WEAR OF FRAGILE COATING BY WATER DROP IMPACT

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ABSTRACT

Damage values of polymethylmethacrylate, epoxy resin and glass under the action of isolated water drop impacts have been calculated as dependent on the drop velocity. It’s stated that the surface layer damage values are proportional to drop diameter in case it’s less than the coating thickness and are independent of the reflected wave stresses, original cracks and exfoliation. Based on calculation results of damages depth of the worn out PMMA layer has been found for a stochastic model of the plane water-drop jet as a water pressure function at nozzle inlet and nozzle movement relative to the surface being treated.

KEYWORDS: water drop, fragile coating, impact, damage, wear.

1. INTRODUCTION

Water jet technologies are employed in various fields of engineering at present. Treatment with the water-drop jet is safe in ecological respect and is therefore often used to remove polymer and other types of coatings from large size articles [1, 2]. In spite of the frequent usage of named technology and great amount of publications in this domain, damage mechanisms and wear kinetics of the coatings aren’t still studied to a required depth. Known in the art calculation methods of damage parameters at isolated drops impacting against a coating surface consume a significant computing time. The water-drop jet and arising at its action on the coating wearing are of a stochastic origin. The available experimental data are hardly sufficient for describing the process quantitatively. From the other hand, there’s also an evident drawback in setting treatment regimes empirically as it’s unwarrantable to carry calculation results over to other materials and process regime parameters.

The aim of the present investigation is to establish quantitative relations between drop parameters and coating properties, from the one hand, and coating wear characteristics, from the other hand, in order to calculate wear intensity and control conditions of the treatment process.

2. INVESTIGATION PROCEDURES

The initial data on the wear mechanism have been derived on the example of polymethylmethacrylate (PMMA). PMMA surface has been treated with a water-drop jet in the water-jet Waterjet Laboratory Hanover (Institute of Material Science, University of Hannover, Germany) [2, 3]. Damaged surface topography has been studied by the scanning electron microscopy using JSM 5610VL microscope. Experimental data on PMMA damage properties obtained in [2] have been taken into account.

Stress-strain state and damages of materials at drop impacting normal to the surface have been calculated by the finite element method. The dynamic axisymmetric problem has been solved for a cylindrical model with a diameter not less than 40 drop diameters and up to 5 mm height (Fig. 1). Drop effect on the 0.1 to 0.63 mm thick coating glued to either a steel substrate (up to 3 mm thick) or a homogeneous body (5 mm thick) made of the coating material has been studied.

Using an approximate analytical dependence [4] an inhomogeneous across the contact area pressure distribution $p(r, t)$ appearing at a normal impact of a
spherical drop has been found. The range of drop diameters (0.06-0.5 mm) and velocities in the impact instance (till 500 m/s) has been chosen on the base of experimental evidences [3].

Besides PMMA, coatings based on epoxy resin (ER) and glass have been estimated on damageability. The following characteristics of coatings set at calculations are presented in the Table: density (ρ), Young’s modulus (E), Poisson’s ratio (μ), sound velocity (c), limiting relative elongation at rupture (ε*), resistance to coating peeling off the substrate (σ*) and shear strength relative substrate (τ*).

<table>
<thead>
<tr>
<th>Material</th>
<th>ρ, kg/m³</th>
<th>c, m/s</th>
<th>E, GPa</th>
<th>μ</th>
<th>ε*</th>
<th>σ*, MPa</th>
<th>τ*, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER</td>
<td>1200</td>
<td>1826</td>
<td>4</td>
<td>0.35</td>
<td>0.025</td>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>PMMA</td>
<td>1800</td>
<td>2236</td>
<td>9</td>
<td>0.32</td>
<td>0.020</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Glass</td>
<td>2500</td>
<td>5441</td>
<td>74</td>
<td>0.22</td>
<td>0.010</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Speed $u_i$ of a drop $i$ in the impact instance is considered to be dependent on its diameter $d_i$, water inlet pressure to the nozzle $p_0$ and nozzle to treated surface distance $L$: $$ u = k_u \sqrt{\frac{2 p_0}{\rho_w}} \cdot \exp \left[ \frac{3 c \rho_w L}{4 \rho_w d} \right],$$ (1) where $k_u$ is the factor accounting for the nozzle resistance, $\rho_w$ is water density and $\rho_a$ – air density, $c$ – the factor accounting for the air resistance.

Based on experimental results [3] the distribution of drops across jet section is taken as uniform. Hence, damage probability of a surface point with coordinates $x$, $y$ is equal to $$ P_i(x, y) = A'_{ji} / (b B) $$ where $A'_j$ is the rated area of the damaged surface region at impact of a drop $d_i$ in diameter at $u_i$ velocity; $b$ is jet section thickness (in motion direction); $B$ – cross-section diameter dependent on distance $L$. For the plane jet it’s set that $B \cong 0.5L$ [2].

Damage depth has been calculated at a given water inlet pressure in the nozzle $p_0$ and given nozzle movement speed $v_0$ by summing up damage depths from individual drops hitting a given point of the coating surface: $$ h(x, y) = \sum P_i(x, y) \cdot \delta h_i, $$ (2) where $\delta h_i$ is calculated damage depth at a water drop diameter $d_i$ impact with speed $u_i$.

The calculation results of the damage depth of the coating have been compared to measurement results fulfilled in [2].

### 3. RESULTS

The analysis of the damaged surface geometry of brittle coatings under the effect of drops falling at different velocities proves that annular cracks and fine chips appear on the surface under rather low velocities (depending on coating mechanical properties) [2]. Under higher velocities of the drops surface layer of the coating is damaged in the form of annular craters. Chippage over the periphery of the contact area is also probable along with formation of shell-like pits originated from craters and microcracks at pressure front passing (Fig. 2). By the volume of removed material the pits are commensurable with craters. At high enough velocities of drop impacting craters whose diameters and depth depend on the material strength as well as drop diameter and velocity are formed on the surface within the drop effective area.
The conditions when damages of each type appear have been found through calculations of the stress-strain state of 2-5 mm thick solid material and relative size of the damaged area where determined as a function of the drop size and velocity. A supposition that there exists some threshold of the drop velocity [4, 5] independent of their diameters below which the damage doesn’t occur has been confirmed (Fig. 3). The threshold velocity value depends upon the material elastic characteristics and strength. Relative dimensions of damages were found to be independent of the drop diameter (within the studied range).

Relative diameter $\delta''$ and depth $\delta h$ of damages in PMMA and ER (Fig. 3) increase in proportion to drop velocity. Damages within threshold $u$ till (2-3) $u$ acquire a circular form and an intact annular region remains in the drop axis vicinity. In case the drop velocity surpasses 2 to 3 times the threshold one, then an annular damage with ~0.4 of the diameter depth transforms into a continuous crater and the intact region in the center disappears.

Fig. 3 Relative dimensions of damages of the surface layer versus drop velocity: a – PMMA; b – glass; c – ER.

Fig. 2 Scanning microscopy image of damaged PMMA coating.

Fig. 4 Stress waves in the coating and the base after 0.29 (a), 0.36 (b) and 0.45 (c) $\mu$s from the moment the drop contacts the coating surface.
In figure 4, a qualitative image of the highest main stresses \( \sigma_1 \) distribution is presented in various moments of 0.25 mm in diameter drop impacting at 500 m/s speed a 0.63 mm thick PMMA coating glued to a steel base. Rated duration of the pressure peak action under the drop at mentioned conditions constitutes according to the model from [4] 0.054 \( \mu \)s. The stress waves are clearly seen in the image as reflected by the base surface. Yet, the level of stresses and the highest tensile strains in the reflected wave are much lower the stresses and strains observed in the coating surface layer as the pressure peak is recorded under the drop. Just during this period the coating surface layer breaks up. The calculations have proved that the reflected stress waves does not in fact influence damage size.

In case of an ideal coating adhesion to the base material, even thin coating layers (0.1 mm) start to separate at a velocity several times higher than that of the threshold \( u' \) which inflicts damage to the surface. With increasing coating thickness the velocity also augments roughly proportional to the square root of the thickness value. The analysis of annular cracks arising at relatively low impact velocities of drops on damaging has shown that most dangerous is the case when the drop hits the center of the region confined by an annular crack propagating through the entire coating depth and its diameter makes up \( \frac{1}{3} \) of the drop diameter. In case the drop falls at a distance from the original annular crack axis that surpasses the drop diameter, then the arising damage is practically independent of whether the original crack is present or not. Analogous conclusions have been derived from calculations of the surface layer damaging when the coating peeling off the base is present. In this case, the coating peeling zone size effect but insignificantly the damage appearing upon the subsequent drop impacts.

Thus established regularities furnish the base for neglecting at least in the first approximation mutual effect of drops and damages on calculations of the first stages of wear of relatively thick coatings. So far, using formula (2) depth of the PMMA layer damaged by a plane water-drop jet issuing from a nozzle at different pressures and velocities of motion relative the treated surface has been determined. Diameters \( d' \) and depth \( \delta' \) of damaged regions have been set according to rated dependencies shown in figure 3a.

Calculated by formula (2) depth values surpassed those found in [2] under the same parameters of the jet. Since approximated models can’t account for a number of factors affecting damage size, particularly, lower pressure at impacting of single drops because of water layers, roughness of damaged surface and debris, discrepancies between calculation results and experiments are unavoidable.

In figure 5, a qualitative image of the highest main stresses \( \sigma_1 \) distribution is presented in various moments of 0.25 mm in diameter drop impacting at 500 m/s speed a 0.63 mm thick PMMA coating glued to a steel base. Rated duration of the pressure peak action under the drop at mentioned conditions constitutes according to the model from [4] 0.054 \( \mu \)s. The stress waves are clearly seen in the image as reflected by the base surface. Yet, the level of stresses and the highest tensile strains in the reflected wave are much lower the stresses and strains observed in the coating surface layer as the pressure peak is recorded under the drop. Just during this period the coating surface layer breaks up. The calculations have proved that the reflected stress waves does not in fact influence damage size.

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