HOW FRICTION COULD INFLUENCE THE SHAPE AND FAILURE MECHANISM IN IMPACT, WITH THE HELP OF A FINITE ELEMENT MODEL

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This paper presents the influence of taking into account friction when a cylindrical projectile hits a perfectly rigid target. Friction could change the behavior of both projectile and target, especially when target also generates friction among its components, as it occurs among layers, yarns and fibers, at different dimensional levels of body armor or other protection systems. For impact of high velocity, it is difficult to assess it by measuring. The model is an isothermal one, in order to point out only the influence of friction and not the changes caused by generated heat. Results of the simulation run with different values of friction coefficient (considered constant) pointed out that its value influences the shape and the failure mechanisms of the projectile. There were discussed maximum values of von Mises stress, evolution of velocity and acceleration of the central point of the free face of the cylinder (the face opposite to the impacted one). Introducing friction, the shape of the projectile after impact is more realistic. Taking into account friction, the projectile is less deformed and there was no edge breakage, at the same time moments, when the model without friction presented several breaks on the edge of the mushroom shape.

Keywords: impact, target, projectile, Johnson-Cook model, friction, failure mechanism.

1. Introduction

Studies dealing with the friction effect in ballistic protection [1], [2], [3] point out that friction could play an important role in arresting the projectile, by ”consuming” a part of the kinetic energy of the projectile. The issue related to friction is that this parameter is not constant during the impact and its value depends on the stage of the projectile failure. It would be very possible that on thin targets, when the projectile breaks through the panel, the friction coefficient between target and projectile to have low values and with less range of variations.

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When the projectile is arrested, it could have higher values due to the high pressures involved in contact, especially when both bodies (projectile and target) are deformed. Also, the difference in kinetic energy of the projectile will be transformed in energy of deformation and heat, the temperature influencing the mechanical characteristics of the materials.

Johnson and Cook [4], [5], [6] proposed a constitutive model for the projectile material, taking into account the strain rate and the temperature and compared the results of simulating the impact of a cylinder to a rigid target, for high strain rates till 10^5 s^{-1} and larger strains than 200%. But, in their early work, the friction was not introduced.

The selection of a constitutive model, its constants should be deduced from laboratory tests that could imitate the actual severe conditions [7], such as high plastic strains and strain rates, high temperatures. It is difficult to design and monitor a laboratory rig allowing for reproducing such conditions and to measure with adequate and sufficient accuracy to make the model useful. For instance, Dion et al. [1] proposed a method to identify material behavior at large strains, intermediate strain rates and elevated temperatures from high speed compression tests and a FE model of the experimental rig was designed and calibrated by the help of dynamic compression tests carried out on known specimen behavior. Having a similar objective, Liu et al. [8] identified DP600 material constitutive model, including influence of hardening, temperature, strain rate, and anisotropy on residual stresses simulation after processing the material. Recently, Burley et al. [1] present a study for evaluating a strain rate sensitivity parameter for plastic deformation of metallic materials, based on impact tests with a hard spherical projectile, followed by calibrating the FE model close to experimental outcomes (displacement-time plots and/or residual indent shapes).

This paper intends to discuss the usefulness of simulating impact and the importance of friction in impact, even if here is a simple model: a cylinder made of an elasto-plastic material sensitive to strain rate that hits a perfectly rigid plate.

2. The model

The geometry of the system is simple, inspired from [4]: a perfectly rigid plate is impacted by a cylinder made of a copper alloy, having the velocity of 300 m/s just before the impact. The diameter of the projectile is 7.52 mm and its length is 25.4 mm. The cylinder could be considered a blunt projectile.

The usual effect of friction (with Ansys) is to consider a coefficient of friction, μ, thus, sliding between the two surfaces introduces a shear stress, τ,

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

where σ_n is the normal stress at the interface, the sign being given in order to point out that this stress acts in the opposite direction of motion. The value of μ is expected to depend on many variables, including the surface roughness (of projectile and target), stress, local temperature, so it is hard to be predicted a priori. A low value (<~0.2) was considered adequate by Burley [1].

In impact cases, the friction coefficient should be a function of normal stress and local temperature of the contact. High contact pressure causes high deformations, with local heating, thus, the friction coefficient depends also on temperature distribution in contact. The motion of the projectile relatively to the target is varying very much, from initial velocity to the residual velocity that could be zero when the projectile is arrested. 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 zero, friction coefficient could vary in a larger range in a short time interval. Friction could have different components (abrasive, adhesive, fluid) and the its coefficient could have different values depending on local conditions (heat release, temperature of bodies in contact, normal stress and mechanical characteristics of the contacting bodies, here including deformation, fragmentation and softening of materials).

The authors selected 0.125 mm as value for the element size. The projectile is made of OFHC-F copper (the same material as in Johnson-Cook work [4], [6]). Tables 1, 2 and 3 present the characteristics necessary for modeling the constitutive model of the projectile material and its failure criterion.

Table 1

Projectile material characteristics.

Characteristic	Value
Density, kg m^{-3}	8960
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 ([4], [6]).

Initial yield stress, Pa	Hardening constant, Pa	Hardening exponent	Strain rate constant	Thermal softening exponent	Melting temperature, ºC	Reference strain rate, (s^{-1})
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 [4]-[6].

Damage constant D1	Damage constant D2	Damage constant D3	Damage constant D4	Damage constant D5	Melting temperature, ºC	Reference strain rate (s^{-1})
0.54	4.89	-3.03	1.4e-002	1.12	1082.8	1

The simulation is run in isothermal conditions, in order to point out only the influence of friction coefficient and not the modification induced by heat generated by friction and deformation in the material parameters. Also, the friction coefficient is presumed constant, here with two values, 0.2 and 0.3.

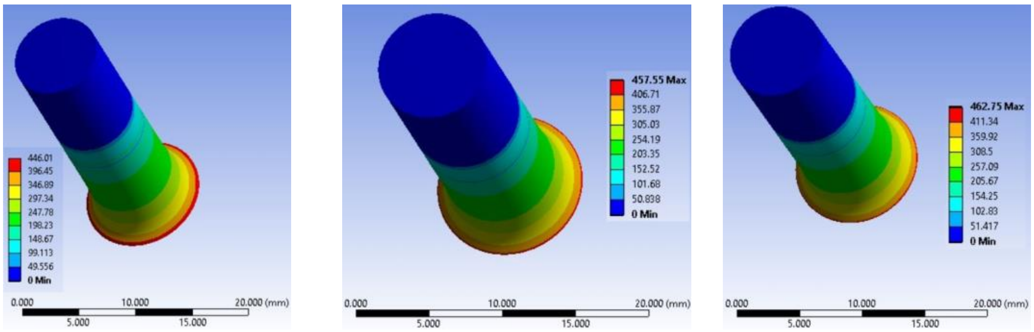
3. Discussion on simulation results

Figures 1 to 3 presents, for the same moments, the von Mises stress distribution for the three analyzed cases. It could be noticed the stages characterizing the failure of the cylindrical projectile:

- the cylinder deforms, especially near the hit target, but it contacts the target with all its initial base (very short time stage) (Fig. 1, the time moment being $t=1\times10^{-5}$ s),
- formation of the mushroom hat (Figure 2 was selected for this stage, time moment being $t=2.5\times10^{-5}$ s),
- development of peripheral shape, with or without local break(s) (Fig. 3).

For the last two stages, there are significant differences in shape for the case without friction and the two others with friction.

Figure 4 presents the evolution in time of the maximum value of von Mises stress. The high maximum of the von Mises stress for the moment $t=2.5\times10^{-5}$ s could be explained by the fact that heating effect is neglected in this simulation, but also the earlier Johnson Cook model overestimated the influence of strain rate on the strength limit. New constitutive models [10], [11] tried to diminish differences between models and experimental results. Also, without friction the material of the cylinder could be pushed in radial direction very fast, so the strain rate at the edge of the mushroom could be very high and the Johnson-Cook model could give a very high value of the strength limit.



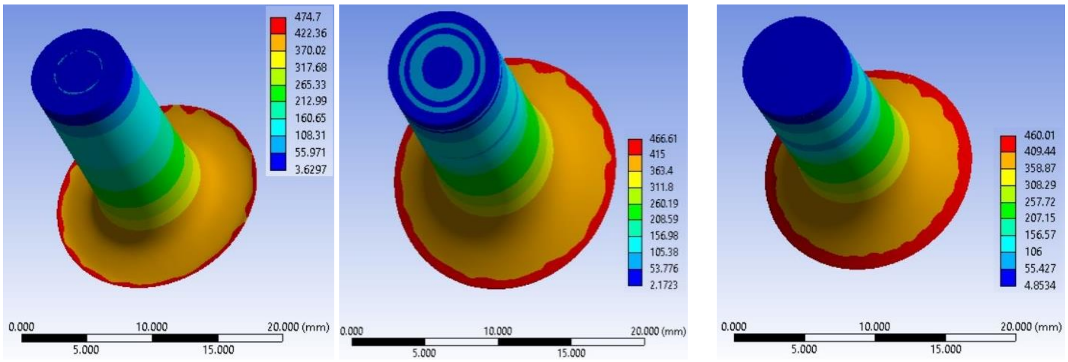
Cof=0 Cof=0.2 Cof=0.3

Fig. 1. Shape of the projectile and von Mises stress distribution, at the moment $t=1\times10^{-5}$ s

In Figure 2, the (imaginary) diameter of the deformed zone of the projectile is inversely proportional to the value of the friction coefficient, meaning that, due to friction, the material near the target is restrained to be expelled (deformed) along the target.

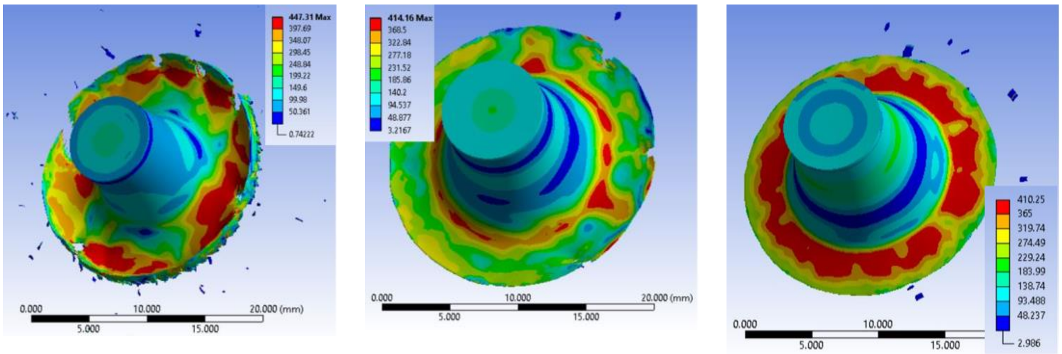
At moment $t=9\times10^{-5}$ s (Fig. 3), fractures appear on the model without friction, the initial one being the deepest. When Cof=0.2, the fractures on the deformed edge of the projectile are fewer and less deep. For a higher value

Cof=0.3, there are no visible fracture on the edge, and the peripheral sector is not visibly detached and rolled as it happens without friction or with a lower value of friction coefficient.



Cof=0 Cof=0.2 Cof=0.3

Fig. 3. Shape of the projectile and von Mises stress distribution, at the moment t=2.5×10^{-5} s



Cof=0 (the maximum value is not on the image) Cof=0.2 Cof=0.3

Fig. 3. Shape of the projectile and von Mises stress distribution (in MPa), at moment t=9×10^{-5} s, for a cylindrical projectile with impact velocity of 300 m/s and perfectly rigid target

Analyzing the curves in Fig. 4, one may notice that simulating without friction, the first moments of the impact are characterized by values in a small range (less than 10%): 447...486 MPa, the higher being for the cases with friction. From this moment to the following one (t=2×10^{-5} s), the stress value has the biggest gradient for the case without friction, when the first break occurs; but the strength limit is noticed only for Cof=0; for the value 0.3 of friction coefficient, the maximum value of von Mises stress remains lower, in the plastic domain of the material, with a maximum at moment t=6.5×10^{-5} s and no visible break is present. From this moment, the evolution of the curves is becoming similar. The absence of friction allows for the material to be easier deformed and hardened, the strain rate being greater that under friction, and thus, the Johnson-Cook model "returns" a higher strength limit for $t=2.5\times10^{-5}$ s. Maybe a more realistic model could be that given in [12] that had taken into account also the temperature and the dependence on strain rate, strain and temperature has another mathematical function.

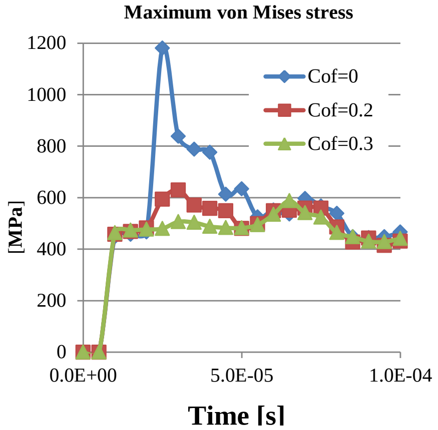


Fig. 4. Maximum values of von Mises stress during the simulation

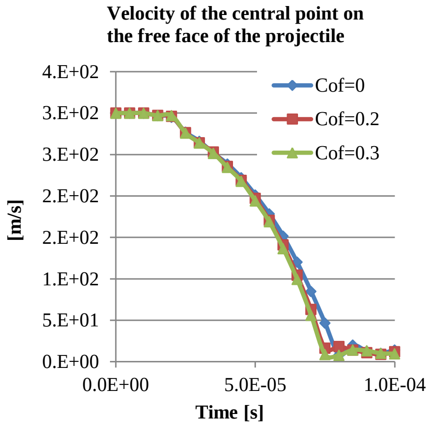


Fig. 5. Velocity of the central point on the free face of the projectile, during the simulation

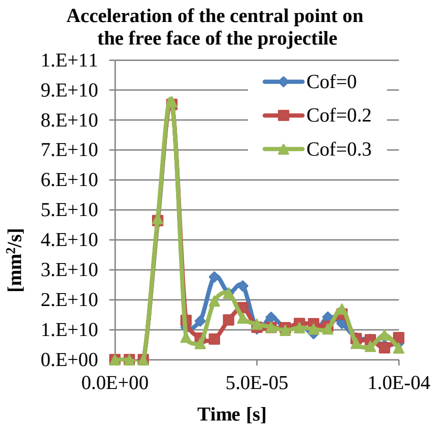


Fig. 6. Acceleration (deceleration) of the central point of the free face of the projectile, during the simulation

Even if the velocity of the opposite face is very low meaning the end of the impact process is near in time, the cylinder material is still stressed, but at lower value (around 400 MPa).

Analyzing the velocity of the central point on the free face of the projectile, there are visible differences from $t=5.5\times10^{-5}$ s, the friction coefficient reducing this velocity more than the case without friction: at $t=7.5\times10^{-5}$ s, the central point has only 8 m/s for Cof=0.3 and 9 m/s for Cof=0.2. Without friction, this velocity is 47 m/s.

The first peak of the acceleration (it could be named deceleration as its variation is from the initial impact velocity till a lower velocity at moment t) is almost overlapping for all three cases, differences could be noticed after that.

A qualitative comparison with a bullet extracted from a flexible target (aramid fabrics) after being impacted with velocity of 400 m/s (Fig. 7) pointed out that processes of damaging the projectile are similar to the virtual projectile this simulation deals with: the shape of the bullet is also like a mushroom, the edge breaks are asymmetrically distributed, one being deeper. Test campaign was done following the standard requirements [13], [14].

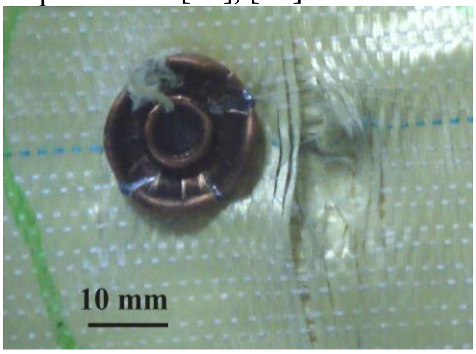


Fig. 7. A 9 mm FMJ bullet extracted from a package of aramid fabrics (the projectile was retained within the package) [15]

4. Conclusions

This paper presents an analysis of three cases, simulating the impact of a cylindrical projectile on a perfectly rigid plate, in isothermal conditions: one without friction between the cylindrical projectile and the target, the other two cases taking into account the friction, but with different values of the friction coefficient, kept constant. 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 [1]. There were discussed maximum values of von Mises stress, evolution of velocity and acceleration of the central point of the free face of the cylinder (the face opposite to the impacted one). Introducing friction, the shape of the projectile after impact is more realistic. Taking into account friction, the projectile is less deformed and there was no edge breakage, at the same time moments, when the model without friction presented several deep breaks on the edge of the mushroom shape.

Acknowledgement

This work is supported by the project ANTREPRENORDOC, in the framework of Human Resources Development Operational Programme 2014-2020, financed from the European Social Fund under the contract number 36355/23.05.2019 HRD OP /380/6/13 – SMIS Code: 123847.

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