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The role of die definition in the numerical simulations of two-points incremental forming processes

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Abstract

The main objective of this work is to investigate the influence of the definition of dies type in the finite element simulation of the two-points incremental forming processes (TPIF). Particular attention is on determining the effect of assigning elastic properties for the 3D printed dies or considering fully rigid on the final results. During the research, three different shapes of dies were analyzed. Simulation results in the form of sheet thickness distributions and measured forces are presented for comparison purposes.

Keywords: two-points incremental forming, finite element method, additive manufacturing

1. Introduction

Standard sheet metal forming technologies, such as stamping, require the development of dedicated tool sets with adequate tool life (Gronostajski et al., 2019; Jeswiet et al., 2008). The costs of these technologies are further increased by the possibly very complex shape of the finished product. These costs are justified for high-volume production, but when low-volume unit production is considered, they are unacceptable. Therefore, to ensure low-volume production, other metal forming methods, such as incremental sheet forming (ISF, also known as single-point incremental forming or two-points incremental forming) are used (McAnulty et al., 2017). This is a sheet-forming technique in which a metallic sheet is formed into a final part through a series of small incremental deformations. This method can also be applied to polymers and composite sheets (Kharche & Barve, 2022). In SPIF, the sheet is generally formed with a round-tipped tool, typically between 5 mm and 20 mm in diameter. The tool, can be incorporated into a conventional CNC machine (Hu et al., 2017), robotic arm (Bârsan et al., 2022) or a similar device (Mohanty et al., 2021). In SPIF, the workpiece/semi-finished part is clamped, and a round-tipped tool is programmed to follow the circumference of a special input toolpath designed with the aid of computer-aided design (CAD) technology. When an additional counter round-tipped tool is used, the method is referred to as double-side incremental forming (DSIF) (Peng et al., 2019). When a supporting die is introduced to SPIF, it is considered as two points incremental forming (TPIF) (Leem et al., 2022). The use of TPIF allows the reproduction of the shape of the support dies very accurately. In this case, only one shaped die is required to obtain a complex-shaped finished product. Usually, conventional milling techniques are applied to deliver the needed shape of the die. However, additive manufacturing techniques have recently been used more often

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to reduce the cost of preparing such designated dies for the TPIF. Printing a variety of shapes allows for making a complex die shape in an uncomplicated and inexpensive way with a limited amount of waste material (Rosoux et al., n.d.).

However, the main problem is selecting the material from which the dies can be manufactured and then designing the tool paths that will consider an interaction between the tip, sheet, and support die. Providing an adequate insight into these problems requires conducting a series of laboratory experiments that are time-consuming and expensive. Therefore, numerical simulations are often used to minimize both the time and costs of the development of new technology. Numerical simulations based on the finite element method allow the calculation of a wide range of incremental forming setups, which are indispensable in the prototyping stage. However, the quality of numerical simulation results depends on the quality of the developed model. In this case, some parameters are often neglected to speed up the simulation but may affect the final output. In the case of the TPIF based on the 3D printed dies, the simplifications introduced in the definition of the die model may play a crucial role.

Therefore, the present study's main purpose is to determine the influence of the die definition, in a standard way as rigid or in a more complex way as an elastic tool, on the final simulation predictions. To achieve that, a numerical model of TPIF was developed first, and then a series of tests with non-rigid and rigid supporting dies were conducted.

2. Numerical model of TPIF

The commercial finite element program Abaqus carried out numerical simulations of the two-points incremental forming with different shapes of the supporting dies and specified deformation conditions. The numerical models developed consider five major elements of the process: round-tipped tool, limiting frame, supporting frame, supporting die and 1mm thick aluminium sheet plate. The round-tipped tool moves along the previously programmed path and is the main forming tool. The limiting and supporting frames do not allow sheet plate movement upward during deformation. The supporting die is located in the assembly's central part and is used as a support for the sheet during the forming operation. All parts, along with the assembly of the TPIF process, are presented in Figure 1.

The constitutive equation based on J2 plasticity was employed for this investigation. The Abaqus/Explicit solver without mass scaling was used to maintain high-quality results and eliminate any possible unphysical artefacts. The shell elements with a single Gaussian integration point (S4R) were used, and the number of elements for the sheet plate discretization was set to 30,000 during the analysis. The number of finite elements was selected by an extensive mesh sensitivity analysis prior to the simulations. The simulations used three shapes of the supporting dies: pyramid, triangular and rectangular. All investigated dies with their dimensions are presented in Figure 2.

In this study, two series of simulations of TPIF processes were prepared in which the influence of elastic properties set to supporting dies was taken into account. In all the simulations, the sheet material is an aluminium alloy with flow stress described by the simplified Johnson–Cook equation with parameters equal: $A = 28$, $B = 130$, $n = 0.22$ and $m = 0.8$. The authors determined the parameters for the Johnson–Cook equation for aluminium based on performed tensile tests.

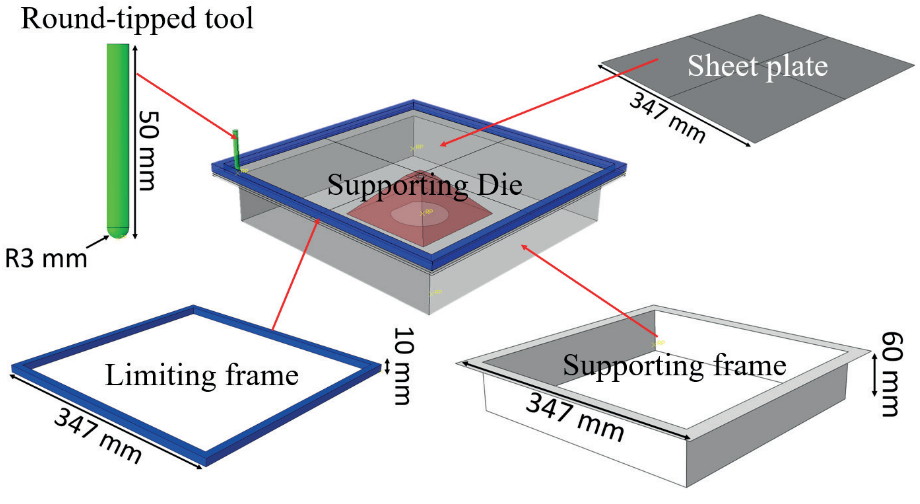

Fig. 1. Subsequent parts and an assembly of the TPIF process in the developed numerical model

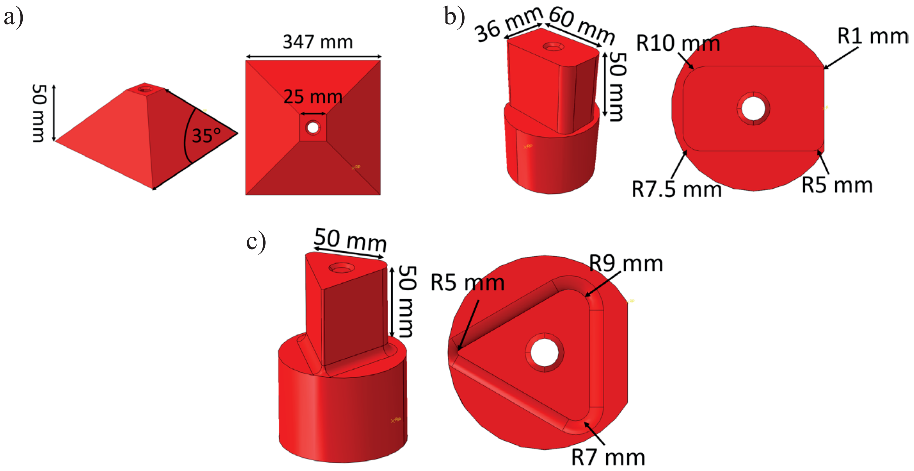

Fig. 2. Shape with the dimension of all supporting dies: a) pyramid; b) rectangular; c) triangle

In the first series of simulations, the limiting frame, supporting frame and die were fixed in every direction. The supporting die was considered fully rigid. The rounded-tip moves along a predetermined trajectory based on information embedded in the *gcode* file. Information about the movement trajectory of the rounded-tip tool along X, Y and Z directions was set into the displacement boundary conditions. An example of the trajectory for the forming tool used in the model with a triangle supporting die is shown in Figure 3.

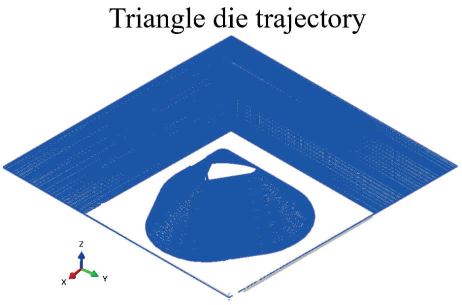

Fig. 3. Trajectory for the rounded-tip tool used in the model with triangle supporting die

The outer edge of the sheet plate is fully constrained and blocked by a limiting frame tool to restrain its radial movement. A Coulomb friction coefficient of 0.1 was used between the tools and the sheet, as this value is commonly considered in sheet-forming simulations.

The second series of simulations were based on similar assumptions, with the only difference being that the supporting die was defined as a deformable tool. The elastic properties of the Ingeo Biopolymer 3D870 (Mehrpouya et al., 2021) were used to consider the material used for the 3D printing process of the dies. The Young modulus was set to 2.865 GPa and Poisson ratio to 0.34. Pyramid, triangle, and rectangular supporting dies were discretized with 15,000 single Gaussian point C3D8R solid elements.

3. TPIF simulations results

The obtained results are presented in the form of plate thickness distribution fields for the first (Fig. 4a) and second (Fig. 4b) series of the simulations.

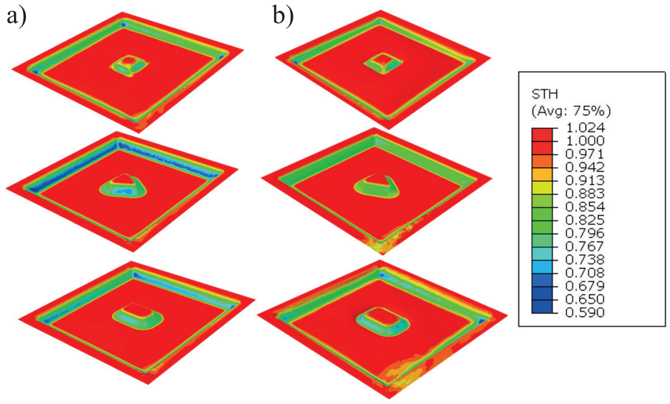

Fig. 4. Thickness distributions after deformation with rigid (a) and elastic (b) supporting die

To qualitatively compare forces recorded during the deformation process, the force-time diagrams were generated for both investigated case studies. Forces were collected from all supporting dies. To make the force evolution trends more transparent, the polynomial fitting curve equation was used and added to the graphs shown in Figure 5.

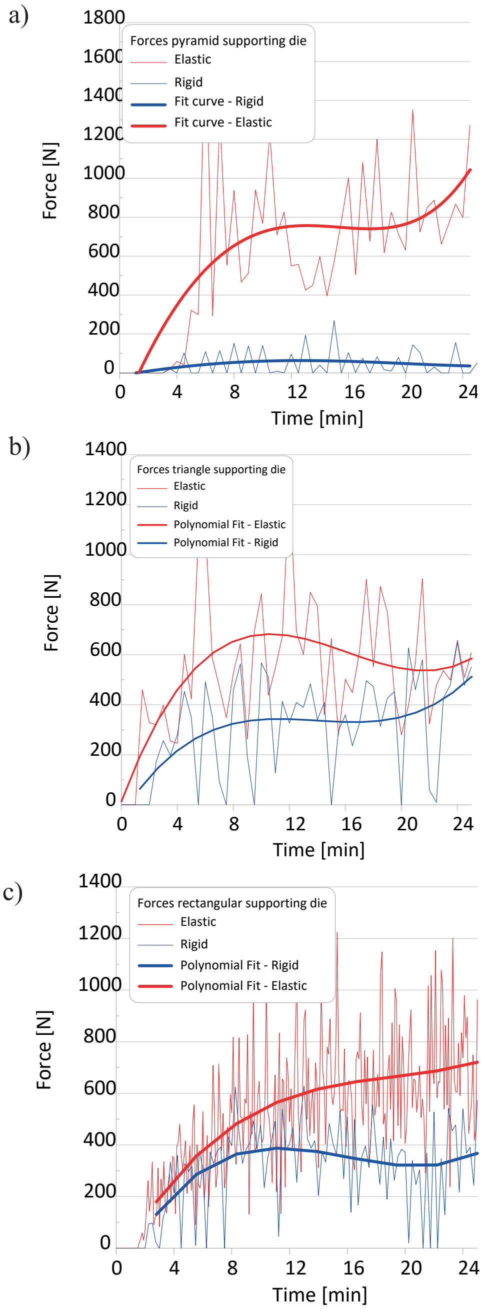

Fig. 5. Forces-time curves with fit trend line from simulations with pyramid (a), triangle (b), and rectangular (c) supporting dies

From the above curves, it can be seen that in the model where dies have elastic properties, registered forces are larger than in models with rigid dies. This is especially evident for the model with a pyramid supporting die where forces are seven times higher. This behaviour is related to the fact that the elastic die deforms to some extent leading to increased contact between the sheet and the die. Initially, the sheet lies only on the upper part of the pyramid, and during deformation, it is deposited on the pyramid die edges. This results in a progressive increase in the area of interaction between the die and the formed sheet. In the case of the triangular and rectangular die, the top surfaces are not symmetrical and do not have side edges, which results in a smaller increase in force during the process than in the case of the pyramid (Fig. 5a, b, c). In addition, a different stress distribution can be observed on the dies. In the pyramid die, a constant stress increase can be seen on all four edges of the upper die surface. In the triangular, the highest stress increases can be observed only on its narrowest edge (Fig. 6b). Similar situation can be observed in the rectangular die (Fig. 6c).

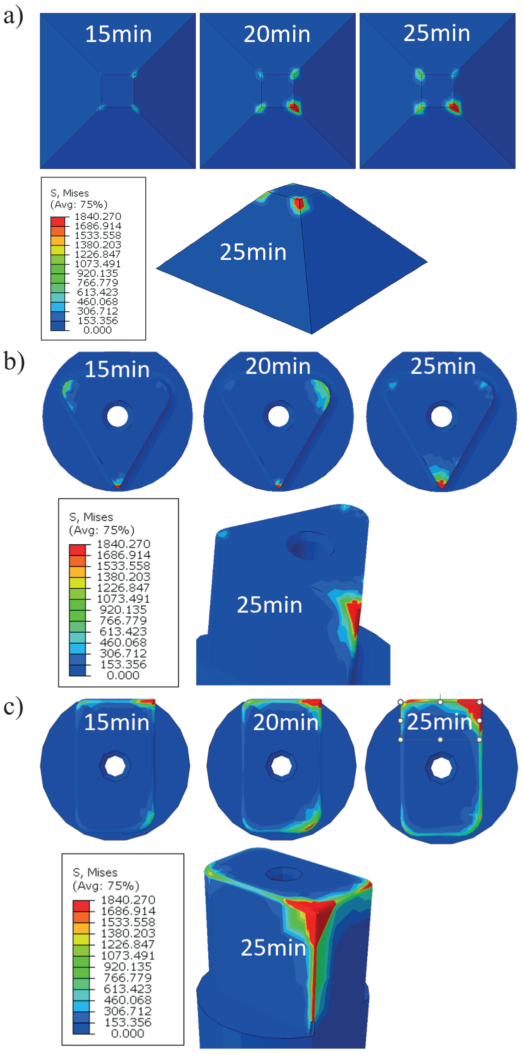

Fig. 6. Stress distributions in the elastic dies during subsequent time steps for pyramid (a), triangle (b), and rectangular (c) supporting die case study

Another effect of assigning elastic properties to dies is a modification in the oscillation of the formed sheet during the process. This oscillation is different for the rigid and elastic dies. After simulations, it was noted that this phenomenon increases when an elastic die is used. In order to quantitatively analyze the range of variation of these oscillations, information was extracted from the current position of pairs of nodes lying on opposite formed edges of the sheet calculated in each timestep of the simulation. The nodes were selected to be located at the extremes of the die upper surfaces. The results of these oscillations on pyramidal (Fig. 7), triangular (Fig. 8) and rectangular (Fig. 9) matrices are shown below.

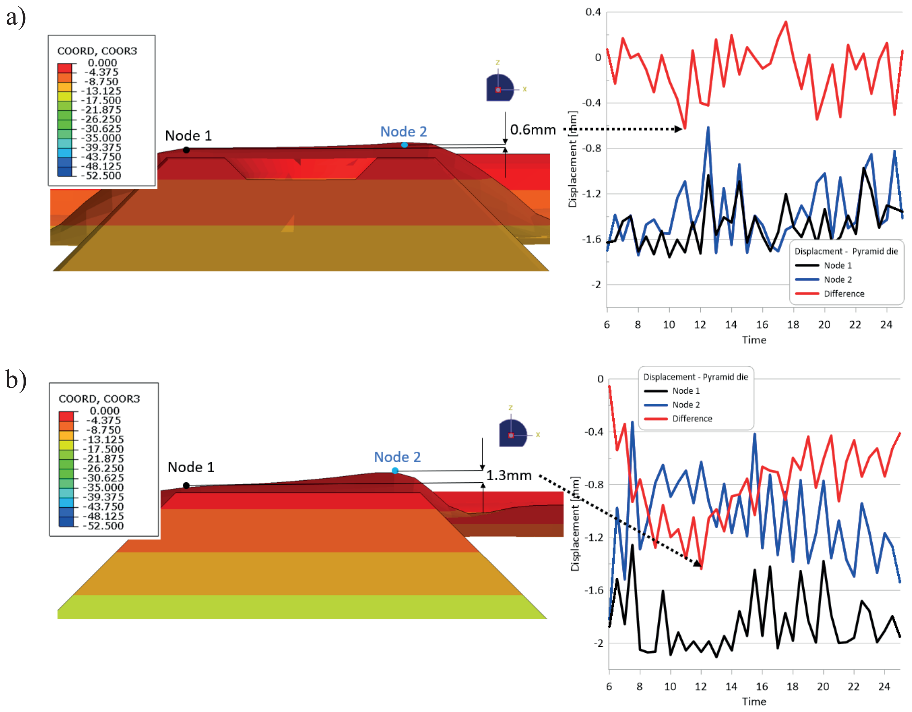

Fig. 7. Displacement of nodes in pyramidal dies: a) rigid; b) elastic

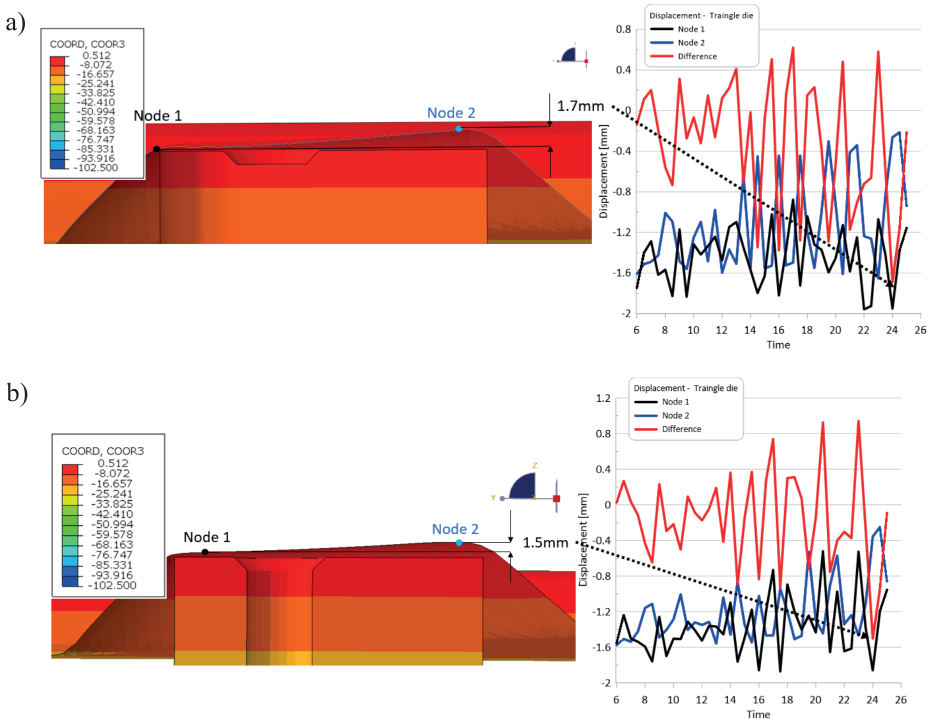

Fig. 8. Displacement of nodes in triangle dies: a) rigid; b) elastic

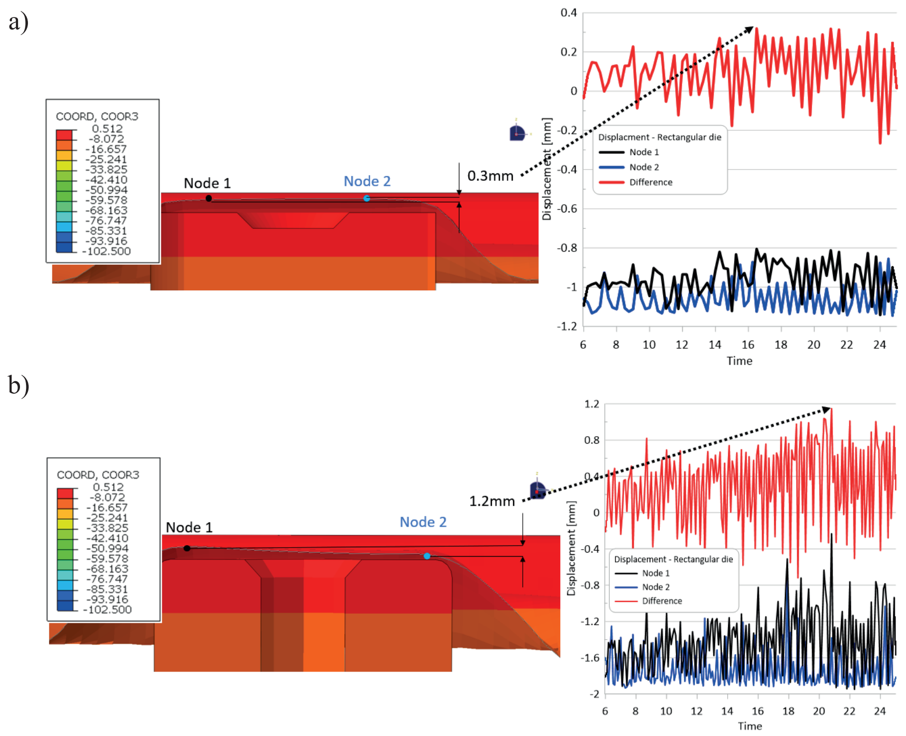

Fig. 9. Displacement of nodes in rectangular dies: a) rigid; b) elastic

From the above results, it can be concluded that for the triangular die, the level of oscillation is similar, and the difference in the position of the two nodes fluctuates around 1.5–1.7 mm (Fig. 8). In the rectangular elastic die, a significant increase in sheet oscillation can be noted. For the rigid die, the maximum difference in the position of the nodes is about 0.3 mm. In contrast, for the elastic die, this value reaches 1.2 mm. When a pyramidal die is used, then the range of the oscillation also differs between rigid and elastic. Even so, the largest difference of 1.3 mm occurs at the beginning of the process, and after 15 min, it becomes similar to the simulation with a rigid die. Figure 10 clearly shows the variations in oscillations for each simulation.

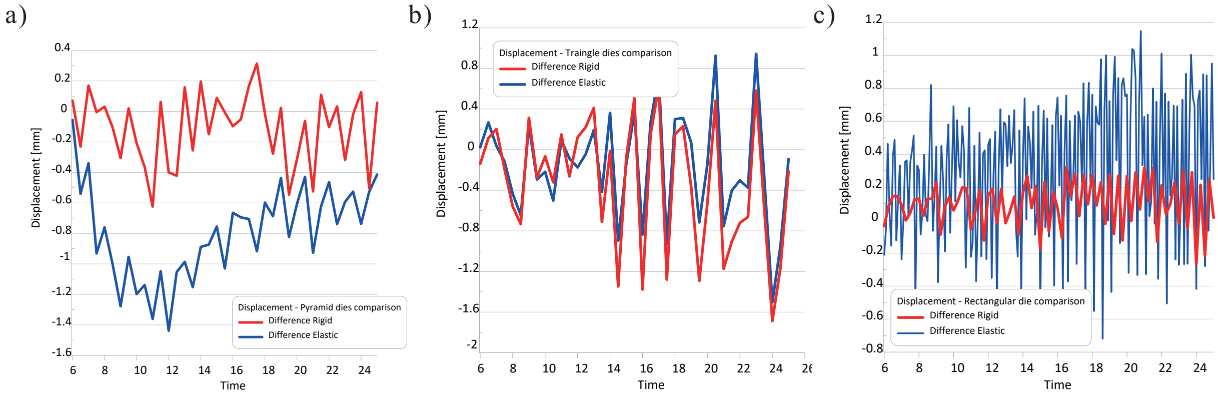

Fig. 10. Variation of oscillations in pyramidal (a), triangular (b), and rectangular (c) matrices

The last aspect analysed in the use of elastic properties for supporting dies in TPIF simulations are the computational costs. All calculations were performed using 24 CPUs. The calculation times are presented in Figure 11.

Calculations performed with elastic dies are significantly longer, often requiring up to three times as much time. Of course, it is possible to use mass scaling in simulations, but it would be necessary to check the impact of scaling on the quality of the results obtained in advance. However, as mentioned, scaling was deliberately neglected to accurately determine the impact of elastic tools in this research.

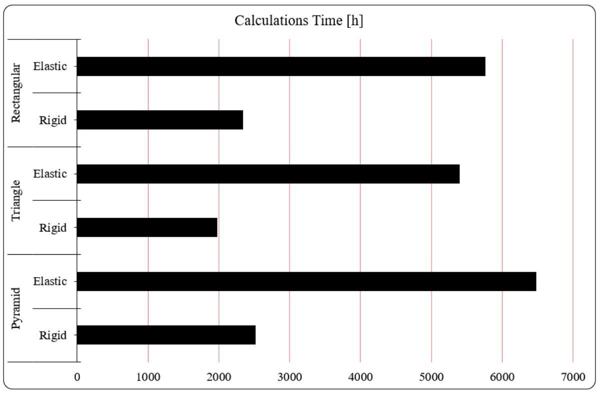

Fig. 11. Time to calculate the TPIF process presented in this work

Conclusions

This paper aimed to determine the influence of supporting dies definition as rigid and elastic material on the TPIF process results. Based on a series of numerical simulations, the following set of conclusions can be formulated:

- when dies are defined as an elastic material, there is an increase in forces compared to rigid dies,
- the degree of oscillation of the sheet during formation with elastic-type dies is increasing,
- the larger contact area between the sheet and the die significantly affects the values of recorded forces,
- the calculation time increases significantly when elastic dies are used.

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