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Erosion problems in pneumatic transport installations on the example of fan rotor blades

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Abstract

In the paper, the analysis of erosion of a fan blade was conducted. Erosion is recorded into two zones on the blade. In the first zone, erosion occurs at the front of the blade and it is caused by particle's impacts during first contact. This is "impact erosion" zone. Second "friction erosion" zone is formed in the place of the next contact, determined by the angle rotation of the rotor $\Delta\varphi$ *and the path of rebound s. The impact takes place at the angle* α *with participation of friction forces. Dependences of particle's velocities on stress, which cause plastic strains on surface layer, were presented. Coefficient of velocity restitution in the stream* $k_s=\beta k$ *was calculated. Restitution coefficient of particle's velocity in a stream always amounts to* $\beta \geq 1$*. Its value can be determined by f.e.: shape of particle's, their diameter, stream velocity. Time* τ *between successive impacts is the function of rotor angular velocity and restitution coefficient k. Angle of rotation* $\Delta\varphi$ *is only depends on coefficient k. The equation describing dependence of angle rotation* $\Delta\varphi$ *on coefficient* k_s *is as follows:* $\Delta\varphi(1+k) = tg(\Delta\varphi)$*. The solution of the equation was presented in a graphical way.*

Keywords: *stream erosion, restitution coefficient, fan blades*

1. Introduction

Pneumatic transport of fine-grained materials is the element of many technological processes. It includes: removal of solid fuel combustion products in energy installations, removal of fine-grained waste being the by-product during cutting and grinding, relocation of powder and granulated products. Convection of material solid particles together with the air or gas stream is the basis of the process. Machine and installation elements (fan blades, cyclones, pipe bends) are in a constant contact with the elevating particles and thus they are subject to erosion. Following zones [1] are distinguished (Fig. 1): 1) "impact erosion" zone being the effect of particles' impact, 2) "friction erosion" zone being the effect of sliding of particles on the surface. In the case of fan blades, zone 1) is formed on the edge of the blade from the side of incoming particles, zone 2) is formed at the end of the blade.

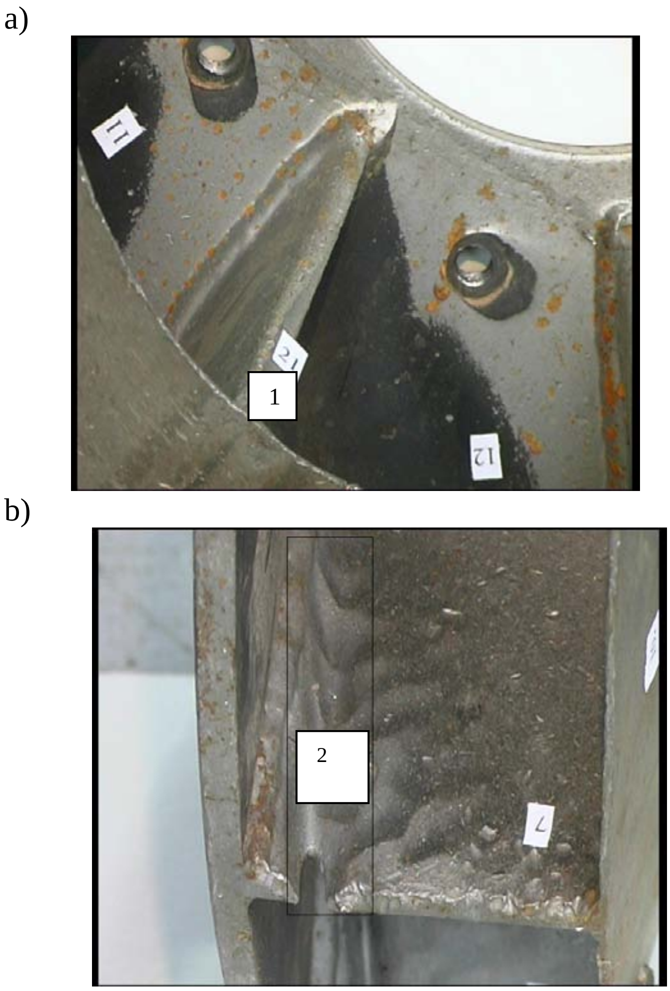

Fig.1. The view of fan blades exploited in erosion conditions:
a) impact erosion zone(1), b) friction erosion zone (2)

Working time of fan blades is mainly determined by the loss of material in the zone (2) (fig. 1b). Working time of rotor mill blade (Fig 2) is determined by zone (1) [2].

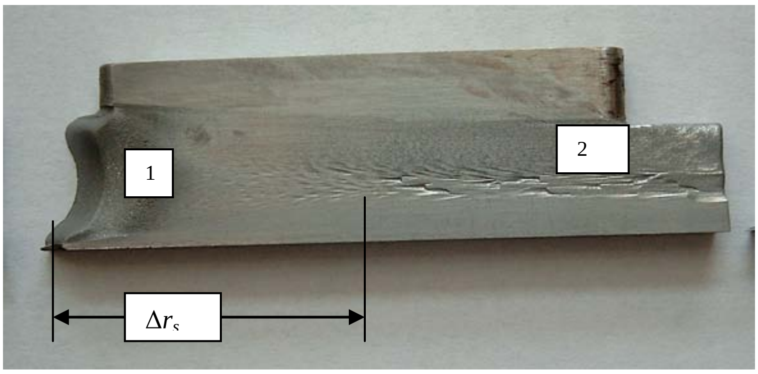

Fig.2. The view of a rotor mill blade: 1 – impact erosion zone, 2 – friction erosion zone

In this paper, the analysis will be conducted what is the effect of the contact of the particle with a fan blade and a pipe bend in impact conditions.

2. First impact of the particle on a fan blade

It was assumed for analysis, that the impacting particle has spherical shape with half space. In reality, particles in the stream have different shapes [3]. Calculation results are subject to given error, but it does not depreciate recorded phenomena. The velocity of particle's impact amounts to vector sum of particle entry velocity V_w and peripheral velocity of contact point of a fan blade $V_l = \omega r$. As velocity ratio $V_w / V_l < 0{,}05$, it can be assumed that the particle impacts perpendicularly to its surface. In this case, contact stresses can be calculated [4] using following equation:

$$\sigma_H = 0{,}837 \rho^{1/5} V^{2/5} E^{4/5}, \tag{1}$$

where: $\frac{1}{E} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$, ν_1, ν_2, E_1, E_2 – Poisson's ratios, Young's modulus of particle and fan material.

The equation (1) shows that, as far as elastic strains are concerned, contact stresses do not depend on particle's radius, but they are a function of modulus of elasticity of contacting bodies and impact velocity. At the given critical velocity of the particle impacting the material, contact stress reaches dangerous value, which corresponds to resistance or yield point. First plastic strain is formed in the place of maximum shearing stress, i.e. on the depth similar to the radius of circular surface of the contact point (Fig. 3a, point B). At $\nu = 0{,}3$, $\tau_{1\max} = 0{,}31\,\sigma_H$ [5]. Material plastic flow appears in this point, when a following condition is fulfilled:

$$\sigma_H = \frac{\sigma_{pl}}{0{,}62} = 1{,}61 \sigma_{pl}, \tag{2}$$

which is met at the critical velocity

$$\upsilon_1 = \frac{(\sigma_{H_1})^{5/2}}{(0{,}837)^{5/2} E^2 \rho^{1/2}} \,. \tag{3}$$

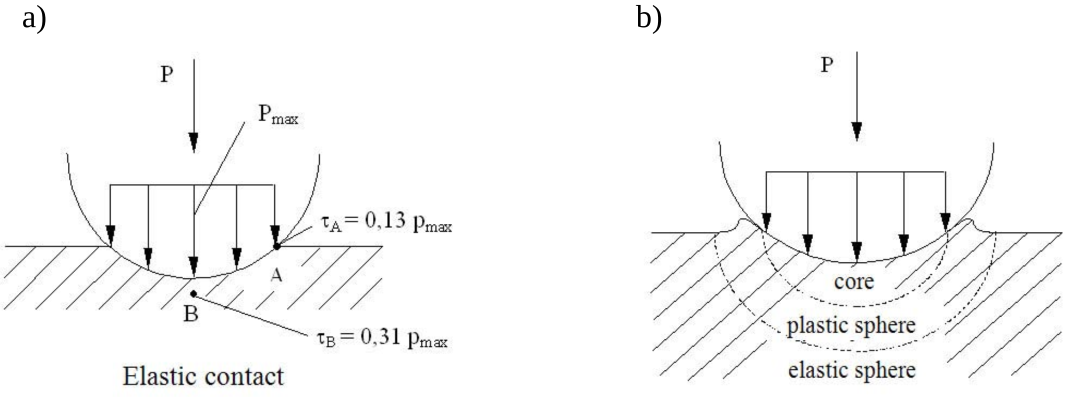

Fig. 3. The scheme of half space strains caused by particle's impact
a) elastic strain ($\upsilon < \upsilon_1$), b) plastic strain ($\upsilon > \upsilon_2$)

When the impact velocity increases, the area of plastified material extends [6] and it reaches the surface (Fig. 3b).

Shearing stresses amount to $\tau_{2\max} = 0{,}133\ \sigma_H$ at the circular edge of contact area on the blade's surface (fig. 3a, point A) at $\nu = 0{,}3$. In this point, radial stresses σ_r spread out and amount to circumferential compressive stresses σ_{Θ}. Thus, pure shear amounting to $\sigma_H(1-2\nu)/3$ occurs along the edge of contact area, where particle's pressure on the blade's surface amount to zero [6]. The output of area of plastic strains on the surface occurs at

$$\sigma_{H2_2} = \frac{\sigma_{pl}}{0.266} = 3{,}7\sigma_{pl} \ , \quad (4)$$

caused by particle's velocity during impact.

$$\upsilon_2 = \frac{(\sigma_{H2})^{5/2}}{(0{,}837)^{5/2} E^2 \rho^{1/2}} . \quad (5)$$

Further increase in particles' velocity causes extending of the plasticization area by particle's sinking (Fig. 3b) – similar phenomena occurs in Brinell's studies [6]. Surface condition of the blade's impact erosion zone is presented in Fig. 4. Critical velocities υ_1 i υ_2 of selected materials from equations (3) i (5) are presented in table 1.

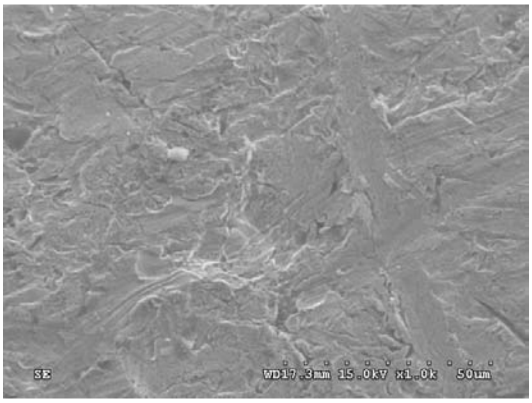

Fig.4. Microphoto of the blade's surface in the area of first impacts of particles.

Table 1. Values of critical velocities for selected materials during dynamic contact of the sphere with half space

Material	Young module E, MPa	Poisson's coefficient ν	Yield point MPa	Tensile strength R_m, MPa	Critical velocity m/s×10^{-2}	
					υ_1	υ_2
Steel 35	2.10^5	0,3	270	550	0,9	47,3
Steel 40 H	2.10^5	0,3	750	900	12,4	162,5
Hatfid's steel	2.10^5	03	800	1000	14,57	190,95
Polyamide	$1{,}1.10^3$	0,38	43	50	72,1	593,4

Radiuses determining location of the blade (in an industrial fan used in pneumatic transport) amount to: inner radius r_w = 1,4 m and outer radius r_z = 1,8 m. At the angular velocity of the rotor ω=146,5 s^{-1}, the velocity of the first impact reaches the value of $V \approx 205$ m/s. It is the value exceeding (by two grades) values υ_1 i υ_2 presented in Table 1. In these conditions, reciprocal interaction of hard particles with blades is elastic-plastic. During this process part of kinetic energy of particles is used for local plastic strain (Fig. 4) and microcutting.

3. Second impact of the particle on a fan blade

After the particle impacts elastic-plastically in the zone (1) it rebounds. [7]. Paper [8] presents how to calculate the point of the next impact basing on the scheme shown in Fig. 5. The first impact takes place in the point A_2 perpendicularly to the blade and the next impacts take place in the point A_3 at the angle ($\pi/2 - \Delta\varphi$). Point A_3 is determined by the angle rotation $\Delta\varphi$ and the path of rebound s. The analysis [8] of the particle's motion in the space between the blades brings the following dependence

$$\Delta\varphi(1+k) = \mathrm{tg}\,\Delta\varphi\,, \tag{1}$$

where: ω – angular velocity of a rotor, τ – time of rebound between the first and the second impact. Time τ is not depends on the blade's location, but it is the function of the angular velocity ω of the rotor and the restitution coefficient k. Angle rotation $\Delta\varphi$ is only determined by the restitution coefficient k [9]. The solution of equation (1) in a graphic-analytical way is presented in Fig. 6.

Coefficient k is calculated using the method of a free drop of the steel globule – aerodynamic air resistance is not taken into consideration [10]. After the globule impacts elastic-plasticly the material, it rebounds with the velocity of υ'', which is lower than the impact velocity υ', i.e.:

$$\upsilon'' = k\,\upsilon'\,. \tag{2}$$

Authors of the paper [8] proposed that coefficient β, amounting to $\beta \geq 1$ should be included to calculate the influence of real conditions on velocity restitution. These conditions are as follows: the particle is generally not made of steel, it is not spherical and a free drop does not takes place in a stream. Thus,

$$\upsilon'' = \frac{k}{\beta}\,\upsilon' = k_s\,\upsilon'. \tag{3}$$

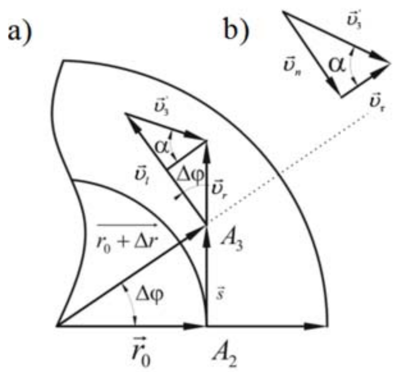

Fig. 5. Calculation diagram for assessing the point and velocity of the second impact of the particle on a fan blade: a) diagram of particle's motion and velocity, b) normal element υ_n and tangent υ_τ of the particle's velocity in the point A_3

The value of coefficient β can be calculated by comparing value Δr (Fig .5), which is calculated by using data in Fig. 6, with value Δr_s determined by the material loss on the blade (Fig. 2). Fig. 3 shows that $r_0 = (\Delta r + r_0)\cos\Delta\varphi$. Thus,

$$\Delta r = r_0\left(\frac{1}{\cos\Delta\varphi} - 1\right). \tag{4}$$

Angle $\Delta\varphi$ can be set using the diagram in Fig 6. It is the coordinate of the point, which is the solution of equation (1) for a given value of coefficient k. Intersection of straight lines $f_1 = \Delta\varphi(k+1)$ and curve $f_2 = tg\Delta\varphi$ gives the location of the point. In paper [13] it was pointed out that coefficient k has values 0,35 – 0,45. k = 0,4 was assumed for calculations. At this value, the point of the second impact is determined by the angle $\Delta\varphi$ = 1,11 and s/r_0 = 1,99 (Fig. 6). Radius r_0 amounts to 190 mm in the blade in Fig. 2. Using these values, Δr amounts to 241 mm basing on the equation (4).

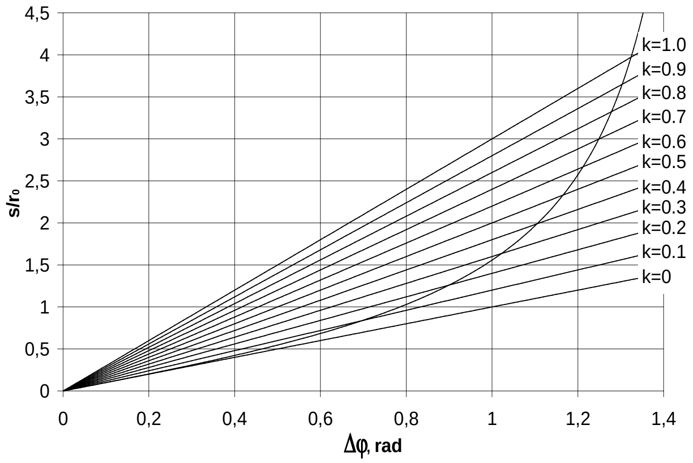

Fig. 6. Diagram of equation's solution (13)

Fig. 2 shows that erosion losses are visible at the middle of the blade's length after rebound in the zone (1), i.e. in a distance $\Delta r_s \approx 30$ mm (zone.2). This value is possible when $\Delta\varphi$ = 0,53 and k_s = 0,05 (restitution coefficient of the particles in a stream), which is calculated using the equation (1). The value of the coefficient β derives from the following equation (3):

$$\beta = \frac{k}{k_s} = \frac{0{,}40}{0{,}05} = 8\,. \tag{5}$$

The analysis of traces of wear in different blades (Fig. 1b, Fig. 2) shows that coefficient β is included in a given interval, because traces of wear are present on a given length. In the examined case, this is the beginning of wear "path" and β = 8. Kinetic energy of the particles in a stream is diversified, thus coefficient β and the path of rebound Δr_s is characteristic for each diversified group of the particles in a stream.

The question arises, what is the further motion of the particle after the second impact in the zone (2). While the first impact was directed perpendicularly to the blade, the second impact occurred at the angle α. This angle is set between the velocity of the next impact and the direction tangent to the blade (Fig. 5). The angle can be calculated using following equation:

Table 2. Values of parameters of skew impact of the particle on a fan blade

Parameter	k_s									
	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0.9	1,0
$\Delta\varphi$, rad	28,66	40,1	47,58	50,4	55,0	58,47	60,76	63,1	64,20	65,92
$1+\frac{\Delta r}{r_0}$	1,139	1,326	1,498	1,608	1,740	1,910	2,040	2,200	2,340	3,440
$\frac{\upsilon_n}{\varpi r_0}$	0,174	0,408	0,621	0,716	0,880	1,070	1,210	1,390	1,510	2,620
$\frac{\upsilon_\tau}{\varpi r_0}$	0,528	0,773	0,960	1,080	1,128	1,364	1,480	1,605	1,710	1,826
α	18,24	27,83	32,9	33,54	37,96	38,1	39,27	40,89	41,44	55,12

$$tg\alpha = \frac{\upsilon_n}{\upsilon_\tau} = \frac{1+\frac{\Delta r}{r_0}-(1+k_s)\cos\Delta\varphi}{(1+k_s)\sin\Delta\varphi} \tag{6}$$

Values $\alpha, \upsilon_n, \upsilon_\tau$ i υ_s are presented in Table 2 taking into consideration value of restitution coefficient in a stream. Analysis of values included in Table 2 shows that velocity of the second skew impact depends on $k_{s.}$ – restitution coefficient in a stream. The higher value k_s is, the higher impact velocity and the higher erosion losses are, which are located at the end of the blade (Fig. 2). Microphoto of blade’s surface in the zone of skew impact (Fig. 7) confirms this type of impact. Traces of plastic lengthwise strains lead to the conclusion that velocity component υ_τ is dominant.[11,12]. It is possible at the low value of the coefficient k_s.

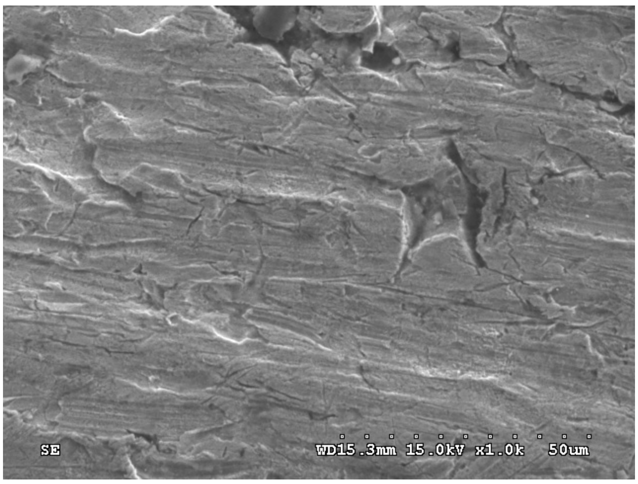

Fig. 7. Microphoto of the surface in the zone of a skew impact

4. Conclusions

Erosion of pneumatic transport installations occurs due to successive impacts of the stream of solid particles. They cause elastic-plastic strain of the surface layer of the element, until the border of plastic strain is reached. Then, the surface layer cracks (Fig. 7).

Coefficient of particle's velocity restitution in a stream $k_{s.}$ determines the location of next impacts, i.e. the location of erosion in blades.

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