# Influence of friction in a case of impact simulation

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DOI: 10.13111/2066-8201.2020.12.4.13

*Received: 25 September 2020/ Accepted: 02 November 2020/ Published: December 2020*


***Abstract:*** *This paper presents an analysis of two cases, simulating the impact of a cylindical projectile on a perfectly rigid plate. One case is run without friction, the second one is run taking into account a friction coeficient between the plate and the projectile. The authors used for the projectile the same material constitutive model for both cases, based on experimental data and model developed by Johnson and Cook. Here, the comparing criteria were the maximum value of von Mises stress, the velocity and acceleration of the central point on the opposite face to the contact face of the projectile. Introducing friction, the simulation is more realistic. Taking into account friction, the projectile is less deformed and there was no edge breakage, at the same time moment.*

***Key Words****: Impact simulation, constitutive model of the material, friction*

## 1. INTRODUCTION

The work of Johnson and Cook [1], [2], [3] compared the simulation of a cylinder impact to tests results, for high strain rates till $10^5 s^{-1}$ and larger strains than 200%. But in their early reports the friction was not introduced.

Woodward [4], in a paper from 1984, evaluated the failure modes in penetration of a metallic target by a projectile and considered the major issue is the energy transformed into plastic deformation and the solutions of restricting the amount of plastic work. He considered that aspects of elastic deformation and friction are of less importance under ballistic conditions. But Ravid and Bodner [5] proposed a dynamic friction coefficient of 0.1 for metal working operations. A lower value of 0.05 should be used for lateral surfaces in impact situations due to the higher velocities and temperatures. Zukas [6] indicated an even lower dynamic friction coefficient of 0.01 for ballistic impact involving metal to metal surfaces. Borvik et al. [7] had formulated an interested conclusion that sliding frictional effects can be neglected for blunt projectiles, but “small frictional effects seem to be present for conical and hemispherical projectiles and should be accounted for in finite element simulations”.

Karamıs et al. [8] consider it is desirable that an armour should be able to withstand the projectile in itself. This can be understood by the damage on the projectile surface. If a target MMC is resistant to a projectile attack, it creates major damage to the projectile by frictional effect (abrasion). A good armour material erodes the projectile. A particle reinforced material holds the erodent in place. These properties depend on the kind of reinforcement, volume fraction and the bonding strength of matrix material and reinforcement particles. Phenomena relating to melting, shear banding, friction welding, etc. play varying roles in the penetration process complicating the response of impact involved bodies. The more friction occurs, the better performance is created as an amount of the kinetic energy of the projectile is consumed for overcoming friction. Frictional characteristic of the armour depends on the reinforcement particle volume fraction and type in the case of composite targets. Friction causes damage to the surface of the projectile tip. Damage types occurring on the tip surface are predominantly macro deformation and breaking of the tip, micro cutting, scratching and adhesion of the matrix material by melting and embedding of particles or yarns in the projectile surface.

Many models for ballistic panels made of fabrics layers and polymeric matrix took into account the friction among fibers, yarns, layers and the friction of yarns and matrix with the projectile surface [9]. Abtew et al. [10] presented an extended review on the failure mechanisms of targets made of fabrics and pointed out that friction between the projectile and the target, at different levels (filament, yarns, layers), absorb the impact energy. Even the damaged target will provide frictional resistance against the projectile motion. If the projectile does not have enough kinetic energy to overcome the frictional resistance, the projectile would be arrested within the target. Researchers modeled the effect of friction force on the energy absorbing mechanisms taking into account the value of friction coefficient as constant, but technical common sense makes the researcher to accept that friction coefficient will be different during the short time of impact because thermal effects, abrasive wear and normal pressure, relative and local velocity between target and projectile will change the value of the friction coefficient. Friction among yarns considerably affects the impact behavior of fabrics panels as it has the ability to keep the fabric structural stability during the impact.

The effect of friction had been excluded in many reports in the impact simulation due to the difficulties to measure the pressure and friction coefficient, especially when these parameters are assumed not to be constant during the impact.

Chai et al. [11] discussed the frictional force on projectile shank indirectly by comparing experimental data and empirical or analytical formulas of the penetration depth, for both concrete and aluminum-alloy targets. The effect of the friction cannot be ignored because of the relatively large affecting area and high contact stresses, where the friction will account for more proportion of penetration resistance, even if they calibrated the value of friction coefficient to 0.01...0.02, based on experimental data. They take into account the case of rigid body penetration, a simplification that influences, however, the friction between projectile and target. The friction resistance was estimated around 10% in total penetration resistance. The difference between penetration in concrete and aluminum-alloy targets is that the increase of penetration depth or impact velocity will make the friction coefficient on the projectile into aluminum-alloy target to decrease due to the formation of a melting or only soften layer on the contacting interface. Thus, the penetration resistance due to friction would decrease with the increase of penetration depth or impact velocity for aluminum-alloy targets.

Coulibaly et al. [12] presented a thermal model, considering that the work of friction force is equivalent to the generated heat at the interface of contacting bodies: the total heat flow $\phi_0$

is generated at the contact surface and is released on both sides through the materials by thermal conduction.

In order to study the sliding process at high velocity with a quasi-instantaneous loading, a particular tribometer has been used, friction being generated by the impact of a projectile on a target. The friction forces, measured at each side of the load sensor are firstly rapidly increasing due to impact, then decreasing to stabilize for most of the test duration, and finally reaching zero (end of interaction and motion). They calculated a mean value of friction coefficient for the time span when the friction force is almost constant (approximately 1000μs).

Friction force level was significantly higher for lower velocities than for higher ones. For both tested normal pressures (110MPa and 280MPa), influence of sliding velocity (from 8m/s to 64m/s) was similar: velocity increase leads to friction coefficient decrease. For a normal pressure of 110MPa, increasing velocity from 8m/s to 64m/s causes a drop of mean friction coefficient from 0.62 to 0.15. For higher pressure (280MPa), the mean value of friction coefficient was decreasing from 0.32 at 8m/s to 0.15 at 63...68m/s. But a frontal impact could change these values.

Holmen et al. [13] applied a high-exponent yield criterion in 3D nonlinear simulations of ballistic impact with rigid projectile (either blunt or ogival).

The models were based on an experimental study on 12mm thick high-strength Weldox 700E steel plates struck by projectiles with a diameter of 20mm and a mass of approximately 200g. Initiation of failure was determined by the Cockcroft and Latham criterion (CL) [14], a combined criterion that took into account the tensile stress and the equivalent plastic strain in a cumulative manner.

The friction coefficient μ increases the resistance to perforation slightly for the blunt projectile. When μ=0.1, which is probably unrealistically high in a perforation problem [7] involving material softening and melting, the residual velocity is 18% lower than with no friction at all.

However, the results with the ogival nose are extremely dependent upon μ since the projectile is always in contact with the plate due to the ductile hole growth perforation mechanism. At μ=0.05 the residual velocity is 82% lower than the residual velocity with no friction at all, and at μ=0.1 the projectile is completely stopped by the plate.

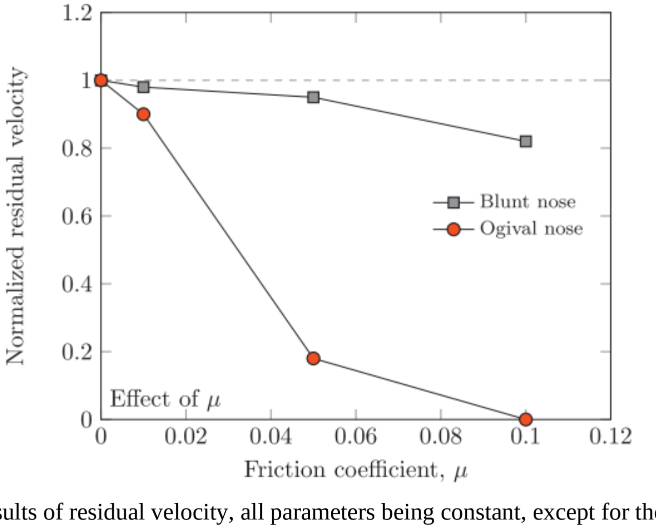



Figure 1. Simulation results of residual velocity, all parameters being constant, except for the friction coefficient. $v_0$=250m/s for the blunt projectile and $v_0$=350m/s for the ogival projectile using a yield-surface exponent a=2 [7]

Thus, μ has a much stronger effect on simulations with ogival projectiles than on simulations with blunt-nosed projectiles (Fig. 1). The authors used Coulomb friction without a cut-off value, meaning that the frictional forces are not limited from above.

In Figure 1, the exponent is for calculating $\sigma_{ech} = \left(\frac{1}{2}(|\sigma_1 - \sigma_2|^a + |\sigma_2 - \sigma_3|^a + |\sigma_3 - \sigma_1|^a)\right)^{\frac{1}{a}}$, $\sigma_1, \sigma_2, \sigma_3$ being the principal stresses [13]. The simulated cases pointed out the issue related to friction in impact processes. A realistic value could be established by measuring the residual velocity and selecting the value of friction coefficient corresponding to the same residual velocity in simulation.

In impact cases, friction could influence the behavior of both projectile and target, especially when target also supposes friction among its components, as it happens among layers of body armor [15, 16]. Even if the energy dispersed by friction is about 10% of the impact energy, for damage mechanisms, especially when arresting the projectile within the target, friction plays a significant role.

## 2. MATERIALS AND METHODS

The model geometry is quite simple, inspired from [1]: a perfectly rigid plate is impacted by a cylinder made of a copper alloy, having the impact velocity 300m/s. The diameter of the cylinder is 7.52mm and its length is 25.4mm. The cylinder could be considered a blunt projectile.

There is also the issue of the frictional contact between projectile and target during the impact. The standard representation of this effect (with Ansys) is to ascribe a coefficient of friction, μ, to the interfacial contact, such that sliding between the two surfaces requires a shear stress, τ, given by

$$\tau = -\mu \cdot \sigma_n \tag{1}$$

where $\sigma_n$ is the normal stress at the interface.

The value of μ is clearly expected to depend on the surface roughness (of projectile and target), stress and other factors, so it is hard to be predicted a priori. Since both surfaces are smooth, a relatively low value (<~0.2) is considered to be appropriate by Burley [17]. In impact cases, the friction coefficient should be a function of normal stress and local temperature of the contact.

It could be presumed that high pressure in the contact zone caused high deformations and the deformation energy is transformed partially in heat and, thus, the friction coefficient depends also on temperature distribution in contact. Also, the relative motion between projectile and target is varying very much, from initial impact value to the residual velocity.

It could be presumed that for small difference in these velocities (initial and residual), the friction coefficient does not vary too much. But when the residual velocity is low, even to zero, as desired for a protection system, friction coefficient could vary in a larger range in a short time interval.

Friction could have different components (abrasive, adhesive, fluid) and the friction coefficient becomes a function with different values depending on local conditions (previous heat release, temperature of bodies in contact, normal pressure and the mechanical properties of the contacting bodies, here including deformation, fragmentation and softening of materials).

The authors selected 0.25mm as value for the element size. The projectile is made of OFHC-F copper (the same material as in Johnson-Cook work [1, 3]). Tables 1, 2 and 3 present the characteristics necessary for modeling the constitutive model of the projectile material and its failure criterion.

Table 1. Material characteristics

| **Characteristic** | **Value** |
|---|---|
| Density, kg $m^{-3}$ | 8960 |
| Specific Heat, J $kg^{-1}$ $C^{-1}$ | 383 |
| Bulk Modulus Pa | 1.29e+011 |
| Shear Modulus Pa | 4.6e+010 |

Table 2. Constants for Jonhson-Cook constitutive model for strength for-OFHC-F copper (from [Johnson, 1983])

| Initial Yield Stress Pa | Hardening Constant Pa | Hardening Exponent | Strain Rate Constant | Thermal Softening Exponent | Melting Temperature C | Reference Strain Rate (/sec) |
|---|---|---|---|---|---|---|
| 9.0e+007 | 2.92e+008 | 0.31 | 2.5e-002 | 1.09 | 1082.8 | 1 |

Table 3. Johnson Cook failure criterion for-OFHC-F copper

| Damage Constant D1 | Damage Constant D2 | Damage Constant D3 | Damage Constant D4 | Damage Constant D5 | Melting Temperature C | Reference Strain Rate (/sec) |
|---|---|---|---|---|---|---|
| 0.54 | 4.89 | -3.03 | 1.4e-002 | 1.12 | 1082.8 | 1 |

Here, the simulation is run for an isothermal case, in order to point out only the influence of friction coefficient and not the modification induced by heat generated by friction in the material parameters. Also, the friction coefficient is presumed constant, COF=0.25.

## 3. RESULTS AND SIMULATIONS

Based on the simulation with and without friction, the stages characterizing the damage of the projectile could be expressed as:

- the cylinder deforms but all its base is in contact with the target (very short time stage),
- formation of the mashroom hat,
- development of the peripheral shape with or without break(s).

Figures 2 to 4 present the von Mises stress distribution for the earliest moment of the simulation.

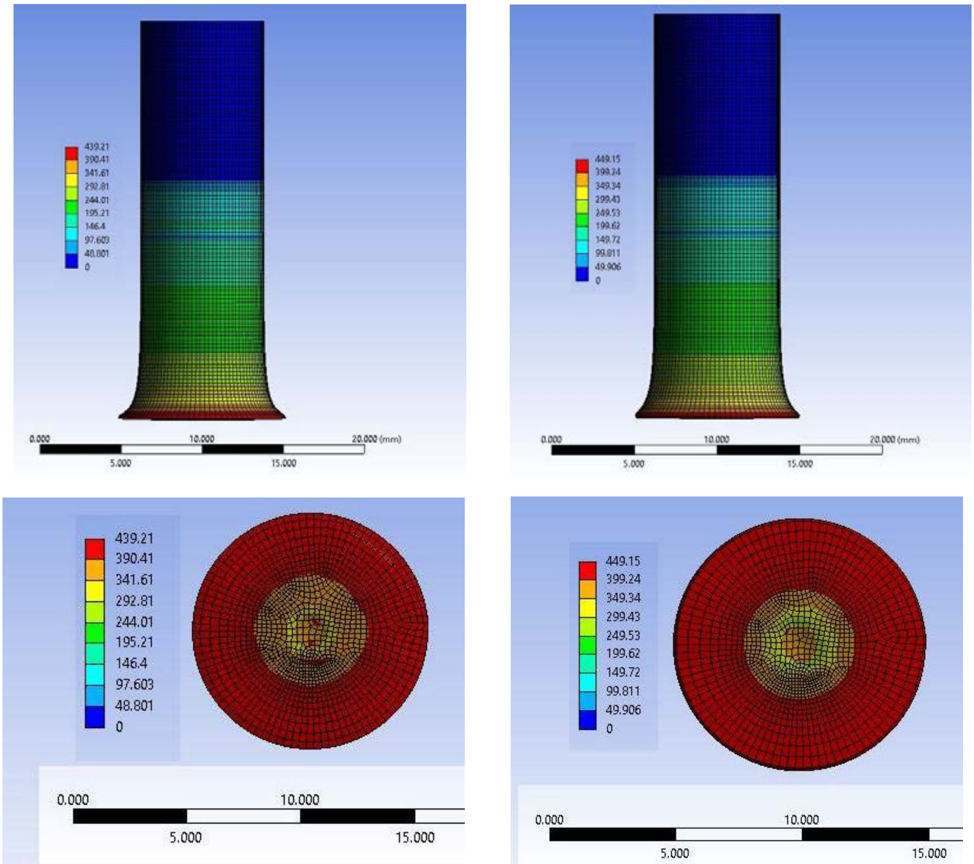
A lateral view (Fig. 2) with stress scale, at moment $t=1\times10^{-5}$s, does not point out significant differences in contact behavior, only a difference in maximum value of this stress (439.21 MPa for COF=0 and 449.15 MPa for COF=0.25).

But at the moment $t=2\times10^{-5}$ s, the shape of the projectile is different. The absence of friction makes the material to flow easier on the rigid surface of the target, the edge volume being not in contact with the target.

When taking into account the friction between the projectile and the target, the material is stunt to flow in a radial direction, thus the shape is not so developed as compared to that without friction (Fig. 3).

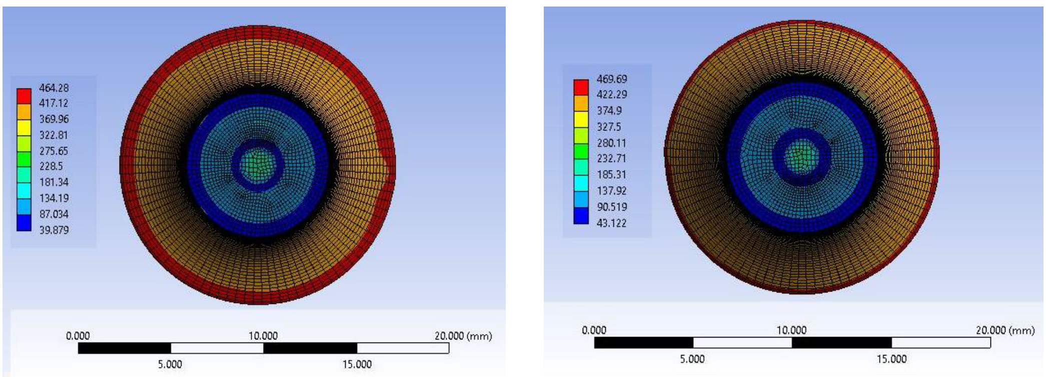
The zone of maximum stress is less extended for the case with friction, but values are very close, higher for the case with friction.

In the case without friction, the first break of the edge is occurring between $t=4\times10^{-5}$ s and $t=5\times10^{-5}$ s (Fig. 4a and b), but in the case with friction, no break of the deformed edge is occurring during the entire simulation of $2\times10^{-4}$ s (Fig. 4c and d).



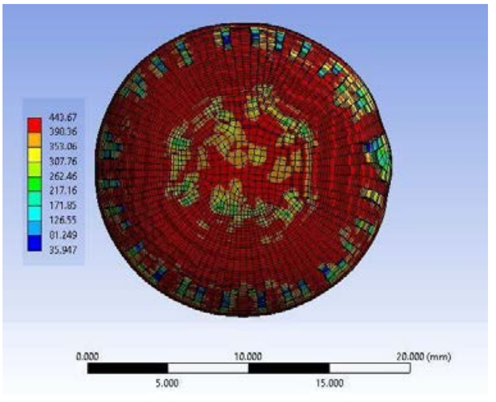

a) without friction b) with friction

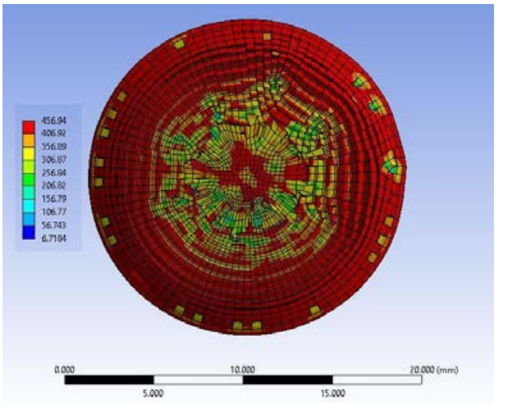
Figure 2. Lateral view of the projectile shape (up) and of the impacting surface (down), at time moment $t=1\times10^{-5}$ s



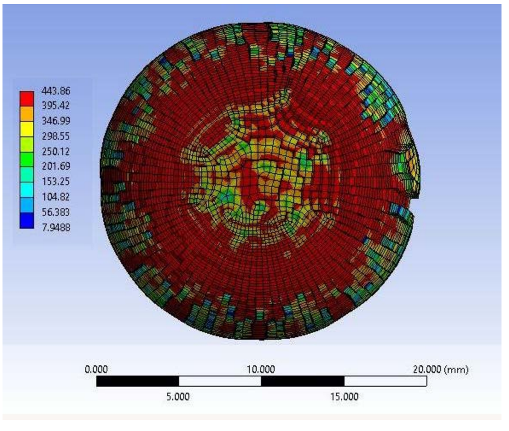

a) without friction b) with friction

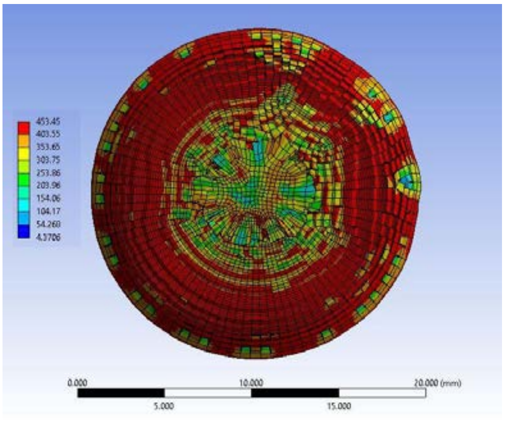
Figure 3. Top view (the target is invisible, here behind the projectile), at $t=2\times10^{-5}$ s, von Mises stress distribution [MPa]





a) t=4×10$^{-5}$ s b) t=5×10$^{-5}$ s





c) without friction, t=4×10$^{-5}$ s d) with friction, t=5×10$^{-5}$ s

Figure 4. Von Mises stress distribution for important moments for mushroom development and failure

In the case without friction, the first break of the edge does not advance very fast and, at t=6x10$^{-5}$ s, the second break appears, the third one being visible at 7×10$^{-5}$ s.

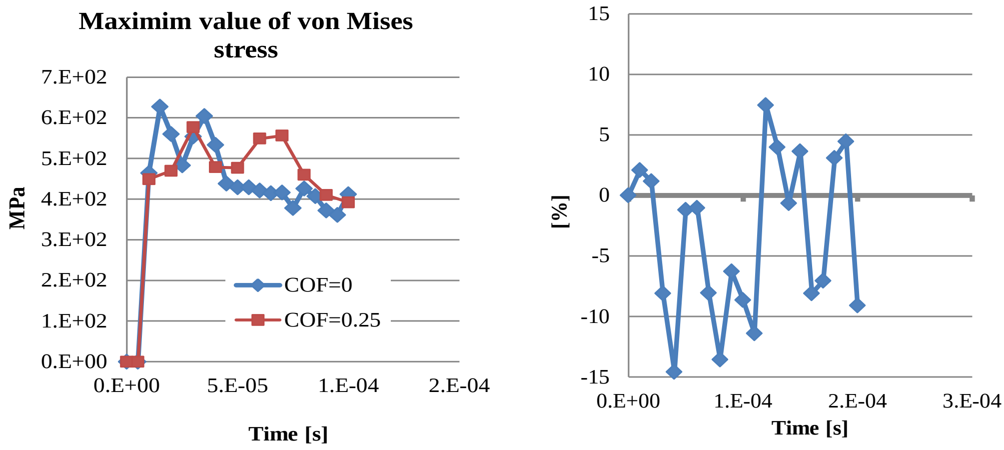
The material in the central zone of the contact is less stressed because friction obstruct its displacement on the target surface (Fig. 4, comparing a) without friction and b) with frictio).

Analyzing the evolution and the values of maximum von Mises stress at each calculated moment (Fig. 5a), the following conclusions could be formulated:

- for this case of impact ($v_0$=300m/s), when taking friction into account, the maximum values of von Mises stress are lower and somehow delayed; Figure 5b presents the difference between maximum values of von Mises stress, calculated as

$$\Delta\sigma_{ech} = \frac{\sigma_{ech(COF=0.25)} - \sigma_{ech(COF=0)}}{\sigma_{ech(COF=0)}} \cdot 100 \quad [\%] \tag{2}$$

- friction delayed the appearance of the first stress peak, and also increased the time between peaks,
- stress peaks are sharper as aspect as compared to those generated when friction is taken into account.




a) b)

Figure 5. Maximum value of von Mises stress during the impact

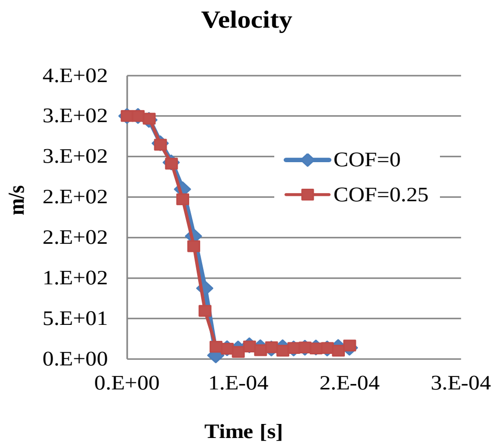



Figure 6. Velocity for the central point on the surface opposite to that in contact

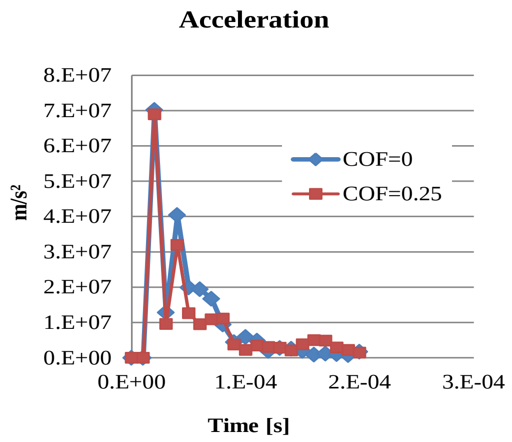



Figure 7. Acceleration for the central point on the surface opposite to that in contact

The plot for velocity of the central point of the cylinder on the face opposite to that contacting the target has no significant differences, as one may see in Fig. 6, but the plot of the acceleration of the same point (Fig. 7) has the second peak higher for the case without friction, meaning that the break of mushroom edge facilitate the advance of the material of cylinder top toward the target.

Friction reduces only with almost 10% the maximum stress induced in the cylinder at $t=7\times10^{-5}$ s on the interior surface of the mushroom hat that is formed in both cases, but it changes the distribution. Figure 8 shows this difference in stress distribution on the interior surface of the mushroom hat.

Figure 9 presents the images at the end of the simulation. Of course, the duration of the impact, till all the material of the projectile is not anymore stressed is faraway, but the important process in damaging the cylinder had already happened.

In the case of friction, there is a crown (sector) when very small particles are detached near the surface, that escapes from the direct contact with the target, this could be explained due to the high tensile stress in this zone. A part of the material in direct contact with the target is “kept” not to flow due to friction, but above this surface, the material is forced to flow and tensile the sector near the contact. This damaging process is visible at t=5x10$^{-5}$ s on both cases, and is continuing till the end of this simulation. It is like a small and local scaling of small volumes of material. Some particles are enterily detached, but others remain like scales, still atached to the main body.

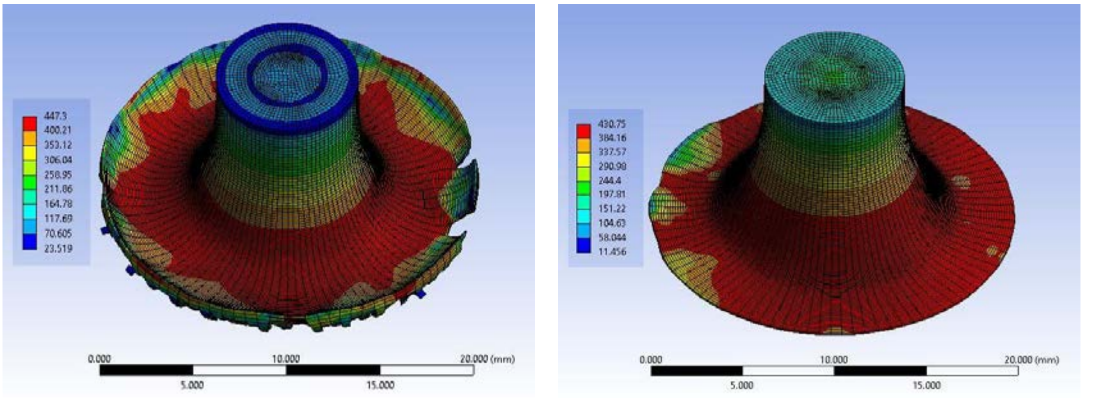
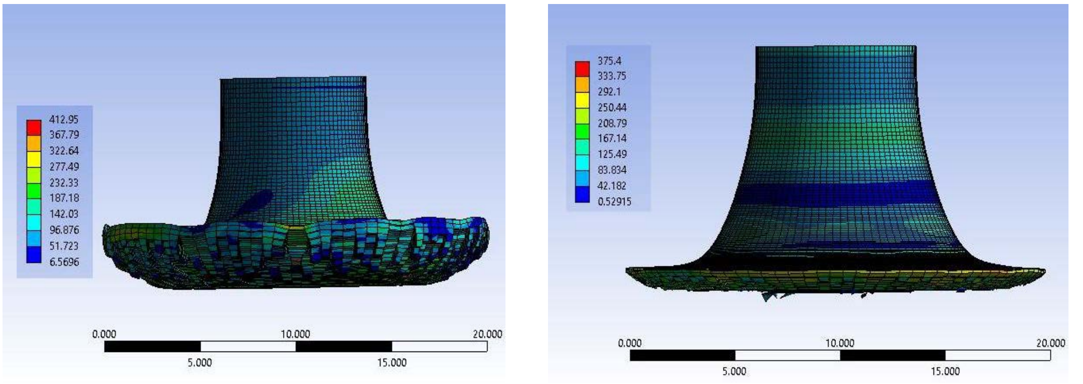



Figure 8. View from above of the projectile, at moment t=7×10$^{-5}$ s




a) without friction b) with friction

Figure 9. Lateral view of the projectile, at time momen t=2×10$^{-4}$ s

## 4. CONCLUSIONS

This paper presents an analysis of two cases, simulating the impact of a cylindical projectile on a perfectly rigid plate.

One case is run without friction, the second one is run taking into account a constant friction coeficient between the plate and the projectile.

The authors used for the projectile the same material constitutive model for both cases, based on experimental data and model developed by Johnson and Cook [3].

Here, the comparing criteria were the maximum value of von Mises stress, the velocity and acceleration of the central point on the opposite face to the contact face of the projectile. Introducing friction, the simulation is more realistic.

Taking into account friction, the projectile is less deformed and there was no edge breakage, at the same time moment (t=6×10$^{-5}$s) when the model without friction presented two large breaks on the edge of the mashroom shape of the projectile.

## ACKNOWLEDGEMENT

This work has been supported by the European Social Fund through the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Burse pentru educatia antreprenoriala in randul doctoranzilor si cercetatorilor postdoctorat (Be Antreprenor!)" "Scholarships for entrepreneurial education among doctoral students and postdoctoral researchers (Be Entrepreneur!)", Contract no. 51680/09.07.2019 - SMIS code: 124539.

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