Proceedings in Manufacturing Systems, Volume 11, Issue 3, 2016, 125–130 ISSN 2067-9238

MANUFACTURING SYSTEMS AND PASSIVE SAFETY

Stanislav ŠPIRK[1,*]

[1] Title (Ing., Ph.D.), researcher, Regional Technological Institute,
Faculty of Mechanical Engineering - University of West Bohemia, Pilsen, Czech Republic

Abstract: *The main point of this paper is simulation focused on passive safety of manufacturing systems. The passive safety of manufacturing system is connected with smaller safety risk compared with another fields of industry (e.g. automotive passive safety, rail vehicles passive safety or terminal ballistics protection). The revolutions of manufacturing system could reach 10000 [rpm]. The tangential speed on the larger diameter of a manufacturing tool can be sometimes higher than a speed of rifle bullet. The safety risk during an accident is significant. The parts could exceed the safety barrier and they can cause fatal injury to the staff. The simulations, presented in this paper, are aimed to the problem of terminal ballistic where the experiment is complicated. The paper summarizes the findings from the field of injuries caused by machine tools. Statistics of injuries are described here as a possible starting point for determining the frequency of occurrence. As an interesting point of research is described evaluation of the safety risk caused by released machine parts. The two possible ways for numerical simulations are shown in this paper. The first approach is the FE (finite elements) simulation. The second approach is SPH (smooth particle hydrodynamics) methodology. The advantages, disadvantages and applications of these methods are described at the end of the paper. The conclusions could represent the first step in simulations for safer structural design of machines.*

Key words: *manufacturing, passive safety, explicit analysis, FEM, SPH.*

1. INTRODUCTION

The aim of this article is the first research about possible simulations for passive safety of manufacturing systems. It is obvious than the passive safety of manufacturing system is connected with more significant safety risks than the ballistic of small pieces. The velocities and revolutions of machines increase in general. The future machines will be connected with new special problems and the passive safety could be one of them. The work is also motivated by demand of a producer who does not want be named (for obvious reasons). The discussed problem is in research connected with large grinders. The real experiment is very complicated and one possible solution for safety risk assessment is computer simulation. This paper may give insight in possible methods of solution. The presented methods are well known but not widely used in this field.

2. ACCIDENTS IN MANUFACTURING INDUSTRY

2.1. Accidents statistics

Motivation to engage in prevention activities can be viewed as voluntary, incentive or coercive, with the first as a preferred source. An extensive cost classification is provided: prevention, accident and costs; fixed and variable insurance costs; direct and indirect costs [9].

The accidents occurrence in industry is object of more studies. Each accident is connected with losses. These losses are established only generally. An empirical study of the costs of occupational accidents was carried out during 1986-87 in 57 furniture companies in Finland, Norway and Sweden, employing 5,000 cabinet-makers. It covered 18 percent of the furniture manufacturing industry from three countries. The cost analyses indicate that the company costs of participating firms in Finland were 0.5%, in Norway 0.3% and in Sweden 0.2% of the total wages using the market pricing model [10].

It is obvious than the economical cost is only one point of view. Nevertheless, the fatalities of employees still exist. The correct approach for initiation of research is a statistical evaluation.

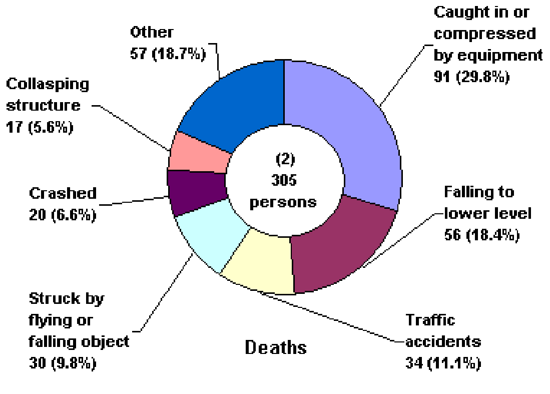


Fig. 1. Types of Accidents in Manufacturing Industry (source: [16]).

---

[*] Corresponding author: Regional Technological Institute,
Univerzitni 8, 306 14 Pilsen, Czech Republic,
Tel.: +420 377 638 728;
E-mail addresses: *spirks@rti.zcu.cz* (S. Špirk)

The present statistics are quite poor in this specific field. A lot of very complex and useful studies are interested in active safety for accident prevention (eg. [1]) and not in the passive safety for accident consequences reduction. The specific data are given by Japanese statistic (Fig. 1.). Here is the injury caused by flying object quite common, but its occurrence is described together with injuries by falling object. Therefore, the informational value is still very low.

2.2. Injuries from parts with significant velocity

Despite the complicated statistical evaluability of the injuries (caused by flying parts), this kind of injury occurs. The most significant occurrence of this kind of injury is probably connected with high-speed manufacturing machines. The angle grinder is good example of a source of fatal injuries as result of disc rapture. The most usual reason of the accident is the violation of manufacturer's or safety instructions.

The examples of fatal injury are available in literature. It is possible to describe one of them. A 35-year male was brought to emergency department with history of accidental neck injury with saw blade. On examination, he was dead. While work of pipe cutting was in progress, the abrasive saw blade suddenly break and shattered in pieces. One piece penetrated the neck of the victim and another piece travelled in the air and injured the left arm of a 12 year child who was playing in the ground about 25 feet away from the site [7].

The manufacturing tool rupture is not easy predictable. This is not problem of angle grinder only. It is clear than this type of accident can occur also during usage of different manufacturing machines. The accident could be also caused by movement of a workpiece. This is also a frequent source of accidents. It is possible cite an example. A part weighting 900 lb. was thrown out of a 48" vertical lathe (Fig. 2). "Machine had made the first pass on top of the spindle and started to make the second pass and the part came out of the chuck. It was in constant surface footage and was speed was probably around 200 to 250 rpm for the spindle." [17]

3. THE ACCIDENT CONDITIONS

3.1. The parameters of accident

The usual type of accident is releasing of rotating part. The final velocity in the time of impact is result of initial conditions. The impact velocity can be established from mass of the part and revolutions on known diameter. Movement of specific part is dependent on many parameters. The impact velocity is generally predictable. Neglecting air resistance allows to consider the kinetic energy constant. It is because the mass of the released part is constant as well as the momentum. With this approach can be estimated the impact velocity for general use. The impact velocity is 150 m/s.

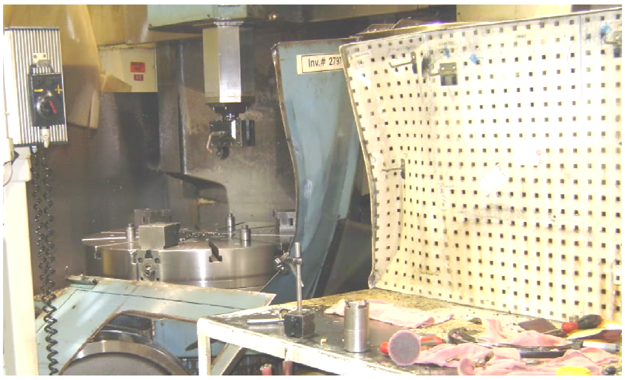


Fig. 2. An example of industrial lathe accident (source: [17]).

3.2. The impact physical phenomena

The main point of our research was to solve an impact. The impact is in classical mechanic contact problem of two or more bodies, with significant contact forces, which occurs in short time. The impact force usually has a greater effect than a lower force applied over longer time. The effect of impact depends highly on the relative velocity of bodies. The real solid body has an elastic and plastic deformation during impact. The plastic behavior could be ignored or simplified in some specific engineering problems (multibody modeling, linear statics analysis). This approach is not applicable for higher velocity impact with complicated elasto-plastic behavior.

The impact during higher velocity is usually connected with large deformation. This causes nonlinearity of this kind of simulations. The condition of small strain, suitable for linear statics analysis, is not valid for impact with elasto-plastic behavior (composed from the elastic behavior and plastic behavior). The material nonlinearity is also significant during the large deformations. Even the stress-strain characteristic of material is depended on the strain rate. Problem during simulations is also connected with material failure and its elimination. The more detailed description is in paragraph 3.4.

4. THE THEORY BASE FOR SIMULATIONS

4.1. Theory of explicit FEM modelling

The beginnings of the development of explicit solvers date back to the 1960s. At that time, such development took place mainly at universities. The HEMP program, whose code was freely accessible, was beginning for today’s software packages. Explicit time integration is suitable for simulating processes which involve large strains and changes in shape. It offers better representation of the nonlinear behavior of materials, and failures. Explicit solvers are generally better suited for problems with complex contact. Therefore, they are a good choice for solving collision problems, crashes, bullet penetrations, and similar tasks.

The essence of an explicit code is Newton’s second law of motion. It is an equation of motion in the matrix form (1). This equation is defined for the given time. In order to maintain equilibrium between dynamic forces, the relationships below must be met [3].

$$\{a_t\} = [M]^{-1}\left(\{F_t^{ext}\} - \{F_t^{\text{int}}\}\right). \tag{1}$$

Here, $\{at\}$ denotes the acceleration vector (at time instant t), $[M]$ – mass matrix, $Ftext$ – vector of external forces acting on the body, and $Ftint$ – vector of internal forces.

Once the internal forces have been defined and some fundamental elements added, an equation for the numerical solution can be obtained in the following form (2).

The element {*Fhoug*} was added to prevent the hourglassing effect, and {*Fcnt*} is a vector of contact forces. Furthermore, {σ_n} is an internal stress matrix, and [*B*] is a strain matrix.

$$\left\{\mathrm{F}_{\mathrm{t}}^{\mathrm{int}}\right\}=\sum\left(\int_{\Omega}[B]^{T}\{\sigma_{n}\}d\Omega+\left\{F^{houg}\right\}\right)+\left\{F^{cnt}\right\}. \quad (2)$$

Solvers that use the explicit code are conditionally stable. This means that they are only stable under certain conditions, referring mainly to the time step size. This, in turn, is related to the propagation of stress waves through the material (see the following equation (3)). Here, *c* is the velocity of the wave propagating through the material, *l* is the characteristic size of an element, *E* is the modulus of elasticity, and ρ the density of the material.

$$t_{comp}\le t_{krit}=\frac{l}{c}=l\sqrt{\frac{\rho}{E}}\;. \quad (3)$$

A great advantage of the explicit method is usage of elements with a single integration point. A downside is the reduced stability of computation. If an element deforms symmetrically, no corresponding change in internal energy takes place. Eventually, the computation leads to an imbalance between the kinetic and the internal energy of the system. This numerical error is known as hourglassing. The total energy must be controlled in dynamic calculations. The recognized critical threshold is an increase in the hourglassing energy above 5 % of the total energy of the system. In extreme cases with a significant hourglassing effect, the simulation run may even crash. Various methods are available to control hourglassing.

4.2. Theory of SPH modelling

The method Smoothed particle hydrodynamics (SPH) was invented for study of non-axisymmetric phenomena in astrophysics by Lucy, Gingold and Monaghan in 1977. "We wanted a method that was easy to work with and could give reasonable accuracy. The SPH method satisfied these requirements. As a bonus we found the SPH was rugged, gave sensible answers in difficult situations, and could be extended to complicated physics without much trouble."[12]

The SPH method is suitable for fluid flow and structural dynamics [2]. It is because this method can use the Lagrangian (useful for dynamic of solid description, with small movement of particles) or the Eulerian description (useful for dynamic of fluid description, with large movement of particles). The Lagrangian *L* for the non-dissipative motion of a fluid in a potential Φ(*r*) per unit mass is [13]:

$$L=\int\rho\left(\frac{1}{2}v^{2}-u(\rho,s)-\Phi\right)dr\;, \quad (4)$$

where *v* is the velocity, *u* the thermal energy per unit mass, ρ the density and s is the entropy. The Euler equations are the equations for the rates of change of velocity, density and position, namely, [13]

$$\frac{dv}{dt}=-\frac{1}{\rho}\nabla P+g^{-1}\,; \quad (5)$$

$$\frac{d\rho}{dt}=-\rho\nabla\cdot v\,; \quad (6)$$

$$\frac{dr}{dt}=v\,, \quad (7)$$

where *v* is the velocity, ρ the density, *P* the pressure and *g* is the body force per unit mass.

The SPH is a mesh-free method for simulation of continuum mechanics, where properties can be interpolated within a certain range. The first fundamental formula is the Kernel approximation.

$$f(x)=\int f(x')W(x-x',h)dx'\,, \quad (8)$$

$$\nabla f(x)=\int f(x')\nabla W(x-x',h)dx'\,, \quad (9)$$

where *h* is the smoothing length and *W* – smoothing function. The interpolation points are identified with the particles with a specified mass. The FE connectivity is replaced by dynamic searching of the nearest neighbor. There is no need for numerical evaluation of partial derivates as with most other methods, but is necessarily to use normalized function.

$$\int W(x-x',h)dx'-1;W(x-x')=0;\left|x-x'\right|>\kappa h\,. \quad (10)$$

The delta function property (from eq. (10)) can be described as position function. The particles begin to interact after their smoothing lengths are in penetration.

The numerical discretization of hyperbolic (transport) equations will results in non-smooth distribution of pressure and velocities. To prevent this problem with stability, an artificial viscosity may be added. This is quite similar problem like hourglassing by explicit FEM (paragraph 3.2). The formulation of artificial viscosity is:

$$\prod_{ij}=\frac{2}{\rho_i+\rho_j}\left(-\alpha\frac{c_i+c_j}{2}\mu_{ij}+\beta\mu_{ij}^{2}\right), \quad (11)$$

where α and β are optional coefficients. The formulation for the Monaghan-Gingold viscosity is dissipation term within governing equation:

$$\frac{dv_i}{dt}=-\sum\nolimits_j m_j\left(\frac{p_i}{\rho_i^{2}}+\frac{p_j}{\rho_j^{2}}+\prod_{ij}\right)\nabla_i W_{ij}\,. \quad (12)$$

4.3. Material models

The pressure-volume behaviour was defined by a polynomial equation of state. In the equation, the pressure *p* was a function of the parameter μ.

$$p = C_0 + C_1 \cdot \mu + C_2 \cdot \alpha \cdot \mu^2 + C_3 \cdot \mu^3 + \\ + \left(C_4 + C_5 \cdot \mu + C_6 \cdot \mu^2\right) \cdot E_i . \tag{13}$$

Here, $\mu = \rho / (\rho_0 - 1)$, $C_0 \ldots C_6$ are material constants, *Ei* is internal energy and the coefficient α is equal to zero when $\mu < 0$. Some of the material constants can be derived from fundamental properties of the material, such as volume compressibility, whereas others can be modeled on equivalent terms of the relevant shock equation of state [5]. A comparison between the shock and polynomial equations of state is given in paper [15] as one of its topics.

The plastic behavior is defined by the Johnson-Cook model [6]. The stress equation is as follows.

$$\sigma_y = \left(C_A + C_B \cdot \varepsilon_P^{C_N}\right) \cdot \left(1 + C_C \cdot \ln \ddot{\varepsilon}\right) \cdot \left(1 - T^{CM}\right). \tag{14}$$

Here, $T = (T - T_{room})/(T_{melt} - T_{room})$, T_{room} denotes ambient temperature, Tmelt is the melting temperature, ε_p is the equivalent plastic strain, ε denotes dimensionless plastic strain, and C_A, C_B, C_N, C_C and C_M are the Johnson-Cook model coefficients for the particular material, which are available in literature [11].

The first failure criterion used was the maximum plastic strain criterion for element elimination. When the limit value is exceeded, the particular element is practically eliminated by reducing its modulus of elasticity to a negligible value. The limit value is determined by the properties of the material. The second failure criterion involved the deviatoric stress tensor. This criterion does not affect the volumetric dependence of stress on strain. The total stress is found from the following equation.

$$\sigma = \left(1 - d\left(\varepsilon_p\right)\right)\sigma_o . \tag{15}$$

Here, σ is the damage full stress tensor, $d(\varepsilon_p)$ denotes the isotropic scalar damage function, and ε_p represents plastic strain.

5. THE SIMULATIONS

5.1. Pam-Shock solver

PAM-SHOCK is an FEM solver which is part of the software package VPS (Virtual Performance Solution) from ESI Group. [14] The software is used for impact and shock simulations and safety assessment. This package is very close to Pam-Crash solver, widely used in the automotive industry [14].

The software Pam-Crash development has continued since 1978 and is connected with the early car crash simulations. Based on the finite element method (FEM), it supports complex-geometry models with a variety of element types. It also offers a wide range of linear and nonlinear materials, including visco-plastic, foam and multi-layer composites, and failure models [4].

As it relies on the explicit formulation in FEM, it is suitable for nonlinear problems with large numbers of contacts (relying mainly on the penalty algorithm).

This software was selected on the basis of references from the defense sector and its ability to solve problems involving the performance of munitions with respect to explosion, cratering, and simulation of kinetic energy penetrators.

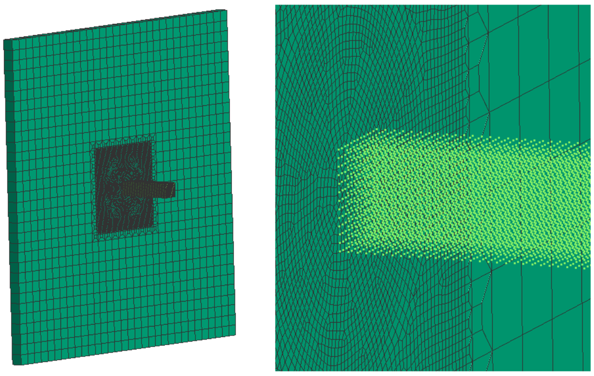
5.2. The FE and SPH models

The linear quadratic elements with eight nodes are used for the FE mesh model creation. The average size of the elements in example shown below was about 0.4 mm. The SPH body was created by conversion from FE mesh. The SPH particle are created in center of FE elements. Therefore, the conformity of fineness is expected (by the same distance between particles 0.4 mm). It is necessary to consider that a uniform order (form uniform FE mesh) is not suitable in some cases for SPH method (tensile instability). But because of comparability is despite used. The used material model is denoted as “Johnson-Cook Model for Solid Elements and SPH”. The model behavior is the same for both methods. The specific material parameters were based on combination of data taken from the literature and data from software JMmatPro. The behavior during high velocity and high temperature impact was validated by ballistics experiments (see [8]).

The model consist from two bodies. The first body represents the sheet with thickness 4 mm. This body is based on FE mesh only (Fig. 3). The material of first part is steel S355 (Czech Standard designation CSN 11523). The second body represent the flying piece with basic dimensions 5 × 5 × 20 mm. This piece is created by FE mesh and by SPH approach with the same material model.

For the second part the tree materials (lead, steel hardox 500, ceramics) are considered. This approach gives the possibility to compare behavior of different materials with usage of method FEM and SPH.

The border nodes of first part (sheet) had fixed displacement in direction of second part (flying piece) movement. The translational initial velocity of second part is 150 m/s. This velocity is selected as a tangential speed of grindstone. The non-symmetric contact between



a b

Fig. 3. The prepared models: *a* – FEM mesh (general view); *b* – Detail on SPH.

parts is used (first part as slave). The contact thickness is set approximately as half of length between SPH particles 0.2 mm. The nonlinear penalty stiffness is set (stiffness parameter 10). The time of solved problem duration is 0.5 ms. The time-step moves between 0.8e-5 ms for FE solution and 0.95e^{-6} ms for solution with SPH implementation.

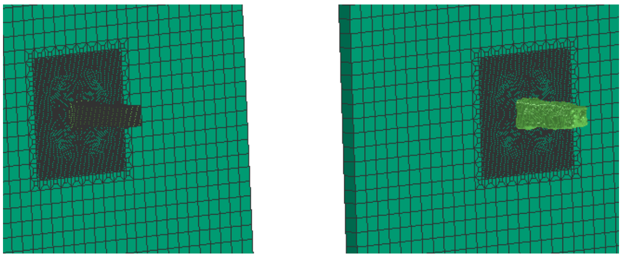
5.3. Simulations

The first expected result is a computation time costs comparison. It is obvious, that the SPH method takes significantly more time comparing to the FE method. From the elapsed times comparison should be assumed, than the SPH method takes six times more time (e.g. elapsed time for computation with material lead is for FEM 2.5 min. and for SPH 18.6 min) for this simple problem.

The comparision of results for different materials is the main point of simulations. It is obvious, than the results for softer materials report better conformity. The best conformity of results is visible for the simulation with lead material (see Fig. 4). The SPH behavior is connected with little different wave propagation in this kind of solved problem. The resultant difference is visible for more brittle materials where problems with failure criterions can occur.

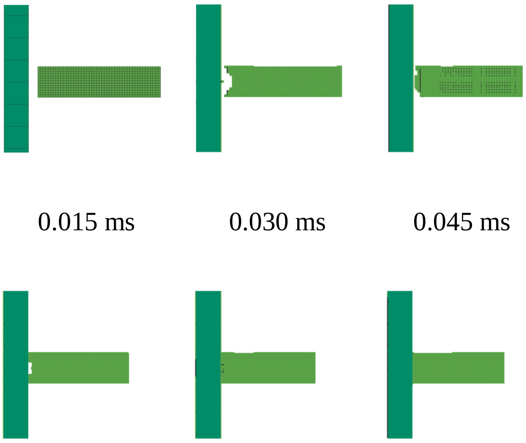
The FE simulations for brittle materials are connected with different kind of problems. The damage occurs during very small strain. The damaged elements lose their mechanical properties. This causes the stability problems of simulations with negative volumes and mesh collapse. In this case the anti-collapse contact could give only a partial solution. In some terminal ballistic problems is the element elimination acceptable. It is clear than in the actually solved FE task will be problem with mass losses which could reach 25% of initial mass (Fig. 5).

The FE method gives the beast results for the hard abrasion resistant steel Hardox. During the assumed velocity is the deformation of impacting part under limit for elements elimination. Therefore the results are not affected by the mass losses. The plastic deformation of impacted sheet (made from steel S355) could be shown as very preliminary result. This result suggests smaller possibility of sheet rapture by small piece (see Fig. 6). This approach will be applicable on real models.



a b

Fig. 4. The resultant deformation of lead part: *a* – FE method; *b* – SPH method.



0.015 ms 0.030 ms 0.045 ms

0.060 ms 0.075 ms 0.090 ms

Fig. 5. The FE simulation of impact connected with mass losses.

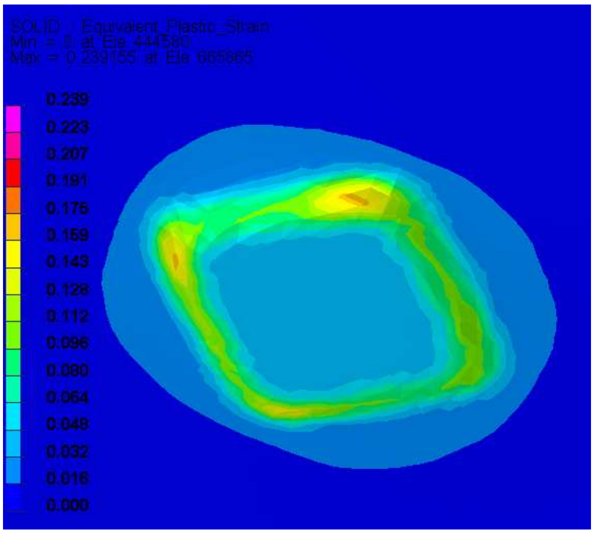


Fig. 6. The preliminary result of plastic strain for impacted sheet (made from steel S355).

6. CONCLUSIONS

The numerical simulations for assessment of passive safety of manufacturing systems are presented in this study. The solution of terminal ballistic problems is very specific for this field but can found application in future. Some results of FE and SPH methods are shown.

It is obvious than the SPH method takes more computation time (in solved problem approximately six times more). The good conformity of FE and SPH results is observed for lead material. As expected the SPH method has no problem with mesh collapse in contrast with FEM. Unfortunately, some problems occurs for SPH method application on the brittle material (see paragraph 4.3). It is shown, that usage of FEM could be problematic because of mesh collapse. In future will be possible to implement new knowledge from usage of SPH method for brittle materials.

The applicability of FE method would be seen from last part of this paper. The impact of two steel materials is there described. There is also shown some preliminary result of part made from Hardox steel.

ACKNOWLEDGMENTS: The present contribution was prepared under project POSTDOC supported by University of West Bohemia in Pilsen (Czech Republic).

REFERENCES

[1] J.M. Stellman, *Encyclopaedia of Occupational Health and Safet*, Geneva International Labor Office, 1998.

[2] G.R. Liu, M. Liu, *Smoothed particle hydrodynamics: a meshfree particle method*, Singapore, 2003.

[3] T. Belytschko, J. L. Lin, C. S. Tsay, *Explicit algorithms for the nonlinear dynamics of shells*, Computer Methods in Applied Mechanics and Engineering, July 1983.

[4] E. Mestreau, R. Lohner, *Airbag Simulation Using Fluid/Structure Coupling*, Aerospace Sciences Meeting & Exhibit, January 1996.

[5] D. J. Steinberg, *Equation of State and Strength Properties of Selected Materials*, Lawrence Livermore National Laboratory, 1991.

[6] G. R. Johnson, W. H. Cook, *A Constitutive Model and Data for Metals Subjected to Large Strains High Strain Rates and High Temperatures*, International Symposium on Ballistics, 1983.

[7] R. V. Bardale, P. G. Dixit, *Accidental sharp force injury – an unusual presentation with abrasive disc*, J Punjab Acad Forensic Med Toxicol, 2012.

[8] F. TIKAL, S.ŠPIRK, J. ŠEDINA, *Backstop and bullet trap design*, Industrial Engineering, 2015.

[9] B. Brody, Y. Létourneau, A. Poirier, *An indirect cost theory of work accident prevention*, Journal of Occupational Accidents, November 1990.

[10] A. Söderqvist, T. Rundmo, M. Aaltonen, *Costs of occupational accidents in the Nordic furniture industry (Sweden, Norway, FInland)*, Journal of Occupational Accidents, June 1990.

[11] T. Borvik, S. Deya, A. H. Clausen, *Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles*, International Journal of Impact Engineering, 2009.

[12] J. J. Monaghan: *Smoothed particle hydrodynamic*s, Annual review of astronomy and astrophysics, 1992.

[13] J. J. Monaghan: *Smoothed particle hydrodynamics*, Institute of Physics Publishing, 2005.

[14] ESI et al., *Impact and high-velocity impact*, available at: `http://virtualperformance.esi-group.com/applications-impact-and-high-velocity-impact-analysis` (`virtualperformance.esi`), accessed: 29-04-2015.

[15] M. Churilova, *Technology of EHIS (stamping) applied to production of automotive parts*, available at: `https://billionbooksbaby.org/pdf-stamping-through-mathematics.html` (`billionbooksbaby.org`), accessed 2016-04-15.

[16] S. Minato-ku., *Industrial Accidents and Occupational Diseases*, available at: `https://www.jniosh.go.jp/icpro/jicosh old/english/statistics/1998/13.html` (`www.jniosh.go.jp`), accessed: 2016-05-24.

[17] F.V. Hook, *SmokStak Shop Equipment Tools and Techniques*, available at: `http://www.smokstak.com/forum/showthread.php?t=6900` (`http://www.smokstak.com`), accessed: 2016-05-25.