Experimental research results of the aluminum alloy erosion wear at variable parameters of the high droplet impact

A F Mednikov¹, A B Tkhabisimov¹, O S Zilova¹ and A A Burmistrov¹

¹ National Research University "Moscow Power Engineering Institute"
Russia, 111250 Moscow, Krasnokazarmennaya, 14

e-mail: mednalex@mail.ru

Abstract. The paper presents the results of experimental research of the aluminum alloy D16T erosion characteristics conducted with variable parameters of high-speed drop impact. Erosion tests were carried out by using the unique research installation URI "Hydroshock rig” Erosion-M" NRU "MPEI". As a result of the work, characteristic points and periods of erosion wear development of an aluminum alloy under various impact conditions were revealed.

1. Introduction

Currently, leading turbine-building plants are developing new wet-steam stages of powerful turbines with extra-long blades, which predetermines an increase in the circumferential speeds of rotation of such blades on the periphery of the wet-steam stages and a completely new level of the urgency of droplet erosion of blade materials [1-4]. In view of this, in recent years, quite active attempts have been made to develop and implement active and passive methods of protection against droplet erosion [5-10]. These measures should lead to an increase in the service life of such blades before the capital repair of the turbine. Without knowledge of the mechanisms of nucleation and development of the destruction of metals in the case of a droplet impact, it is not possible to solve the problem of significantly increasing the erosion resistance of extra-long blades by using various methods of protection.

To date, there is no sufficiently comprehensive understanding of the kinetics of the destruction of plastic materials under high-speed drop-impact effects with varying collision parameters. A lot of attempts have been made to create universal models of erosion [11, 12], some of which are based on energy, statistical and phenomenological approaches, while others are based on the mechanism of fatigue destruction of metals. Virtually all models have some or other disadvantages, which significantly reduce the limits of their applicability. This situation is due primarily to the complexity and variety of interrelated phenomena occurring in the high-speed interaction of liquid particles with the metal surface.

Earlier in the MPEI V.A. Ryzhenkov conducted experimental studies of blade steel 20kH13 erosion wear (see Figure 1) under different impact conditions (variable collision velocities (\(C_{imp}\)) and droplet diameters (\(d_d\))), which made it possible to establish some of its characteristic features, namely:

1) the first period in the kinetics of erosion wear (incubation stage) is characterized by the \(E_m\) value, constant for different collision conditions (for \(d_d = \text{var}\) and \(C_{imp} = \text{var}\)). Regardless of the collision velocity \(C_{imp}\) and the diameter of the drops \(d_d\), all the tangents drawn to the curves on the period with the maximum erosion rate intersect on the ordinate axis at the same point \(E_m\).

2) also, irrespective of the collision velocity \(C_{imp}\) and the size of the droplets \(d_d\), all the tangents to the curves on a period with a steady erosion rate intersect on the ordinate axis at the point \(E_{st}\).

The foregoing allows us to make the assumption that the quantities \(E_m\) and \(E_{st}\) are indirect characteristics of metals from the point of view of their erosion resistance, at least for the steels 20kH13 and 12kH13 studied earlier. To determine the maximum (\(\dot{E}_m\)) and steady (\(\dot{E}_{st}\)) relative erosion rates and
the construction of nomograms of the erosion resistance of the metal, it is necessary to determine these characteristic points $E_m$ and $E_s$ located on the ordinate axis of the dependence $E=f(m)$ (see Figure 1), where $E$ - depth of wear, $m, m$ - the amount of liquid deposited per unit surface area, kg/m$^2$. To determine the characteristic points $E_m$ and $E_s$ on erosion stands and installations, "curves" of erosion of the samples of the metal under investigation are obtained with at least two different collision velocities $C_{imp}$ and two sizes of liquid particles $d_d$.

**Figure 1.** Curves of erosion wear of steel 20kH13 under various impact conditions ($d_d=var$ and $C_{imp}=var$) [13]

Discovered earlier by V.A. Ryzhenkov these regularities in the kinetics of erosion failure make it possible to determine a fairly simple technique for calculating the erosion wear of metals with a relatively small number of experimental studies [13]. As can be seen from Fig. 2, the dependence $\dot{E}_m=f(C_{imp})$; $\dot{E}_s=f(d_d)$; $\dot{E}_m=f(d_d)$ in logarithmic coordinates are represented with some approximation by straight lines.

**Figure 2.** An example of the construction of the dependence $\dot{E}_m=f(d_d)$ for steel 20kH13 at $C_{imp}=275$ m/s and $C_{imp}=350$ m/s and the dependence $\dot{E}_m=f(C_{imp})$ at $d_d=1500$ μm (→ the dependences obtained experimentally; -- the dependences obtained by the reconstruction) [13]

This approach allows us to construct a nomogram with sufficient accuracy for engineering calculations to determine the maximum $\dot{E}_m$ and the established velocity of erosion for a particular metal with certain properties. After the determination of $\dot{E}_m$ and $\dot{E}_s$, it is possible to determine the average depth of erosion...
wear, depending on the amount of liquid that hit the unit area or the time of the impact. Based on the findings of V.A. Ryzhenkov [13] the fundamental dependences of the rate of blade steel 20kh13 erosion wear on the collision velocity \( C_{imp} \) and the size of the liquid particles \( d_d \) indicate the presence of a critical point, the so-called "pole", upon attaining which, with an increase in the velocity of liquid particles, the effect of the drop size on the wear rate expressed in parameters of the maximum \( \dot{E}_m \) and steady-state \( \dot{E}_s \) relative erosion rates (see Figure 2). As can be seen from Figure 2, as a result of the transition through this point (the "pole") of the convergence of dependencies at high collision velocities-drops of smaller size start to exert the greatest influence on the rate of erosion wear, which may indicate a significant revision of the approach to designing promising "extra-long" blades and developing new erosion-resistant materials and passive methods of protection. The influence of the "pole" on the rate of plastic materials erosion wear with varying parameters of the high-speed drop impact has not been fully studied to date.

To create a "pole" model of erosive destruction of metals and alloys, the present work was aimed at carrying out experimental studies to determine the effect of high-speed drop impact on the wear kinetics of a "model" metal, the aluminum alloy D16T, which, due to its erosion characteristics, allows such studies to be carried out in a wide range of collision velocities and sizes of liquid particles.

### 2 Methods of research

Tests of aluminum alloy D16T experimental samples were carried out by using the unique research installation URI "Hydroshock rig" Erosion-M" NRU "MPEI", entered in the Russian Federation register of unique stands and installations [14]. Experimental studies of aluminum alloy D16T samples were carried out at the given collision velocities of the samples \( C_{imp} = 200, 250, 300 \) m/s with water droplets of known diameter \( d_d = 800, 1000 \) μm. The time for testing the samples varied. To construct an erosion curve for one speed and one drop diameter, at least ten different exposure times were selected.

To perform a comparative analysis of the erosion tests results, the dependence of the erosion wear average depth \( E, \) m on the mass of the liquid deposited on the eroded surface \( (m, \) kg/\( m^2 \)) was constructed. In addition to the collision velocity and droplet diameter, the following parameters were measured during the studies: the distance between the droplets \( (l_d, \) m), the number of drops that collided with the sample \( (N_d) \) during the exposure time \( (\tau, \) s), the area of the eroded surface on the sample \( (S_{er,} m^2) \), weight loss of the sample \( (\Delta m, \) kg). The mass loss of sample was calculated by the formula:

\[
\Delta m_{ij} = m_{0j} - m_{ij}
\]  

where \( m_{0j} \) is the initial mass of the \( j \)-th sample; \( m_{ij} \) is the mass of the \( j \)-th sample after the \( i \)-th experiment; \( i \) is the number of the experiment.

The relative mass loss of the \( j \)-th sample was calculated by the formula:

\[
\Delta m_{relj} = \frac{\Delta m_{ij}}{m_{0j}}
\]  

The relative test time was calculated by the formula:

\[
t_{relj} = \frac{t_{ij}}{t_j}
\]  

where \( t_{ij} \) is the time of the \( i \)-th experiment of the \( j \)-th sample; \( t_j \) - total test’s time of the \( j \)-th sample; \( i \) is the number of the experiment.

The average depth of erosion wear \( (E, \) m) was determined from the following relationship:

\[
E = \frac{\Delta m \cdot (\rho_M \cdot S_{er})^{-1}}{\rho_M}
\]  

where, \( \rho_m \) is the density of the sample metal, kg/m³.

The mass of water deposited on the sample surface of was determined from the following relationship:

\[
m_w = m_d \cdot N_d
\]  

Where \( m_d = V_d \cdot \rho_d = \frac{\pi {D_d}^2}{6} \cdot \rho_w \) is the mass of one drop, kg; \( V_d \) - volume of a drop, \( m^3; \) \( D_d \) - droplet diameter, \( m; \rho_w \) - water density, kg/m³; \( N_d \) - number of drops that hit the sample during exposure time \( \tau \).

The number of drops that hit the sample during the exposure time is defined as:

\[
N_d = K_c \cdot Z \cdot n_{col} \cdot \tau
\]
where $K_c$ - capture coefficient equal to the ratio of the erosion wear zone average height to the distance between the droplet centers; $Z$ - number of drops; $n_{col} = C_{imp} \cdot (\pi D)^{-1}$ - collision frequency, 1/s; $D$ - diameter of samples bracing on the rod, $m$.

Parameter $m$ (kg/m$^2$), characterizing the amount of liquid dropped per unit area of the eroded surface is:

$$m = m_d \cdot K_c \cdot Z \cdot \tau \cdot (S_{er})^{-1} \quad (7)$$

The test results are presented in the form of dependences $\Delta m_{rel} = f(t_{rel})$.

Using the scanning electron microscope TESCAN MIRA 3 LMU, images of an erosion track were obtained on the tested samples, reflecting the change in the topography of the surface and the dynamics of its destruction with increasing exposure time of the samples at the test bench.

3. Results and discussion

As a result of a samples from an aluminum alloy D16T tests series at a given collision velocities of the samples ($C_{imp} = 200, 250, 300$ m/s) with water droplets of known diameter ($d_d = 800, 1000$ μm), were obtained kinetic erosion curves in the coordinates $\Delta m_{rel} = f(T_{rel})$ (see Figure 3). To determine the characteristic points $E_m$ and $E_{st}$, the obtained dependences were reconstructed in the coordinates $E = f(m)$ (see Figure 4).

![Figure 3](image)

**Figure 3.** Curves of an aluminum alloy D16T erosion wear at water droplet impact various parameters

![Figure 4](image)

**Figure 4.** Curves of an aluminum alloy D16T erosion wear at water droplet impact various parameters:

1 - $C = 200$ m/s; $d_d = 800$ μm; 2 - $C = 250$ m/s; $d_d = 800$ μm; 3 - $C = 300$ m/s; $d_d = 800$ μm
The obtained images of the erosion track on the tested samples reflecting the change in the surface topography and the dynamics of its destruction with an increase in the samples relative exposure time at the rig are shown in Table 1.

Table 1. Images of an aluminum alloy D16T samples surface after erosion tests at a droplet diameter 800 μm and three different collision velocities

| Collision velocity $C_{imp}, m/s$ | $t_{relj}$ | $t_{relj}$ | $t_{relj}$ | $t_{relj}$ |
|------------------------------------|------------|------------|------------|------------|
|                                    | 200        | 250        | 300        |            |
| $I_{rel1}$                         | $I_{rel7}$ | $I_{rel3}$ | $I_{rel9}$ | $I_{rel5}$ |
| $I_{rel2}$                         | $I_{rel8}$ | $I_{rel4}$ | $I_{rel15}$| $I_{rel16}$|
| $I_{rel3}$                         | $I_{rel10}$| $I_{rel6}$ | $I_{rel14}$|             |
| $I_{rel4}$                         | $I_{rel11}$| $I_{rel13}$|             |             |
| $I_{rel5}$                         | $I_{rel12}$|             |             |             |
| $I_{rel6}$                         | $I_{rel18}$|             |             |             |

As a result of the tests were obtained kinetic curves of erosion wear of aluminum alloy D16T, showing the presence of an incubation period, periods with maximum and steady erosion rates. Also, intensification of the wear process with an increase in the collision rate and droplet size was noted, with an example of a sharp decrease in the relative time before the onset of destruction (incubation period). The obtained images of the surface topography of the samples made it possible to reveal a qualitative picture of erosion failure with increasing width and depth of the erosion track on the samples with time. An increase in the exposure time of the samples leads to an increase in the width of the erosion track by 1.2-1.5 times with increasing diameter of the droplets. The processing of the erosion tests results made it possible to obtain the dependence of the erosion wear average depth $E$ on the amount of liquid dropped per unit surface of sample $m$. The obtained dependences for varying collision parameters ($C_{imp} = 200, 250, 300$ m/s, $d_d = 800, 1000$ μm) made it possible to reveal the characteristic points $E_m = -0.35 \times 10^{-2}$ m and $E_{st} = -0.125 \times 10^{-2}$ m. The subsequent erosion tests at velocities $C_{imp} = 200, 250, 300$ m/s and droplet diameter $d_d = 1200$ μm will allow to construct nomograms for determining the maximum $E_m$ and steady $E_{st}$ erosion rates for aluminum alloy D16T at already determined characteristic points $E_m$ and $E_{st}$ and confirm the presence of a "pole" in the erosion wear of various structural materials.

4. Conclusions
The determination of the metal destruction fundamental laws under the high-speed drop impact with subsequent development of the erosion wear "pole" model will allow us to use the results obtained in the future for development technological bases increasing the erosion resistance of metals and alloys by using...
various passive erosion protection methods: protective coatings formation, different kinds of surface hardening and/or it’s modification.

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