# MECHANISMS OF EROSION WEAR IN PIPES CAUSED BY A STREAM OF SOLID PARTICLES

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*Abstract*

*In the paper an analysis of pipe bend erosion was conducted. This erosion was compared to the erosion of flat samples. The function of particle velocity change: $v/v_o = e^{-\alpha f}$ was assessed and contact stress caused by the centrifugal force of inertia of solid particles (diameter $d < 0,1$ mm) in the bend material was calculated.*

*Keywords: erosion, pipe bend, contact stress*

## 1. Introduction

The contact of the jet of solid particles with the material surface causes its erosion. The magnitude of loss depends on three primary factors: 1) properties of the material exposed to erosion, 2) abrasive material, 3) the environment in which the erosion takes place. As far as erosion wear is concerned, only the material exposed to the impact of the particles is the subject of the analysis. In industrial practice, it concerns machine elements and installations that transport granular material. These are mainly: pump impellers, fans, turbines and pipe bends as well as Diesel engine elements [1]. General cause of the losses is common to all installations but each erosion case has its own characteristics. The magnitude of material loss may be different for different values of kinetic energy, glancing angles, shape, hardness and strength of granules of the abrasive material. The environment of the pipe bend is the most suitable for analyzing different glancing angles of impacting particles.

In this paper an analysis of erosion losses in the bend pipe covered with protection layer of polyurethane rubber was made

## 2. Analysis of particle motion in a pipe bend

The particle of the abrasive material slides on the surface of the bend. During this process friction force $F_t$ influences the particle. The value of this force depends on the pressure of centrifugal force $F_b$ and friction factor f, i.e.:

$$F_b = m\frac{v^2}{R}, \quad F_t = f\,m\frac{v^2}{R}, \tag{1}$$

where: m – mass of the particle. The resulting action of the force $F_t$ is the decrease of the particle velocity. The friction force performs the work, which for elementary displacement *ds,* equals

$$dA = F_t ds = f m \frac{v^2}{R} ds. \tag{2}$$

Particle velocity on the way *ds* changes from value *v* up to *(v+dv)* and kinetic energy from $mv^2/2$ to $m(v+dv)^2/2$. The change of kinetic energy is equal to friction force $F_t$

$$\frac{mv^2}{2} - \frac{m(v+dv)^2}{2} = f\frac{mv^2}{R} ds. \tag{3}$$

After taking into account that $ds = v\, dt$ and value of $(dv)^2$ is negligibly small, equation (3) may be presented as follows:

$$dv = -\frac{fv^2}{R} dt \tag{4}$$

After integration with the initial conditions $t = 0$, $v = v_0$ particle velocity is equal to

$$v = \frac{v_0}{1 + \frac{fv_0 t}{R}}. \tag{5}$$

Derivative $\delta v / \delta t = a_t$ describes tangential deceleration of the particles which can be calculated from the equation

$$a_t = -\frac{v^2{}_0}{R} \frac{f}{(1+\frac{fv_0 t}{R})^2}. \tag{6}$$

The path of the particle in the bend was calculated on the basis of equation (5) after its integration. Having taken into account the initial conditions of motion $s(t=0) = 0$, the following equations was obtained

$$s = \frac{R}{f} \ln(1 + \frac{fv_0 t}{R}). \tag{7}$$

Particle position in the bend in time *t* is described with angle $\alpha$:

$$\alpha = \frac{s}{R} = \frac{1}{f} \ln(1 + \frac{fv_0 t}{R}). \tag{8}$$

Equations describing velocity and tangential acceleration were obtained after eliminating of the variable *t* from equation (5) and (6)

$$v = v_0 e^{-\alpha f}, \quad a_t = -\frac{v_0^2}{R} \frac{f}{e^{2\alpha f}} = -a_n f e^{-2\alpha f}. \tag{9}$$

The decrease of relative velocity $v/v_0$ was calculated for several types of particles and different friction factor *f* on the distance $\alpha = \pi/2$. The decrease values are as follows:
- quartz sand (f = 0,2),                   $v/v_o = 0{,}73$,
- wood (f = 0,5),                       $v/v_o = 0{,}45$,
- wood with sand impurity (f = 0,3),   $v/v_o = 0{,}62$.

The time which the particle remained in the bend ($\alpha = \pi/2$), was calculated from equation (8)

$$\Delta t = \frac{R}{fv_0}(e^{f\alpha} - 1). \tag{10}$$

For $R = 1{,}1$ m, $v_0 = 100$ m/s, $\Delta t_{sand} = 0{,}0094$ s, $\Delta t_{wood} = 0{,}011$ s, $\Delta t_{sand+wood} = 0{,}0097$ s. The change $v/v_o(\alpha)$ and $a_t/a_n(\alpha)$ is also presented in Fig. 1.
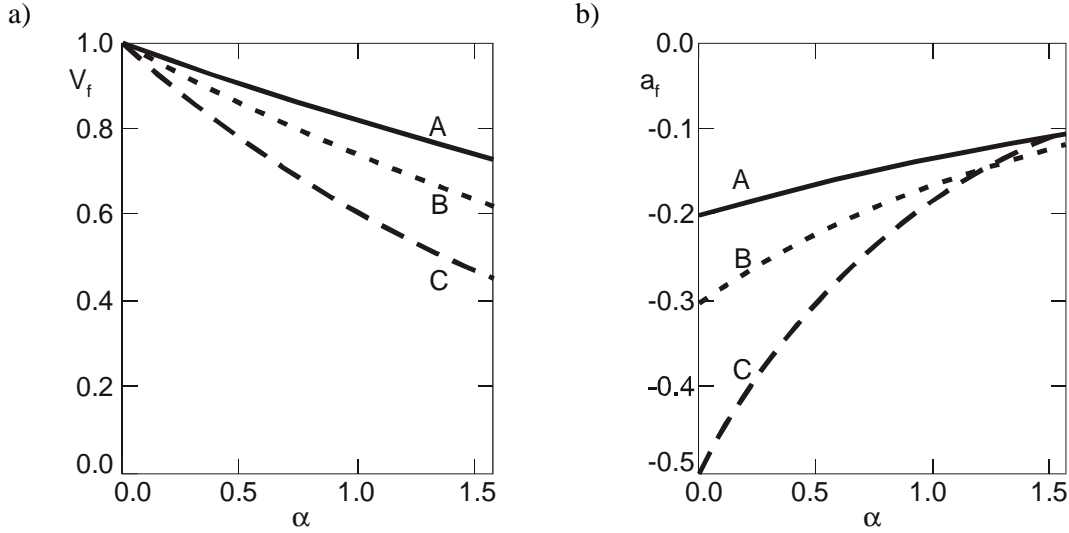


*Fig. 1.   Dependence between angle distance of the quartz particles (A), blend of quartz and wood particles (B), wood particles (C) :  relative velocity v/v_o,  b) acceleration a_t/a_n ($\alpha$)*

Several conclusions can be drawn from the analysis of Fig 1a. From the practical point of view, materials which guarantee large values of deceleration of the particles – i.e. materials with large friction factor – should be used in cyclones. On the other hand, the lowest possible velocity losses  are required if pneumatic conveying is considered. Therefore, materials with very low friction factor are used in this case.

Erosion caused by particle impact, after which the particle rebounds, is another possible version of the erosion in the pipe bend. This mechanism concerning erosion of ventilator rotor blades is presented in [2,3] papers. Coefficient of velocity restitution after impact plays significant role in this wear mechanism [4].

## 3. Contact stress caused by inertia

Particle radius is very small compared to bend radius. Therefore a load model of sphere pressure on a flat surface was assumed for stress calculations [2]. In this case contact stress $\sigma_H$ is equal to

$$\sigma_H = 0.62\sqrt[3]{\frac{F_0}{r^2}\left(\frac{1}{E_1} + \frac{1}{E_2}\right)^{-2}} = 0.62\sqrt[3]{\frac{mv^2}{Rr^2}\left(\frac{1}{E_1} + \frac{1}{E_2}\right)^{-2}} \cong \sqrt[3]{\rho\frac{r}{R}\left(\frac{1}{E_1} + \frac{1}{E_2}\right)^2 v^2}, \tag{11}$$

where: $F_0$ – centrifugal force of inertia, $E_1$, $E_2$ – Young's modulus of the particle and bend material, r – particle radius, m – particle mass.

In the case when the sand particle  (r = 0,2 mm, $E_1$ = 400 GPa, density $\rho$ = 4 g/cm$^3$) slides on the surface of a bend made of steel ($E_1$ = 208 GPa, R = 1,1 m) the value of contact stress is as follows:

$$\sigma_H = 10^{-6} \sqrt[3]{4 \cdot 10^3 \frac{0.2 \cdot 10^{-3}}{1.1} \left( \frac{1}{208 \cdot 10^9} + \frac{1}{400 \cdot 10^9} \right)^{-2} 100^2} = 514 \, \text{MPa}.$$

Particle radius is much smaller $r^* = 1/20 \, r$ when particle has feather edges (even if the mass remained unchanged). In that case contact stress increases to $\sigma_H^* = \sqrt[3]{400} \, \sigma_H = 3787$ MPa. This value of the stress can cause plastic strain and shearing in the upper layer of the material.

## 4. Bend and flat sample erosion

The analysis of the progressing wear of the pipe bend presented in Fig. 1 shows that the losses of protection layer started at point C described with the angle $\alpha = 15°$. The shape and size of the crater changed during the experiment. The glancing angle of impacting particles at the edge of the crater approached 0, whereas at the bottom of the crater it approached 90 (point L). Curve CL in Fig. 1b shows the progressing erosion inside the material layer. The protection layer was completely destroyed in the place where $\alpha = 20°$ (point L in Fig. 2b). Particles impacting different parts of the pipe bend may fall at the angle $0 \leq \alpha \leq \alpha_{max}$. Contact angles correspond to points M and N (Fig. 2a) [1]. For the point N:

$$\cos\alpha_{max} = (R - d)/R; \quad \alpha_{max} \cong 66°.$$

A question arises why the erosion occurred in a particular place and not on the whole area of the bend. To answer the question, a research was conducted in order to show how different glancing angles effected the loss protection layer in the flat samples. The material analyzed was polyurethane PU-01. The experimental conditions were as follows: air pressure p = 0,5 MPa, intensity of flow of the particle abrasive amounted to 630 g/min, particles diameter r = 0,1 mm. The experiment was conducted on three samples..



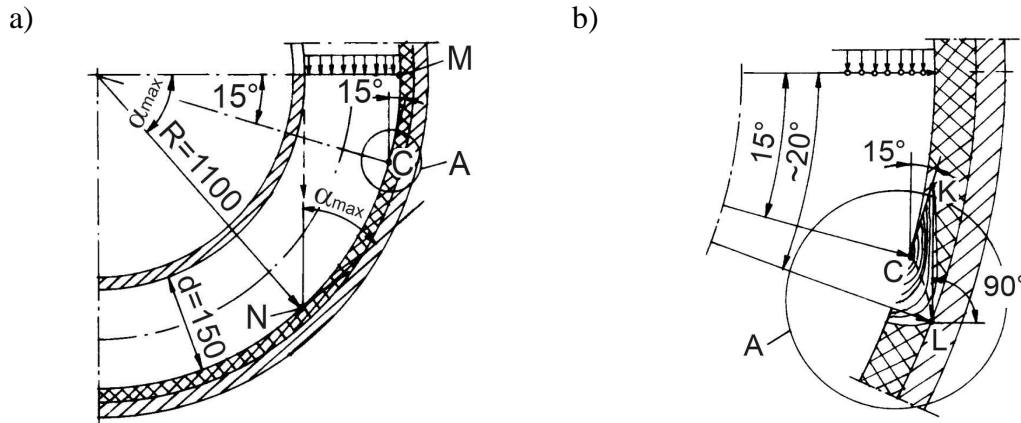Fig. 2.The diagram of flow of the abrasive granules in pipe bend: a) $\alpha_{max}$ – maximum glancing angle of impacting particles on the pipe bend wall, b) location of forming losses in the layer of polyurethane rubber

The loss was measured in one minute intervals for each glancing angle of impacting particles. The obtained results were approximated with straight lines y = ax, presented in Fig. 3a. Fig. 3b shows the magnitude of wear of the polyurethane depending on the glancing angle of the abrasive. The most significant wear of the material was obtained for the angle which amounted to approx $15^O$. This fact can be confirmed by analyzing the wear of the same material in the pipe bend (Fig. 2).
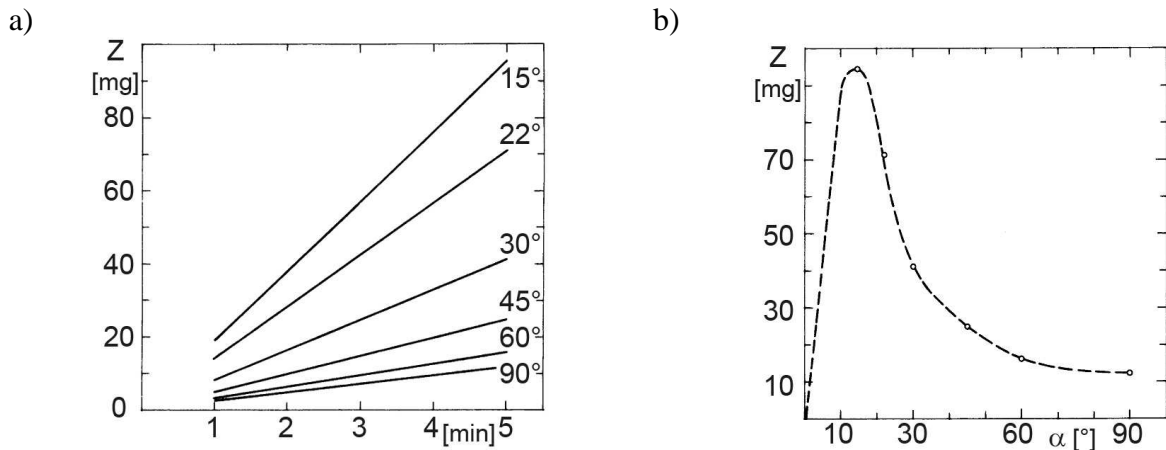
Fig. 3. *Erosion of polyurethane PU-01 under the influence of abrasive jet depending on:*
*a) time for different glancing angles, b) glancing angle.*

As it is presented in Fig 2 and 3, maximal erosion velocity in a pipe bend and a flat sample is recorded at this same glancing angle of particles impacting on a flat sample and the angle formed by stream of particles and tangent to a pipe bend. Erosion is located only at this point which means that the particles rebound after they strike into a pipe wall. Rebounded particles protect further part of the bend from erosion. This mechanism leads to inventing a new bend construction [5] presented in Fig. 4. The pipe bend (7) has a caving (4) filled by material (3). This material can be easily replaced and refilled using a hole (5) in the bottom part of the caving. A stream of particles moving near the wall reduces velocity after impacting the material (3) and constitutes protection layer for other parts of the bend after it leaves the caving (6).
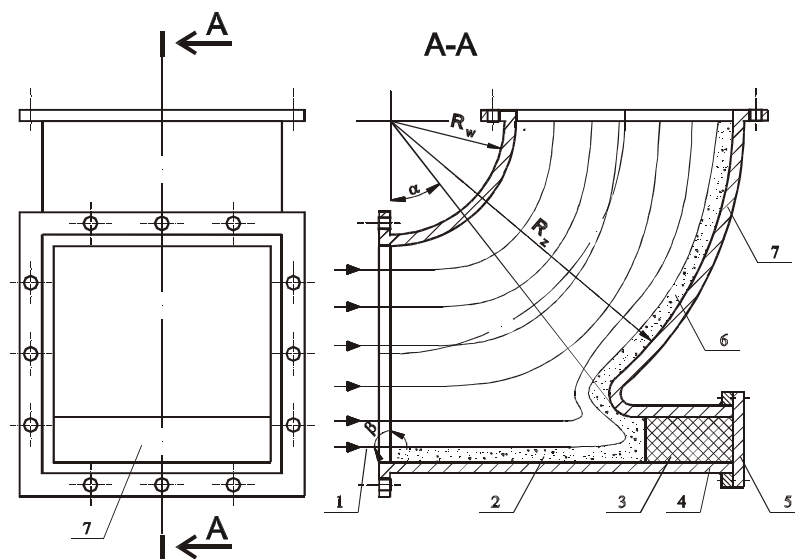


Fig. 4. *Diagram of pipe bend construction with a replaceable element that is subject to erosion*

## 5. Conclusions

1. Decrease of the particle velocity caused by centrifugal force of inertia depends on friction factor. Particle deceleration decreases with angular distance. Initially the deceleration is the greater the higher values of the friction factor there exist. After angular distance of $\pi/2$ the deceleration is practically independent of the friction factor.

2. Contact stress caused by centrifugal force of inertia of the particles may lead to plastic strain and shearing in the upper layer of the material
3. Maximum erosion velocity in a pipe bend and a flat sample takes place at the same glancing angle of impacting particles and the angle formed by a stream of particles and tangent to a pipe bend.

## 6. References

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[5] Zgłoszenie patentowe P-329729 „Konstrukcja łuku rurociągu o zwiększonej odporności na działanie erozyjne strumienia cząstek stałych''.