \) – stream impact angle

Rys. 3. Schemat stanowiska badawczego: 1 – doprowadzenie sprężonego powietrza, 2 – manometr, 3 – przewód ciśnieniowy, 4 – zawór zamykający, 5 – kierownica o średnicy 6 mm i długości 120 mm, 6 – strumień piasku, 7 – próbka, 8 – uchwyt mocujący, 9 – przewód wentylacyjny, 10 – komora robocza, 11 – pojemnik z piaskiem, l = 15 mm – odległość próbki od wylotu strumienia piasku, \( \alpha = 90^\circ \) – kąt padania strumienia

Table 1. The content of specific grain fractions in quartz sand

<table>
<thead>
<tr>
<th>The diameter of the grains of quartz sand [mm]</th>
<th>0.6 – 0.4</th>
<th>0.4 – 0.315</th>
<th>0.315 – 0.2</th>
<th>0.2 – 0.102</th>
<th>&lt; 0.102</th>
</tr>
</thead>
<tbody>
<tr>
<td>The content of specific fractions [%]</td>
<td>2.8</td>
<td>14</td>
<td>52.8</td>
<td>28.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The toughness \( U \) was determined in the trials performed on three samples by means of Charpy’s hammer weighing 15 kg. The samples had a sharp notch in the shape of a “V” letter. The tests of immediate stretching were conducted with the use of an extensometer at a measurement length of 25 mm. The nominal diameter of the samples was 5 mm. The study involved three samples of each type of steel. The specific energy of deformation \( W \) was the arithmetic average of the values of fields under the stretch curves in the system of coefficients \( \sigma-\varepsilon \) (stress – deformation).
RESULTS OF THE RESEARCH

Figures 4, 5, 6, and 7 present the results of the erosion trials of specific materials and at three angles of incident particles of the abrasive material, i.e. 30°, 60°, and 90°.

**Fig. 4.** Relation between weight loss and duration of the erosion test performed on samples of steel NC6 (the angle of abrasive particles: 30°, 60°, and 90°)

**Rys. 4.** Zależność między ubytkiem wagowym i czasem trwania testu erozji próbek stali NC6 (kąt padania ścieńiwa: 30°, 60°, 90°)

**Fig. 5.** Relation between weight loss and duration of the erosion test performed on samples of steel 42CrMo4 (the angle of abrasive particles: 30°, 60°, and 90°)

**Rys. 5.** Zależność między ubytkiem wagowym i czasem trwania testu erozji próbek stali 42CrMo4 (kąt padania ścieńiwa: 30°, 60°, 90°)
The values of erosive wear referring to the points in specific Figures are an arithmetic average from the tests performed on three separate samples for given parameters of the test. The analysis of the correlations between the weight loss and the duration of the test samples of specific materials shows that, in the applied conditions of the tests, their linear wear can be adopted from the beginning of the process. This is confirmed by high coefficients of the correlation $R^2$ of straight lines type $y = ax$, approximating the experimental data. This also means that the process of erosion took place with steady intensity.
(speed) equal to the coefficient \(a\). Table 2 presents the summary of the values of the speed of erosion (a) and the converse of the product of toughness and specific work of deformation to rupture (1/(\(U\cdot W\))) referring to a given material and specific conditions of the test.

**Table 2.** A summary of erosion speed of tested steel samples and the value of the function 1/(\(U\cdot W\)); \(U\) – toughness, \(W\) – specific work of deformation to rupture of the sample

<table>
<thead>
<tr>
<th>The incident angle of the particle</th>
<th>NC6</th>
<th>42CrMo4</th>
<th>20MnCr5</th>
<th>S235JR</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>0.0789</td>
<td>0.0744</td>
<td>0.0626</td>
<td>0.0595</td>
</tr>
<tr>
<td>60°</td>
<td>0.0639</td>
<td>0.0476</td>
<td>0.0469</td>
<td>0.0498</td>
</tr>
<tr>
<td>90°</td>
<td>0.0442</td>
<td>0.029</td>
<td>0.0287</td>
<td>0.0386</td>
</tr>
<tr>
<td>1/((U\cdot W)) (\text{[cm}^2/(\text{J}\cdot \text{MPa})])</td>
<td>19.305·10^{-4}</td>
<td>8.915·10^{-4}</td>
<td>0.989·10^{-4}</td>
<td>1.113·10^{-4}</td>
</tr>
</tbody>
</table>

The resulting data provide a chart of the relations of the speeds of erosion \(a\) (incident angle of abrasive particles: 30°, 60°, and 90°) at the function 1/(\(U\cdot W\)) of the steel NC6, 42CrMo4, 20MnCr5, and S235JR. The common property of the tested materials is that the speeds of erosion were biggest at the angle of 30° and smallest at 90°. This is characteristic of materials featuring plastic properties [L. 1, 5]. Each material is characterised by a specific toughness \(U\) and the specific work of deformation of the sample in the tensile strength test \(W\).
The analysis of the data shown in Figure 8 shows that the lack of a linear correlation between the speed of erosion $a$ and the specific work of deformation and toughness was expressed in total as $1/(U\cdot W_{os})$. Based on this relation, it is suggested that both greater toughness and specific work of deformation should correlate to a smaller speed of erosion.

CONCLUSIONS

1. The speed of erosion at the incident angles of stream particles 30°, 60°, and 90° is constant and smallest for the angle 90°.
2. The lack of a linear correlation between the speed of erosion $a$ and the specific work of deformation and toughness, totally expressed as $1/(U\cdot W_{os})$, results from a different mechanism of rupturing the particles in hard and plastic materials (e.g., steadily NC6 and S235JR).

REFERENCES

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Streszczenie

W pracy analizowano wpływ wybranych właściwości mechanicznych materiałów na ich zużycie erozyjne wywołane ustalonym strumieniem cząstek stałych. Proces zużycia jest funkcją cech materiałowych pary materiałów wzajemnie oddziałujących na siebie w danym środowisku, tj. materiału konstrukcyjnego i cząstek wywołujących erozję. Ubytki erozyjne następują po osiągnięciu stanu krytycznego uszkodzenia elementu powierzchni materialu pod wpływem energii kinetycznej padających cząstek ściernia. Zaproponowano, aby stan krytyczny towarzyszący powstawaniu ubytków erozyjnych był reprezentowany przez udarność ($U$) i pracę właściwą odkształcenia próbki podczas jej rozciągania do zerwania ($W$). Badaniu poddano następujące materiały: NC6, 42CrMo4, 20MnCr5, S235JR.