A FE Billet Model and A Spring-Mass-Damper Model for The Simulation of Dynamic Forging Process: Application to A Screw Press

Jean-François Mull[1,a], Camille Durand[1,b], Cyrille Baudouin[1,c], Régis Bigot[1,d]

[1]*Arts et Metiers Institute of Technology, Université de Lorraine, LCFC, HESAM Université, F-57070 Metz, France*

[a]*jeanfrancois.mull@ensam.eu*, [b]*camille.durand@ensam.eu*, [c]*cyrille.baudouin@ensam.eu,* [d]*regis.bigot@ensam.eu*

Abstract

In forging processes, the determination of blow efficiency is very important, as it quantifies the part of the stroke energy actually transmitted to the billet. Thus, forging processes should be deeply analyzed in order to better understand the stroke energy conversion, accurately estimate blows efficiency and thus better predict process parameters. In this paper, a spring-mass-damper vibration model is proposed to describe forming operations of a screw press. Parameters specially adapted to the machine-tools system are identified thanks to a stroke without billet. Thereafter, the experimental upsetting of a copper cylinder is realized, and two independent numerical simulations are performed. First, the billet upsetting is simulated by FE simulation with no consideration of the elastic and damping effect due to the machine-tools behavior in order to determine a relation between the load and the billet height. Then, forging load from the FE simulation is used to perform another simulation of the forging process with the spring-mass-damping model. Results show that the model is relevant to simulate load and ram displacement. Moreover, simulation can predict the distribution of the energy during the simulation and the blow efficiency can be calculated. This new way to obtain blow efficiency might improve productivity in process development and provide a better understanding of energy driven machine.

Keywords

Dynamic; Machine behavior; Process modelling; Numerical simulation; FE simulation

1. Introduction

For energy piloted forging machines, the prediction of the energy actually transmitted to the billet for each blow is important in the conception of a forging sequence. Because it allows to determine the number of necessary blows and thus optimize the sequence. Therefore, a deep analyze is required to determine the distribution of the energy during the forging process and calculate the blows efficiency. For that, it is needed to consider billet and machine behavior. Different approaches were proposed to model energy driven machines. For hammers, studies focused on the impact of the machine foundation [1] or the machine structure [2], [3]. But in every cases, dynamic models proposed were an association of springs, masses and dampers with a different degree of freedom. In order to perform the simulation of the whole forging process, it is needed to couple the billet model and the machine model. For a hammer, Vajpayee et al. [4] realized simulations of forging process by considering a press model constituted of one spring and two masses. Billet behavior was modelled by Siebel law allowing the calculation of the forging load during the simulation. The influence of process parameters as impact velocity and model parameters on the process efficiency and clash load was studied. This method is not time consuming, but it does not allow to use FE simulation for complex geometries and obtain accurate predictions of billet behavior. Three different ways to couple FE billet model and press model were defined for forging process: offline-coupling, model integration and co-simulation [5]. Offline coupling simulates the machine and billet behavior in separate environments, the results of one is used for the calculation of the other. Model integration simulates the machine and billet behavior in the same environment allowing direct interactions. But simple machine model is required to keep reasonable calculation time. Furthermore, the co-simulation is a mix of the previous methods, where the machine and billet behavior are simulated in different environments but linked with a third software which manages a synchronized cycle. Kroiß [6] developed an integrated model considering the interactions between billet, tools and machine for a cold forging application. Optimization were realized on the die dimensions and punch position to obtain high workpiece accuracy. A coupled multibody-finite element simulation (MBS-FEM) for sheet metal forming application was developed [7]. From a 3D CAD of the press structure, the MBS model of a mechanical press was established after several assumptions on press part geometries. A mass was attributed to each element of the press and connections between each of them was defined. Then, the machine model was coupled with the FE simulation of the sheet upsetting to obtain a co-simulation of the whole forging process.

In this study, a spring-mass-damper vibration model is proposed to describe the forming operation of a screw press LASCO SPR400. Model parameters are identified with experimental measurement of load and impact velocity during a stroke without billet allowing to obtain parameters adapted to the machine-tools system. Then, the cold upsetting of a copper specimen is experimentally performed to validate the prediction of the model. Furthermore, two simulations are performed independently. First, a FE simulation of the copper upsetting is realized with no consideration of the elastic and damping behavior of the machine and tools. This simulation provides a relation between billet height and forging load. Then, a second simulation with the spring-mass-damper model using the relation between load and billet height from FE simulation as an input is performed. Results from the second simulation are compared to the experimental measurement concerning load and ram displacement and the simulated energy distribution during the forging process is studied.

2. Method

2.1. Definition of the model and identification of associated parameters

2.2. Experimental protocol

The screw press of the study is the LASCO SPR400 from the Vulcain platform in Metz, France. The press has a portal frame structure and is equipped with a direct electric drive motor providing the forging energy. A load sensor constituted of strain gauges is fixed on the lower toolholder of the press. The lower tool is directly screwed on the load sensor and the upper tool is fixed to the upper toolholder. In order to study the press behavior, a stroke without billet is performed experimentally, in this case, the shock is generated by the collision between the upper and the lower tools. One stroke settled to reach 9% of the maximum press stroke energy is performed. Load signal from the sensor and ram displacement are recorded during the blow. The ram displacement is obtained with a magnetic coding system integrated to the machine.

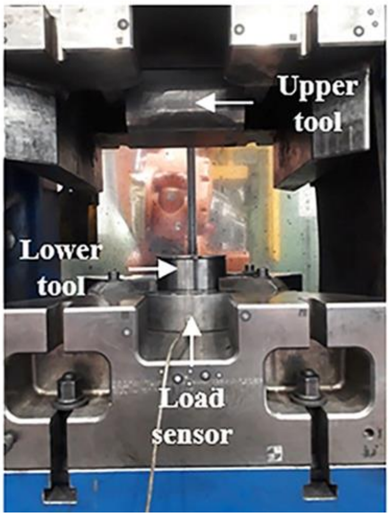

Fig.1. View of the experimental assembly in upper dead point position

The ram velocity when the upper tool impacts the lower tool is deduced from the ram displacement. The numerical derivative of the ram displacement provides a large error for the evaluation of the ram velocity because of the short time period of the measurement (0.1 ms). One way to reduce this error is to fit the displacement curve with a differentiable function and derive it analytically to obtain velocity [8]. The 20 ms before the impact between the upper tool and the billet are considered. The displacement curve is fitted by a quadratic function with MATLAB® and the function *polyfit*. The derivative of the quadratic function is calculated and is evaluated at the moment of the contact between the tool and the billet. It provides an impact velocity equal to 0.20 m/s.

2.3. Model of the stroke without billet

A two degrees of freedom spring-mass-damping vibration model is proposed to describe the press behavior during a stroke without billet (Fig.2). This model is constituted of two masses, two dampers and three springs. The two masses represent the part in motion in the system (tools, toolholders, ram, screw, flywheel). The spring k_{Moving} and the damper c_{Moving} link the two masses and model the elastic deformations and damping effects between the parts in motions in the system. The spring k_{Fixed} and the damper c_{Fixed} model the elastic deformations and the damping effects of the frame. During the experiment (cf. section 2.2), a load sensor is placed on the table of the press to be impacted by the upper tool. This sensor has an influence on the system behavior and needs to be considered. Hence, the spring k_{Sensor} is introduced in the model. This spring is linked to the mass 1 and the fixed part.

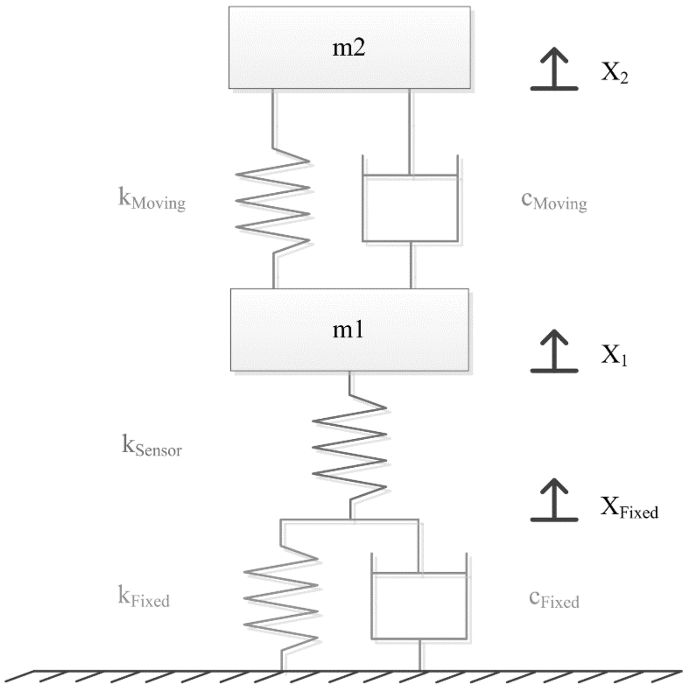

Fig.2. Model of the screw press and load sensor system for a stroke without billet

The application of the fundamental principle of the dynamics to the mass 1 and the mass 2 provides the dynamic equations of the system as presented in equations (1) and (2). The spring k_{Sensor} and the Kelvin-Voigt system constituted of the spring k_{Fixed} and the damper c_{Fixed} are in series. Thus, the load applied to the spring k_{Sensor} and the Kelvin-Voigt system is the same. This equality is written in equation (3).

$$m_2\ddot{X}_2 = -k_{Moving}(X_2 - X_1) - c_{Moving}(\dot{X}_2 - \dot{X}_1) \quad \textbf{(1)}$$

$$m_1\ddot{X}_1 = k_{Moving}(X_2 - X_1) + c_{Moving}(\dot{X}_2 - \dot{X}_1) - k_{Sensor}(X_1 - X_{Fixed}) \quad \textbf{(2)}$$

$$-k_{Sensor}(X_1 - X_{Fixed}) = -k_{Fixed}X_{Fixed} - c_{Fixed}X_{Fixed} \quad \textbf{(3)}$$

With X_1 the displacement of the mass 1, X_2 the displacement of the mass 2 and X_{Fixed} the displacement of the upper point of the spring k_{Fixed} according to their position at $t=0$. The stiffness k_{Sensor} is obtained from the sensor manufacturer documentation and is equal to 6.67 GN/m. The initial velocity of the masses 1 and 2 is fixed to 0.20 m/s as in experimental conditions. The model is implemented in MATLAB SIMULINK and the numerical solution of the equations of the model is obtained with the fixed-step solver ode8 (Dormand-Prince method).

2.4. Parameters identification

The identification of the model parameters is realized with the MATLAB module “Parameter Estimation”. The load signal simulated at the spring k_{Sensor} is fitted to the load signal measured with the sensor during experiment. The program starts to solve the model equations to obtain a numerical solution and the squared error between experimental signal and numerical solution is calculated. This cost function is minimized according to the Trust-Region-reflective algorithm and provides model parameters presented in Tab.1.

Tab.1. Model parameters

m_1	2471 kg
m_2	117 150 kg
c_{Moving}	1.51x10^5 N.s/m
c_{Fixed}	0 N.s/m
k_{Moving}	2.26x10^9 N/m
k_{Fixed}	4.86x10^9 N/m

The experimental load signal and the simulated load to the spring k_{Sensor} with parameters from the Tab.1 are presented in Fig.3

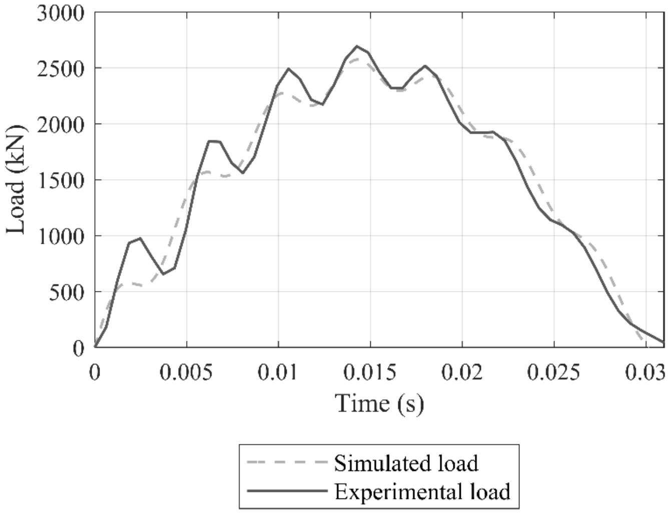

Fig.3. Experimental and fitted load signals

2.5. Validation of the predictive capacity of the model for copper cylinder upsetting

2.5.1. Experimental protocol

The experimental assembly is the same as presented in section 2.2 but in this case the cold upsetting of a copper billet is performed. The specimen is a cylinder of 29.9 mm diameter and 59.7 mm length placed on the lower tool. No lubricant is used during experiment. Concerning process settings, the velocity of the ram is regulated before the impact to provide 60% of the maximum press energy. The load from the sensor and the ram displacement are recorded during the stroke. The method presented in section 2.2 is used to estimate the impact velocity equal to 0.51 m/s. Final billet height is measured and is equal to 19.8 mm.

2.5.2. FE simulation for the determination of the forging load as a function of the billet height

The upsetting of a copper cylinder of 29.9 mm diameter and 59.7 mm high is simulated with the FE software Forge® NxT 2.1. The material behavior is described by a constitutive law of Hansel-Spittel whose parameters are selected from the database of the software. Friction behavior is modelled by Coulomb limited Tresca model. The friction coefficients are defined equal to $\mu/\overline{m}$ = 0.15/0.26. Thermal exchanges with air and dies are considered, the associated heat transfer coefficients are respectively equal to 10 W.m^{-2}.K^{-1} and 10 kW.m^{-2}.K^{-1}. A 2 mm size tetrahedra element is chosen for the mesh. Elastic and damping effects due to the machine-tools system are not considered in this simulation. Results from FE simulation allow to obtain the forging load as a function of the billet height for the interval from 16.3 mm to 59.7 mm. In order to use the simulated forging load with the spring-mass-damping model, it is required to express the forging load as a continuous function of the billet height. In this purpose, the load from the FE simulation is fitted by a polynomial of degree 10 noted *P* (Fig.4).

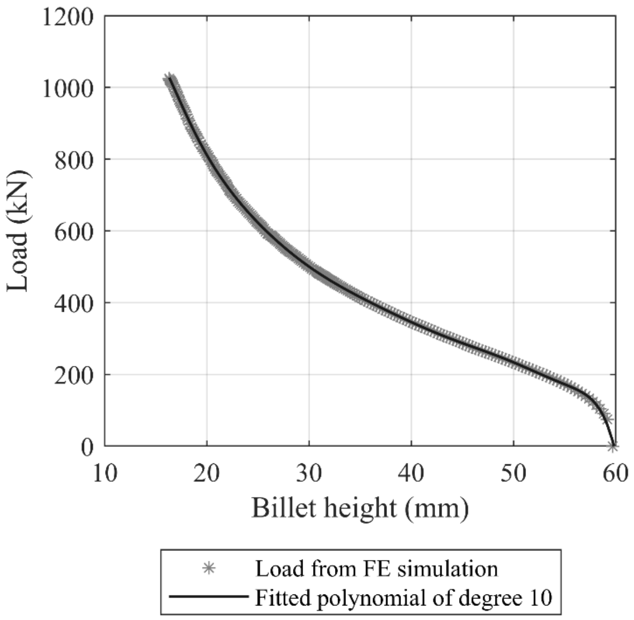

Fig.4. Load as a function of the billet height from FE simulation and fitted polynomial of degree 10

2.5.3. Billet-Interface-Machine (BIM) model

For the simulation of billet upsetting the spring-mass-damping model is completed as presented in Fig.5.

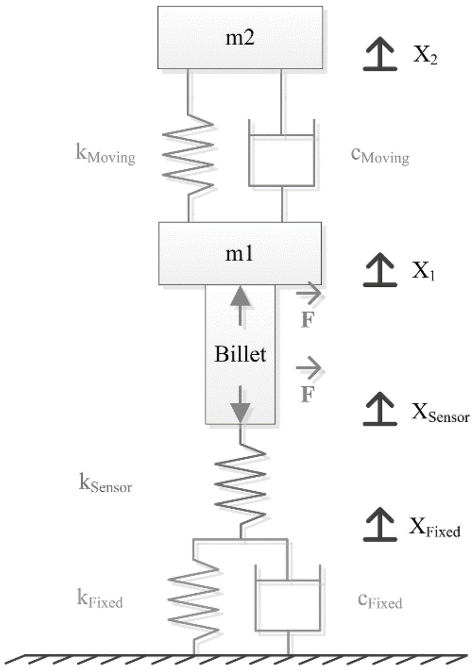

Fig.5. Billet-Interface-Machine (BIM) model

The application of the fundamental principle of the dynamics to the mass 1 and the mass 2 provides the dynamic equations of the press system in equations (4) and (5). The spring k_{Sensor} is directly linked to the billet, thus the forging load from the billet is directly applied on the spring, the relation is written in equation (6). Equation (7) is obtained as explained in section 2.3.

$$m_2\ddot{X}_2 + k_{Moving}(X_2 - X_1) + c_{Moving}(\dot{X}_2 - \dot{X}_1) = 0 \quad (4)$$

$$m_1\ddot{X}_1 - k_{Moving}(X_2 - X_1) - c_{Moving}(\dot{X}_2 - \dot{X}_1) = -F \quad (5)$$

$$-k_{Sensor}(X_{Sensor} - X_{Fixed}) = F \quad (6)$$

$$-k_{Sensor}(X_{Sensor} - X_{Fixed}) = -k_{Fixed}X_{Fixed} - c_{Fixed}X_{Fixed} \quad (7)$$

With X_1 the displacement of the mass 1, X_2 the displacement of the mass 2, X_{Sensor} the displacement of the upper point of the spring k_{Sensor} and X_{Fixed} the displacement of the upper point of the spring k_{Fixed} according to their position at $t=0$. As it can be seen, the reaction force from the billet F is required to performed simulations of the billet upsetting. F is calculated for each increment of the simulation with the polynomial P identified in section 2.5.2. At each moment, the billet height can be express by $X_1 - X_{Sensor} + h_0$ with h_0 the initial billet height. Thus, the load can be calculated such as $F = P\ (X_1 - X_{Sensor} + h_0)$.

The model is called "Billet-Interface-Machine" (BIM) model because it allows the coupling of these three aspects in simulation. The billet behavior and the impact of friction at the interface between material and tools are considered thanks to the expression of the forging load from the FE-simulation. Furthermore, the machine-tools behavior is described by the spring-mass-damping model which considers damping effects and elastic strains in the system. The BIM model is implemented on MATLAB® SIMULINK® with the parameters from the Tab.1, simulation parameters are the same as presented in section 2.3. The numerical simulation is realized by fixing the initial velocity of both masses to -0.51 m/s as in the experimental conditions.

3. Results and discussion

The load measured by the sensor and the simulated load for k_{Sensor} are presented in Fig.6. During the forging process, the simulation underestimates the load compared to experiment before 0.06 s. Then, a slight difference can be noticed between experimental and simulated load until reaching the maximum blow force with a maximum relative deviation of 2.5%. The maximum blow force predicted by simulation is 1.5% lower than the measured value. The forging time, defined as the time to reach the maximum blow force, is equal to 124.7 ms in experiment and 125.8 ms in simulation giving a relative deviation of 0.01%. After reaching the maximum blow force, bigger differences are observed between simulation and experimental results. The simulated spring back time equal to 15.3 ms is smaller than the experimental spring back time equal to 27.8 ms. This means a relative deviation equal to 45%. The Fig.6 also shows the ram displacement obtained by experimental measurement and by simulation. 0 corresponds to the initial contact between the tool and the billet. The ram displacement is accurately predicted by the simulation during the whole forging process. The minimum experimental and simulated displacements show a relative deviation of 0.3%. From the moment of the contact between the tool and the billet to 25 ms, damped vibrations can be observed on the experimental ram displacement. The amplitude of the vibration is very low compared to the global signal. No vibrations can be observed on the simulated signal. In simulation, the final billet height is estimated to 19.5 mm meaning a relative deviation of 1.5% compared to the experimental result. It can be noted that the billet height simulated with the BIM model is always in the interval of identification of the polynomial P.

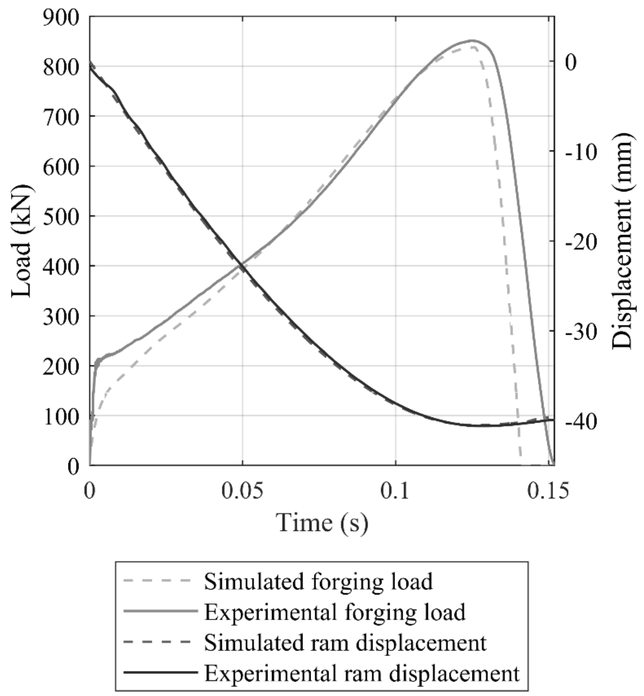

Fig.6. Forging load and ram displacement measured with the load sensor and press displacement sensor, load in k_{Sensor} and ram displacement simulated for the upsetting of copper cylinder upsetting

The distribution of the energy of the system for each blow is presented in the Fig.7. The model considers 4 types of energy: the kinetic energy of the masses, the elastic energy stored by the springs, the damped energy dissipated by the dampers and the billet energy considering the plastic energy and the energy dissipated in the friction between tools and material. At the beginning of the stroke, all the energy is coming from the motion of the two masses. Thus, the energy is purely kinetic and can be calculated as $\frac{1}{2}.(m_1+m_2).v_0^2$.

It can be seen on the Fig.7 that until reaching the maximum blow force the kinetic energy decreases during the forging process whereas the billet energy and the elastic energy increase. Then, the billet energy remains constant while the kinetic energy increases and the elastic energy decreases. Concerning damped energy, it never exceeds 0.02% of the total energy. 98% of the initial kinetic energy is converted into billet energy at the end of the forging process. This value represents the efficiency of the stroke. During the blow, 2% of the available energy is turned into elastic energy. After reaching the maximum blow force, the elastic energy is turned again into kinetic energy in the acceleration of the masses 1 and 2 in the opposite direction of the stroke.

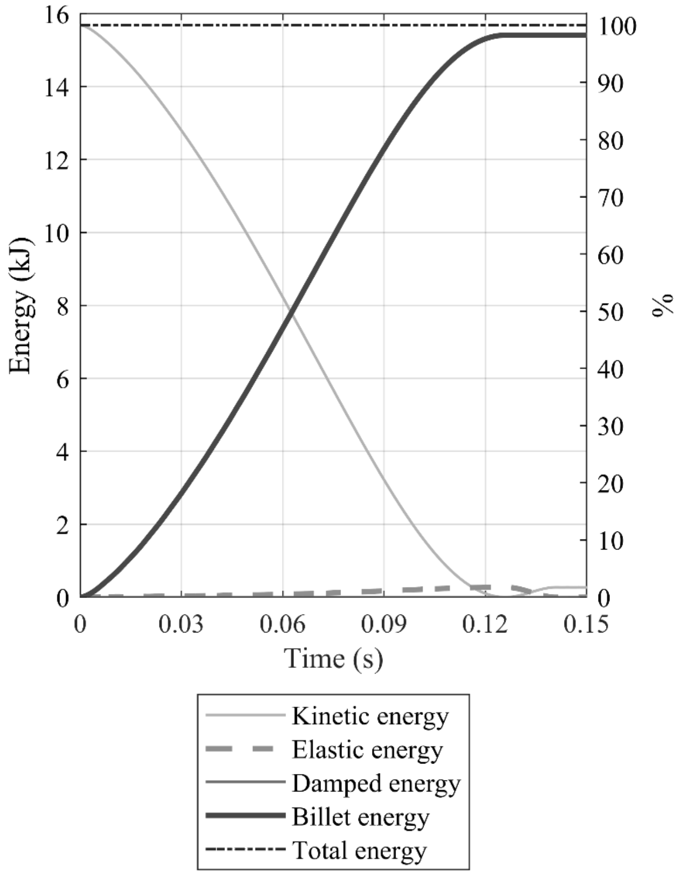

Fig.7. Distribution of the energy for one simulated blow on a copper specimen

Results have shown that the forging load and the ram displacement can be predicted by the simulation. The determination of the forging load with FE simulation and a fitted polynomial is suitable to simulate the whole forging process. The FE simulation allows to obtain the forging load in ideal conditions, i.e. with no consideration of the press behavior. Then, the 2nd numerical simulation allows to determine the part of the stroke energy transmitted to the machine-tools system and process variables associated to the operation.

In our case, the machine-tools system has a small impact on the forging process. Indeed, only 2% of the initial stroke energy is turned into elastic energy. The experimental study case corresponds to a soft blow, where most of the available energy is transmitted to the workpiece. For soft blows, small loads and large billet deformations are noticed [9]. Thus, the model provides a good representation of the energy distribution during the forging process. As the energy transmitted to the billet can be predicted by the simulation, it is possible to assess the efficiency of the blow.

It was noticed that the damped energy remains very low compared to the stroke energy. For this given forging operation, the damped energy can be neglected. As it can be seen in .

Tab.1, the damping effect is only caused by the relative displacement between the masses because k_{Fixed} is equal to 0. In the case of a soft blow, vibration modes are not activated enough and the relative displacement between the masses is too low to dissipate a significant part of the stroke energy in the damper. For hard blows [9], the damped energy might be more important and could become significant.

In this study, the forging operation is the cold upsetting of a copper cylinder. It simplifies the experimental protocol by allowing to neglect thermal effects, thus the measurement of the billet temperature and the transfer times are not required. Simulations of more complex workpiece for hot materials could be intended. However, it is needed to keep an axisymmetric geometry for the workpiece, because the press behavior is only considered for the vertical axis of the press in the model. Thus, this methodology brings a new way to cross FE model and spring-mass-damper press model without the need to couple two softwares. The consideration of the energy dissipated in the dynamic effects in the machine implies an improvement of the accuracy of the numerical simulations and a better prediction of the process variables.

4. Conclusions

This study presents an experimental methodology to model forming operations in the case of a screw press. Model parameters were identified with the measurement of the ram impact velocity and the load during a stroke without billet. Then, independent simulations crossing a FE model and the spring-mass-damper model for copper cylinder upsetting were performed. FE simulation allowed to determine a relation between load and billet height used as an input of the simulation performed with the spring-mass-damper model. Experimental copper upsetting was led with measurement of the load and ram displacement. Simulation results show a good agreement with experimental measurements. The following conclusions were drawn:

1. Measurements of the ram impact velocity and the forging load during a stroke without billet is enough to determine specially adapted model parameters for the screw press.
2. The use of FE simulation to predict the forging load required for the simulation of the forging process with a spring-mass-damper press model is suitable to predict the process variables. It provides a complete representation of the system without developing a coupling between two software.
3. The model of the whole forging process can predict the distribution of the energy in the system during the forging process. Thus, it is possible to determine the part of the stroke energy transmitted to the billet and calculate the blow efficiency for a given forging operation.

Acknowledgement

The authors would like to express their sincere appreciation to Sebastien Burgun and Alexandre Fendler for their technical support in the realization of the experimental protocols. Moreover, we wish to thank MANOIR INDUSTRIES for their financial support in this research project.

References

[1] M. Novak et L. El Hifnawy, « Vibration of hammer foundations », *Int. J. Soil Dyn. Earthq. Eng.*, vol. 2, nº 1, p. 43-53, janv. 1983, doi: 10.1016/0261-7277(83)90026-8.

[2] V. Gregorian, M. M. Sadek, et S. A. Tobias, « Noise generated by a laboratory drop hammer and its interrelation with the structural dynamics and process parameters », *Int. J. Mach. Tool Des. Res.*, vol. 16, nº 4, p. 301-318, janv. 1976, doi: 10.1016/0020-7357(76)90040-8.

[3] S. Vajpayee, M. M. Sadek, et S. A. Tobias, « Prediction of linear noise-load relationship for impact forming machines », *Int. J. Mach. Tool Des. Res.*, vol. 22, nº 1, p. 1-6, janv. 1982, doi: 10.1016/0020-7357(82)90015-4.

[4] S. Vajpayee, M. M. Sadek, et S. A. Tobias, « The efficiency and clash load of impact forming machines to the second order of approximation », *Int. J. Mach. Tool Des. Res.*, vol. 19, nº 4, p. 237-252, janv. 1979, doi: 10.1016/0020-7357(79)90013-1.

[5] C. Brecher, M. Esser, et S. Witt, « Interaction of manufacturing process and machine tool, chap 5 », *CIRP Ann.*, vol. 58, nº 2, p. 588-607, 2009, doi: 10.1016/j.cirp.2009.09.005.

[6] T. Kroiß, U. Engel, et M. Merklein, « Comprehensive approach for process modeling and optimization in cold forging considering interactions between process, tool and press », *J. Mater. Process. Technol.*, vol. 213, nº 7, p. 1118-1127, juill. 2013, doi: 10.1016/j.jmatprotec.2012.09.004.

[7] K. Swidergal *et al.*, « Experimental and numerical investigation of blankholder's vibration in a forming tool: a coupled MBS-FEM approach », *Prod. Eng.*, vol. 9, nº 5-6, p. 623-634, déc. 2015, doi: 10.1007/s11740-015-0640-9.

[8] R. Chen *et al.*, « A Stereo-Vision System for Measuring the Ram Speed of Steam Hammers in an Environment with a Large Field of View and Strong Vibrations », *Sensors*, vol. 19, nº 5, p. 996, févr. 2019, doi: 10.3390/s19050996.

[9] T. Altan, G. Ngaile, et G. Shen, *Cold and Hot Forging: Fundamentals and Applications*. ASM International, 2005.