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Contribution to characterization of metal forming machines: application to screw presses

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Abstract

Finite Element analyses are established in the metal forming industry, with the aim to fulfill three objectives: predict tooling lifetime, predict the energy required to obtain the desired part and predict the thermomechanical path leading to the optimal microstructure. Currently, simulations allow good predictions regarding forging operations with currently used material, like steel, but concerning high performing materials, significant difference are observed between numerical and experimental results. This study aims at understanding this disparity between numerical and experimental results, for screw presses. Different methods have been employed to determine the press stiffness, using fast cameras and 3D tracking points systems.

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Keywords: Screw press; Stiffness; Characterization; Simulation

1. Introduction

There is extensive literature focusing on the material deformation during forging process, but only few studies are interested in the forging machines behavior. However, the mechanical behavior of forging machines influences the forging process and therefore the forged products.

Studies have been carried out to characterize the flexibility matrix of sheet metal forming presses to describe the elasticity of presses under vertical and lateral loads [1, 2]. The flexibility matrix defined with 6 degrees of freedom represents the linear press load-deflection relationships, together with an equivalent clearance vector to take into account the initial non linearity due to press geometric errors such as guidance clearances. Such matrices were determined for hydraulic, eccentric and screw presses [3, 4]. Another study proposed a measuring method to determine that flexibility matrix for hydraulic and eccentric presses [5]. Some other papers also focus on flexibility matrix but on the case of massive forging process. For example, [6] focuses on the static and dynamic behavior of eccentric presses and [7, 8] combined the flexibility matrix definition with Finite Elements simulations respectively in the case of a screw press forging blades and of multistage cold forging process. The dynamic vibrations were also measured in the case of eccentric press and [9] described a method to reduce the vibrations of the ram, while [10] analyzes the dynamic characteristic of high speed press bed comparing measurements to Finite Elements results. More precisely concerning the behavior of screw presses, the paper [11] analyses deformations arising in these presses and gives a formula for their theoretical stiffness. The theoretical stiffness is then compared to the real-stiffness defined considering contact deformation, oil film deformation and foundation deformation. The observation of an inadequate consideration of interactions between the forging process and the forging machine in the simulation was also made by [12] in the case of multistage forging with an eccentric press. Moreover, the authors set up a new interesting method to measure deflection and tilting behavior of presses during forging operations using a dynamic photogrammetry system.

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In our study the focus is set on a screw press, as this kind of press is frequently used in the industry and is an energy restricted machine. This paper is a first step towards the understanding of screw press mechanical and dynamical behavior. First of all, two kind of upsetting tests were performed on the screw press. The results obtained were compared to the ones obtained numerically with Finite Elements simulations. Those tests allow to better understand the reaction of the screw press and to highlight the difference between experimental and numerical results. Thus, a characterization of the press appears as necessary. Different methods were then employed to determine the screw press frame stiffness and the results obtained are discussed.

2. Description of screw press

The screw press of our study is the Lasco SPR 400 screw press from the Vulcain platform in Metz in France (Fig. 1a). The structure of the press is detailed in Fig. 1b. This screw press has a multi-piece frame made of cast-iron and constituted of the bedplate on which is fixed the inferior die holder and then the inferior die, four uprights including pre-stressed tie rod made of steel, and the cross-head. Under the bedplate are springs damping elements to ensure low vibration press operation. The moving part of the press is the ram made of high-grade cast steel, fully stress relieved, and which allows the fixation of the superior die holder and then the superior die. On each upright, there is a sliding guide made of steel and set at an angle of 45 degrees allowing the guidance of the ram thanks to its sliding guide made of bronze. The ram guiding system is set at an angle of 45 degrees so that it is able to maintain constant clearance in spite of heat expansion.

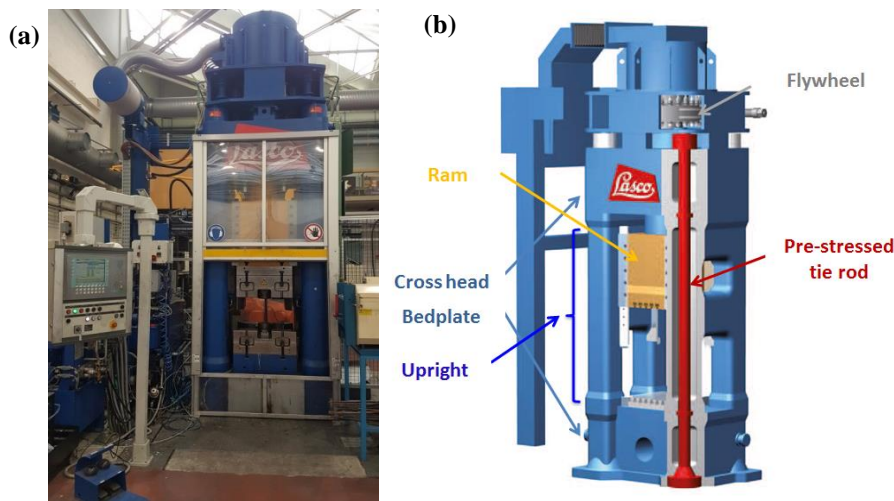


Fig. 1. (a) Screw press Lasco SPR 400; (b) the structure of the screw press [13].

The ram is connected to the screw and nut system which initiates the translation motion of the ram. In our case, the nut is mobile since it is fixed to the ram. It is the screw which is connected to the frame via a pivot linkage. The screw and nut system always leads the ram motion, but without any translation motion from the screw. Concerning the materials of the screw and nut system, the screw is made of chrome, nickel and molybdenum high-alloyed steel, and the nut is made of bronze.

The screw press has a direct electric drive and uses energy stored in the cast flywheel to provide the forging force. Indeed, a reversible electric motor is built directly on the screw and on the frame and is directly connected to the flywheel. The screw is threaded into the ram and does not move vertically. To reverse the direction of flywheel rotation, the electric motor is reversed after each down stroke and upstroke.

Since a screw press has no mechanical dead point, the machine never stops caused from overload, therefore the press ensure its protection thanks to a slipping clutch between the screw and the flywheel. The slipping clutch activates if an unintended die-to-die blow is triggered, preventing damage to the machine.

The press also has integrated sensors and allows the recording of the press force exerted in the forming process and the displacement of the ram during the forming process. The exerted force is measured and recorded by strain gauges, located on the cross-head of the press. A displacement measuring system with a magnetic coding allows recording the ram position in comparison with the bottom dead point of the system, for each increment.

3. A disparity between experimental and numerical results

3.1. Description of upsetting tests

Upsetting tests were performed under the screw press with grooved flat dies. Two materials were tested: a carbon steel C17 and a superalloy the Inconel 625 (NiCr22Mo9Nb). Testing parameters are summarized in the Table 1. In order to protect dies from damages, dies are not in contact when the maximal ram stroke is reached, but it's the tapping blocks which endure the shock. Actually, there is a distance of 7.8 mm between the superior and the inferior die.

Billets were heated in an oven powered by an electrical resistance and the billet temperature was controlled by thermocouples

K placed in a martyr billet. Tools were pre-heated and their temperatures were controlled by an infrared thermometer.

Table 1. Tests performed under screw press.

	Material	Diameter (mm)	Height (mm)	Dies	T° dies (°C)	T° heating (°C)	Heating time	% of energy
Test 1	Steel C17	27	88,3	grooved flat die	50	1150	1h08	100%
Test 2	Inconel 625	70	100	grooved flat die	250	1000	1h49	100%

Those two upsetting tests were then numerically simulated with the Finite Element Software Forge. For the simulations data setting, all the boundaries conditions were chosen to correspond to the real tests: a bilateral sticking contact was defined between dies and billet to represent grooved flat dies, convection between the billet and the air has a medium coefficient and thermal conduction between the billet and dies depends on the pressure applied on the billet. Concerning the material behavior, rheological laws of corresponding materials were chosen in the database of Forge.

3.2. Analysis of tests results

For the case of steel upsetting, the forming force versus the displacement of the ram is plotted Fig. 2. Here a weak material is being formed and the force increases progressively with the ram stroke. This is a characteristic curve for an inelastic collision: the billet struck by the ram deforms, and this deformation absorbs most of the force of the collision. So here, the energy developed by the press is significantly dissipated into the plastic deformation of the billet. In our case, it is also visible that the billet was deformed until reaching the tapping blocks. Indeed, at the end of the curve, the ram displacement goes beyond zero, which corresponds to the bottom dead point of the system and the force increases very significantly. When the tapping blocks are reached, a part of the energy developed by the press is transmitted to the press frame as elastic deformation. This generates the slight vibrations of the frame at the ram rising, just after the end of the strike. And at the moment of the strike on the tapping block, an elastic deformation of tools is induced by the shock.

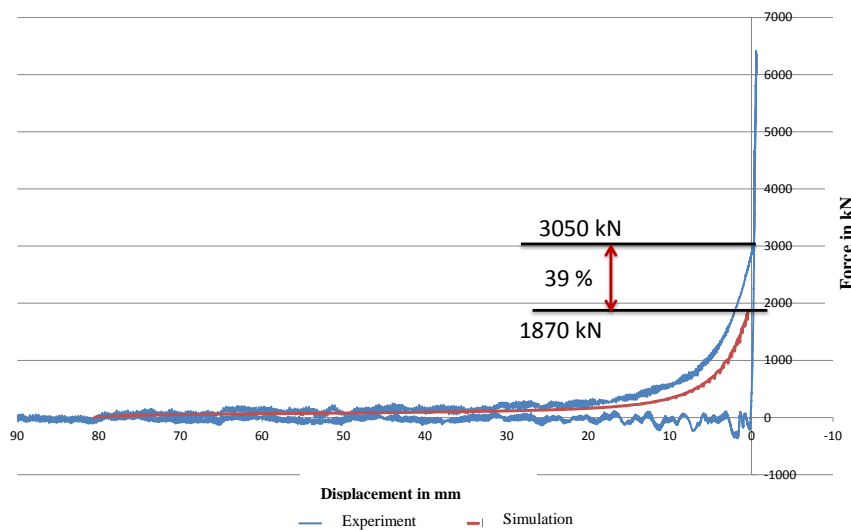


Fig. 2. Force versus displacement for upsetting of carbon steel C17.

Concerning the confrontation of experimental and numerical results, the two curves are following the same tendency, but there is a significant difference for the maximal force. Let's precise, that here the maximal force value corresponds to the force obtained at the end of the plastic deformation of the billet and not at the maximal force obtained at the end of the process as the tapping blocks are reached. The numerical simulation underestimates the necessary forging force of 39% compared with the experiments, which is not negligible. Thus, the simulation overestimates our press capacities.

This overestimation of the press capacity may be explained by the fact that in a first approach the simulation considered the press as purely stiff. Which significates that the press was modelled in a way that all the energy developed by the press is dissipated in useful energy for the plastic deformation of the billet. The elastic deformation of the press frame is thus, totally neglected, increasing the forging efficiency. This overestimation could also come from the definition of the material behavior.

For the upsetting of Inconel 625, the forming force versus the displacement of the ram, resulting from experiment and simulation are plotted Fig. 3. The Inconel is a high resistive material, and it clearly appears that the tendency of the curves significantly differs from the previous ones obtained by upsetting steel. First of all, at the same amount of energy, the displacement of the ram in the case of Inconel is lower than for the carbon steel: at similar temperature the Inconel yield stress is higher than the one of the carbon steel.

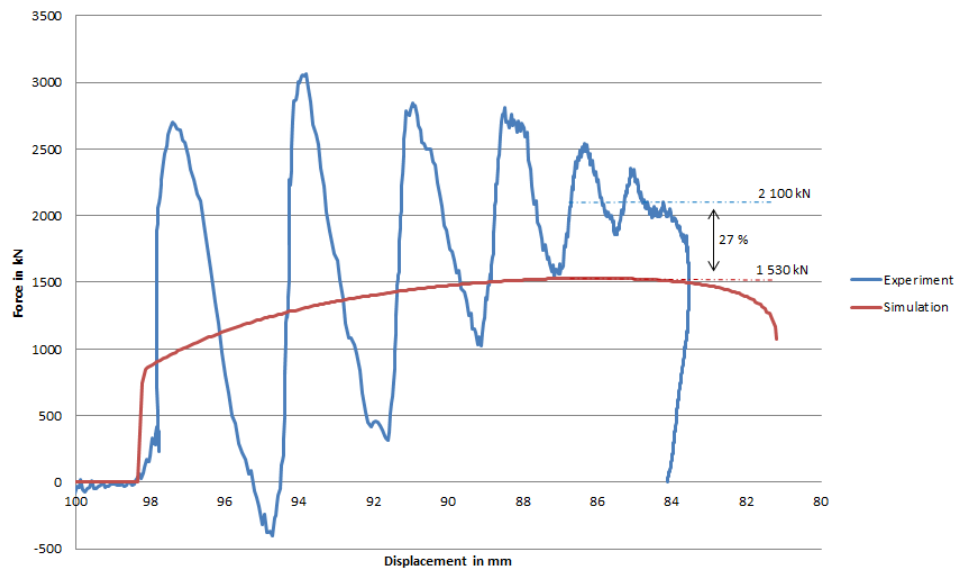


Fig. 3. Force versus displacement for upsetting of Inconel 625.

Moreover, there are important variations of forces as soon as the superior die comes in contact with the billet. These forces variations illustrate the vibration of the press frame. As the Inconel is a highly resistive material, when the superior die is in contact with the billet, the energy developed by the press is not only consumed by the billet as plastic deformation, but is also dissipated in the elastic deformation of the press frame. These forces variations are characteristics of an elastic collision. The force variation amplitude decreases progressively with the deformation of the billet, which significates that the billet absorbs energy and has damping effects.

Regarding the comparison of experimental and numerical results, in the case of elastic collision, numerical simulation does not succeed in representing the frame vibration through oscillating forces. And this is normal since the press was considered as perfectly stiff in the simulation. Thus, the elastic deformation of the press is not taken into account in the numerical model, and thus cannot properly simulate elastic collision.

By comparing the maximal force reached by simulation and the maximal mean value of experimental force, it appears that the simulated force is 27% lower than the real maximal mean value. So here also the simulation underestimates the necessary forging force and overestimate the press capacity. But here again this is due to the pure stiff modelling of the press.

All those differences observed between simulations and experiments should be qualified by the fact that experimentally the forces are measured at the press cross-head, and therefore far away from where the strike takes place. This may also explained the negatives forces values reached, if the sensor is located on a belly and not on a node of flexion. The exactitude of experimental values can be discussed, whereas the software Forge gives the force values on the superior die.

Those two upsetting tests and simulations associated show well that the hypothesis of a perfectly stiff press is not sufficient to model correctly the forming process and thus estimate correctly the forging forces necessary. A press stiffness value has therefore to be included into numerical models. That is why our press stiffness has to be characterized.

4. Press stiffness characterization

To determine the screw press stiffness, several methods have been used. First the press stiffness has been calculated by considering cases in which all the energy developed by the press is dissipated in the press frame as elastic energy. This is the method of the elastic potential energy. The press stiffness was also evaluated considering the press as a spring and deducing its behavior law thanks to the force versus displacement curves of bare strikes, without any billet. Finally the stiffness was determined experimentally by measuring the press elongation during a strike.

4.1. Elastic potential energy method

If the press is considered as a spring with a constant stiffness K , the following equation can be written:

$$F = K \Delta x \text{ ou } \Delta x = F/K. \quad (1)$$

With F the effort applied and Δx the elongation of the press frame.

In the case of a bare strike, without any billet, it can be assumed that all the energy developed by the press E_{total} is dissipated in elastic energy $E_{elastic}$. Thus the following equation is verified:

$$E_{total} = E_{elastic} = \frac{1}{2} K \Delta x^2. \quad (2)$$

And in this last equation, if Δx is replaced by F/K , another equation is obtained for the stiffness constant of the press frame K :

$$K = F^2 / 2E. \quad (3)$$

Thus, knowing for a given energy, the force developed by the press, the press frame constant stiffness K can be deduced. One must be careful with the condition of application of this formula: it can be only used for cases in which all the energy developed by the press would be dissipated in forming energy. Then, cases with high energy and in which the slipping clutch would play a role should not be taken into account with the formula.

In our case, several strikes were performed on the screw press with percentage of energy ranging from 1% to 8% of 31,5kJ the maximal energy of the press. The results are plotted Fig. 4. The stiffness value seemed to stay constant with the increasing percentage of energy, and the stiffness mean value calculated upon the 24 strikes is: $K_{F^2/2E\ mean} = 2,5 \cdot 10^9 \text{ N/m}$.

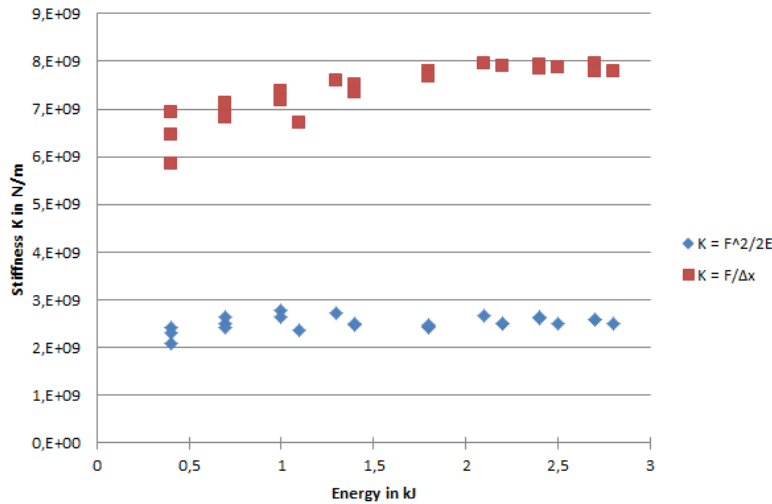


Fig. 4. Press stiffness K obtained with elastic potential energy method and press behavior's law method in function of energy.

4.2. Press behavior's law method

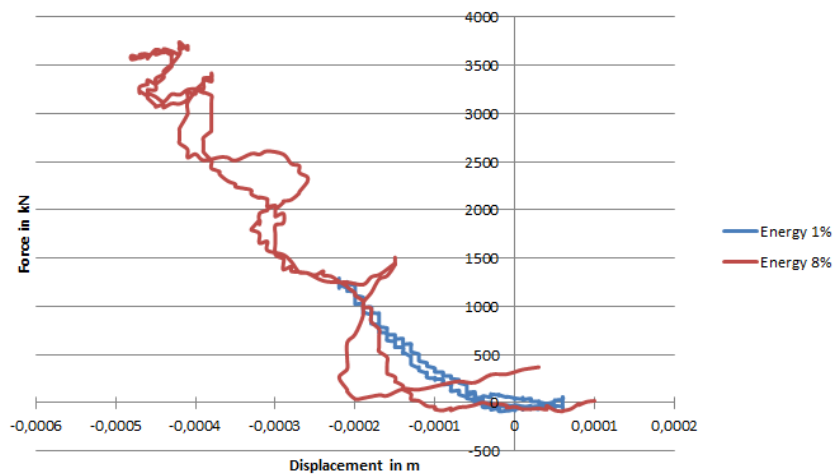


Fig. 5. Force versus displacement curves for bare strikes with 1% and 8% of maximal energy of press.

The 24 strikes with energy ranging from 1% to 8% of the press maximal energy were also used to plot the force versus displacement curves (Fig. 5). Then for each strike, the behavior's law of the press considered as a spring was deduced. Indeed, referring to equation (1) the stiffness K of the press corresponds to the slope of the curves when the tapping blocks are in contact with the ram. The results are plotted Fig. 4 and compared with the previous results of the stiffness obtained with elastic potential energy. The stiffness values obtained with the press behavior's law method are slightly increasing with the increase of energy. A stiffness mean value is calculated for this method: $K_{F/\Delta x\ mean} = 7,4 \cdot 10^9 \text{ N/m}$.

4.3. Method of measurement of upright elongation during an upsetting process

In order to determine the press frame stiffness experimentally, the elongation of the press frame should be measured during a forming operation. To do that, external acquisition systems are necessary:

- A fast camera (maximal acquisition frequency of 120 000 pictures/s), was placed facing the press, with a lighting projector allowing a continuous lightning of dies previously equipped with sights to follow their displacements during strikes.

- The Pontos, a 3D tracking point system based on the principle of triangulation (maximal acquisition frequency of 1300 pictures/s), was placed on the other side of the press, in a way to measure the elongation of the frame during forging operations. Reflecting stickers were placed on one of the press upright and the Pontos followed these sticker points during forging (Fig. 6).

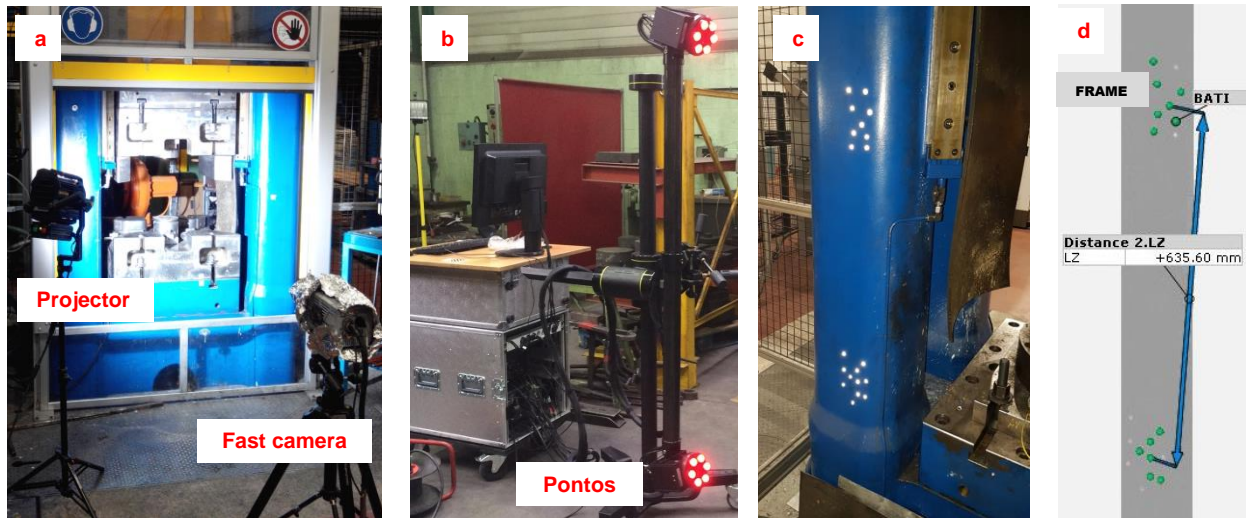


Fig. 6. (a) Set-up of fast camera and its continuous lighting projector; (b) set-up of Pontos; (c) stickers placed on one press upright; (d) display of Pontos software showing initial distance between selected stickers.

Besides, to be able to measure a frame elongation, experimental conditions have to be chosen so that one part of the energy developed by the press is dissipated in the press frame: either a bare strike without any billet, or an elastic collision, or an inelastic collision until reaching the tapping blocks. Whatever the case chosen, the forging time has to be long enough to allow the external acquisition systems to record enough data. For the elongation to be visible, the maximal forging force has to be maximized, since the elongation depends directly on the forging force (1). To define the optimal experimental conditions, the maximal forces obtained in different conditions have been compared:

- Maximal force obtained for a bare strike: 3744 kN.
- Maximal force obtained for an elastic collision on Inconel: 3059 kN.
- Maximal force obtained for an inelastic collision on C17 when reaching the tapping blocks: 6414 kN.

The force being significantly higher in the case of the inelastic collision until reaching the tapping blocks, those experimental conditions were chosen. Moreover, in order to maximize the forging time, billets had a high aspect ratio allowing recording even more data.

For those tests, upsetting operations of carbon steel C17 on grooved flat dies were performed as previously described (Table 2). To verify the repeatability, the same test was performed two times in the same conditions.

Table 2. Test parameters and results for two upsetting tests on steel C17.

	Material	Diameter (mm)	Height (mm)	Dies	T° dies (°C)	T° heating (°C)	Heating time	% of energy	Real energy (kJ)	Real force (kN)	Max elong. Pontos (mm)
Test A	Steel C17	27	88,3	grooved flat die	50	1150	1h08	100%	29	6414	0,109
Test B	Steel C17	27	87,95	grooved flat die	50	1150	1h10	100%	28,6	6369	0,109

Results were found to be repeatable, elongation and displacements curves are overlapping for both tests, thus for more clarity, in the following results analysis, only the test A will be studied in details. On Fig. 7 one can see that the sudden increase of the press frame elongation happens when the maximal displacement of the ram is recorded, which means when the tapping blocks are reached.

With the forces recorded by the press sensor and the upright elongation, it is possible to determine the press stiffness, with equation (1). Nevertheless, to determine the Δx , meaning the upright elongation, it is not possible to employ directly the data recorded by the Pontos. Indeed, the elongation recorded by the Pontos on one press upright, is an elongation measured on the distance between two stickers, in our case 635 mm. But it is the elongation of the total height of the upright that is required, meaning on 3685 mm. Thus, Fig. 8 is obtained by representing the stiffness K values in function of the time, for the period during which tapping blocks are reached and the force maximum, considering a linear press frame deformation. The press stiffness value varies, since the force and the elongation are varying too. A mean value of the stiffness is then calculated:

$$K = 11,6 \cdot 10^9 \text{ N/m.}$$

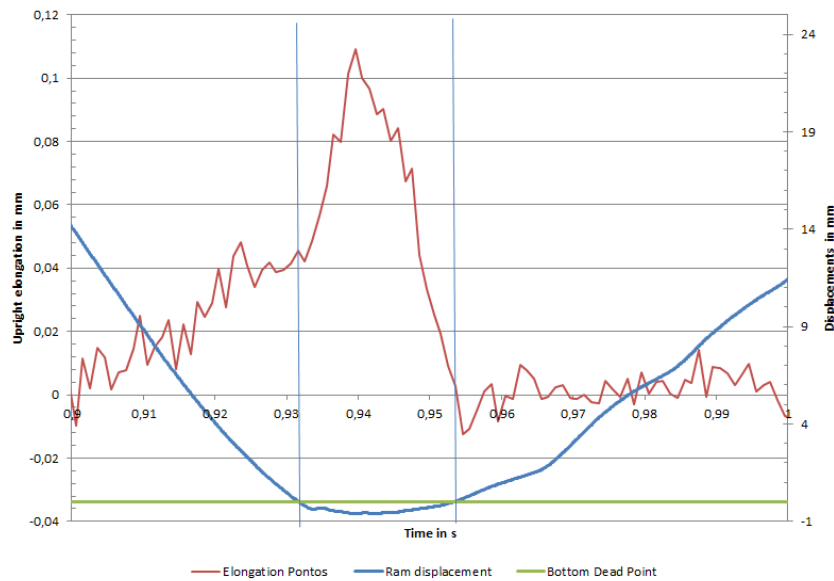


Fig. 7. Ram displacement and upright elongation for test A in function of time.

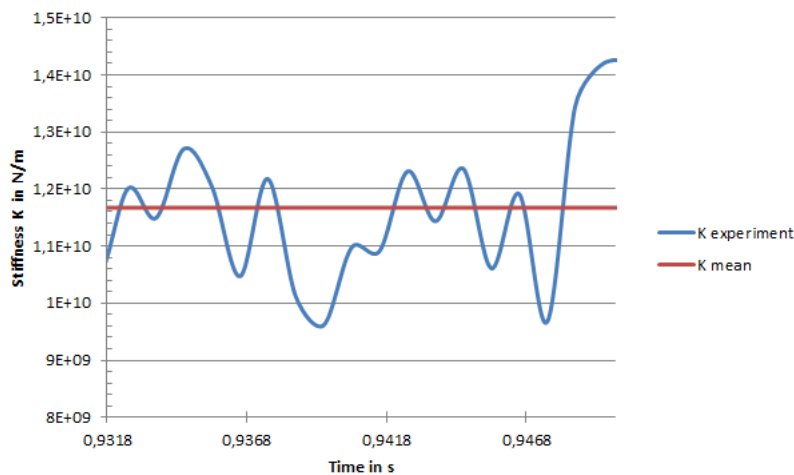


Fig. 8. Upright stiffness in function of time obtained by measuring upright elongation during upsetting.

5. Discussion

The three methods presented give three different values for the press stiffness (Table 3) but all values are in the same order of magnitude.

Table 3. Summary of different stiffness values obtained with different methods.

	Elastic potential energy method	Press behavior's law method	Measurement of upright elongation
Stiffness K in N/m	2,50E+09	7,40E+09	11,6E+09

First all these three values could be discussed as the three methods described to determine the press stiffness are using the data coming from the press integrated force sensor placed on the cross-head, and not closer to the striking zone. Then, these differences in stiffness values can partially be explained. The elastic potential energy method and the press behavior's law are giving a stiffness value not only of the press frame, but of the press and the die holders and dies. Indeed, the data used to deduce the press stiffness for those two methods are coming from strikes performed with the die holders and dies. To get rid of the die holders and dies own stiffness, the same methods could be used but without mounting the dies on the press. The Hooke's law can also be employed to determine the stiffness of dies and dies holder, considering their geometry and their material properties. Then, the difference in stiffness value between the elastic potential energy method and the press behavior's law method could originate from the lack of precision of the press integrated displacement sensor. This sensor gives a value of the relative position of the ram compared to the bottom dead center of the system. Thus, the information given by this sensor is a ram displacement

relatively to the press frame and not to the ground. For that reason, results of the press behavior's law could be altered. To solve that problem, the same experiment could be carried out with the addition of a fast camera recording the position of the ram at the collision. The information obtained would be more precise, and it will be possible to have more information concerning the dies elastic deformation. Finally the method measuring the upright elongation, gives a stiffness value for the upright of the press and not for the entire press. Thus, this value cannot directly be compared with the other ones, as it does not correspond to the same stiffness. Moreover the measurement in that case was done when upsetting a steel billet, whereas the other methods are using data of a bare strike without any billet. Besides, the exactitude of the stiffness value obtained by measuring the upright elongation can also be discussed as the Pontos measures an elongation only on a portion of the upright and with a limited frequency of acquisition.

Thus, this study on the screw press stiffness should be continued by placing more force and displacement sensors at different zones on the press frame and by developing the use of external acquisitions systems.

6. Conclusion

This study is a first step towards the understanding of screw presses behavior. Elastic and inelastic collisions under the screw press have been analyzed and three different methods have been proposed to define the press stiffness. One method was using a 3D tracking point system. The three methods provide three different values of stiffness, but roughly speaking in the same order of magnitude. Some probable origins of these differences are evocated.

To better understand the press reaction, the cross-head could be monitored during strikes. Besides, results could be improved by integrating more sensors at different zones of the press frame, in order to have reliable and precise acquisitions of forces and displacements. The elastic deformation of dies should be studied in details in order to decouple that phenomenon from the press behavior during measurements. In parallel a detailed mass- springs model of the screw press has to be defined. Finally, concerning numerical simulations, a sensitivity study on press stiffness should be done in order to determine the influence of the stiffness value in the numerical model of screw presses.

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