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TECHNICAL-ECONOMIC CALCULATION OF CONVENTIONAL AND INCREMENTAL FORMING

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Abstract: Recent developments in incremental forming have given rise to novel manufacturing methods that are very flexible and have the potential to be profitable for small-batch production and rapid prototyping. The manufacture of various parts using the same tooling system is made possible by the incremental shaping of sheets, which also results in significant material and energy savings. Although incremental forming offers greater flexibility, lower costs, and shorter lead times, a more thorough sustainability assessment is lacking. The research on the technical-economic calculation differences between conventional and incremental forming is presented in this paper in order to provide a summary of the research progress on the sustainability evaluation of incremental forming and to further to explore its potential application.
Key words: incremental forming, mould cost, conventional forming.

1. INTRODUCTION

Incremental forming (IF) doesn't need any part-specific tooling, in contrast to conventional forming techniques. It is a versatile shaping technique that works well for producing small quantities of user-specific shapes. For materials with reasonable form-ability, the IF technique has been acknowledged as a promising production alternative to conventional forming, [1, 2].

Cold plastic deformation is a method of material processing intended to produce changes to both the shapes and sizes of finished pieces without removing any material, as is the case with aching processes. Pieces designed for mass and large-scale production in series using conventional plastic deformation processes are produced. These pieces are highly developed and planned for high productivity, but they also have low levels of flexibility and high manufacturing costs. This inconvenience led to the development of a new flexible process, specifically the incremental sheet forming process (ISF). This relatively new method of deforming plastic as it is being heated up enables the creation of small- and medium-scale series products, quick prototyping, and the production of unique items. Conventional tabloid piece processing relies heavily on custom shapes with a variety of more straightforward or more complex forms (punches and mold) in order to produce finished pieces at higher manufacturing costs. It is not necessary to utilize complicated machines to carry out the incremental manufacturing process; instead, a simple shaft with low costs and universality, i.e., suitability for a wide range of product categories, can be used. In addition to processing centres with numerical commands, incremental augmentation can be carried out; its productivity is significantly higher than that of conventional augmentation. A specialized tool will be required because the incremental manufacturing process requires the creation of pieces with high levels of precision and complex shapes.

Advantages of ISF over conventional sheet metal forming are as fallow: There is no need for a die, as there is in conventional sheet metal forming, because the process may be controlled entirely by CNC procedures. Because there is no longer a need to build a die, eliminating the die from the manufacturing process lowers the cost per piece and shortens the turnaround time for low production runs. The better per-piece speed and lower per-piece cost, however, offset the time and expense to create a die for high production runs. The form-ability of metal materials under the localized deformation induced by incremental forming is better than in traditional deep drawing, according to several authors, [3], The ISF procedure, however, suffers from a loss of precision, [4].

In the following table, additional strengths and weaknesses of incremental forming are highlighted, (Table 1), [5]:

Table 1. Strengths and weaknesses of incremental forming model, [5]

Strengths	Weaknesses
- As a result of the divide and conquer strategy being adopted, tasks can easily be broken down; - Initial delivery costs have decreased; - It deploys resources incrementally; - Because the client starts using fundamental modules at the beginning of phase 1 and continues using them through phase 5, it may quickly deduce faults. These go through a lot of testing; - When requirements are recognized up front, it is a good tool to use; - When projects have extensive development timetables, it is a good idea to use it; - When projects use new technology, it is a good idea to use it; - It is useful when there is a requirement for early benefit realization due to funding schedule, risk, program complexity, or other factors; - Early in the software life cycle, it swiftly produces functional software; - Changing the scope and criteria is less expensive and more adaptable; - Each iteration can be easily managed; - Iterations make risk management simple.	- It necessitates careful planning and design; - It is more expensive than the waterfall model; - System definitions should be comprehensive and unambiguous, - Project complexity may rise as it is built steadily, adding complexity with each addition. This may increase the likelihood of mistakes and defects, as well as make it more difficult to manage and maintain; - Higher prices: The overall cost of the project may be more than with other development approaches because each increment necessitates its own planning, design, coding, testing, and deployment; - Having trouble monitoring progress It can be hard to monitor the development of the project as a whole when numerous increments are being created at once. This may make it more difficult to see possible problems early and take preventative measures; - A large increase in communication overhead may be necessary to make sure that everyone is on the same page when each increment is produced by a new team or individual; - Increased testing time: Since each increment requires its own testing phase, the project's completion may be delayed if testing takes up more time overall.

2. TYPES OF INCREMENTAL FORMING

A variety of processes that are all characterized by the fact that a localized area of deformation spreads across the entire surface of the part are used incremental numeration. A new technique for increasing speed that makes use of fast-moving machines with numerical controls and is appropriate for small-series production is known as "incremental forming method", Figure 1. Without the need for a unique tool geometry, incremental augmentation is a group of creative, adaptable processes that can produce a variety of part shape, [6]. As the spine performs a rotational movement and an advancing movement, the incremental forming process is fixed in the grasping device, which is located on the mass of the machines, [7]. It is crucial to understand that this process involves a great deal of weight and resistance, [8]. In the event of incremental bending at a single point, a semi-circular spline with a predetermined local deformation trajectory will be used to achieve the desired final shape. In contrast to conventional ambushing processes, *incremental forming at one point* is characterized by good geometrical plasticity and accuracy. A procedure that uses a sleeve with a hollow semi-spine on either side of the semi-fabricator's table is called *incremental machining on both faces* (Figure 2), and it is superior than incremental machining at one point. The support tool will move at the same time as the forming tool and will act locally. For this reason, the results obtained with incremental forming on both sides are considerably better in terms of geometric precision and increased plasticity of the formed piece compared to incremental forming in a single point, [9]. The most important criterion to express the plasticity limit of the material in the forming process in a single point is the maximum angle of forming, [10].

The meanings of the notations involved in Figure 1 are as follows: d is the diameter of the forming tool, [mm]; α represents the angle of the part wall, [^{0}]; h defines the height of the piece, [mm]; n is the rotational movement of the tool, [rot/min]; Δz represents the tool displacement on the Z axis, [mm], and Δy is the tool displacement on the Y axis, [mm].

The incremental forming process is carried out using a model (support tool) and the movement is in the vertical direction, the semi-finished sheet metal being fixed in a clamping device. The tool will move along the model, and the piece that will be obtained will take the shape of the respective model. The model (support tool) can have an intermediate or final form, [11].

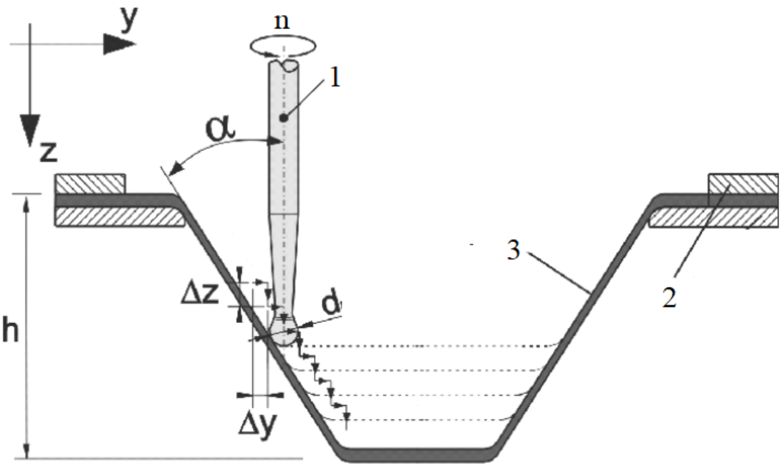

Fig. 1. The basic principle of the incremental forming process, [7]: 1 – the incremental forming tool; 2 – the fixing device of the semi-finished product; 3 – semi-finished product

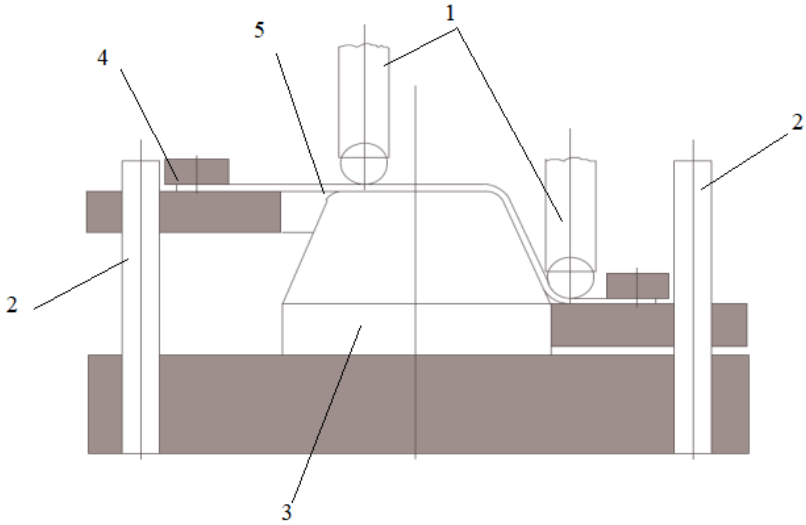

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Fig. 2. Incremental forming on both sides using a support tool (model), [11]: 1 – forming tool; 2 – supports for supporting the device for holding the semi-finished product; 3 – support tool; 4 – fixing device; 5 – semi-finished product

The trajectory on which the tool moves is essential for increasing productivity. For this reason, different incremental forming processes have been developed, such as: an outward tool movement process and a continuous inward tool movement process. Since the deformation of the central shape is not involved, the quality of the surface is increasing [11]. The experimental test shows that in the second process, the shape of the part obtained by incremental forming approaches the designed one, [11].

Also, according to another criterion, incremental forming can be: negative incremental forming (Figure 3a) and positive incremental forming (Figure 3b).

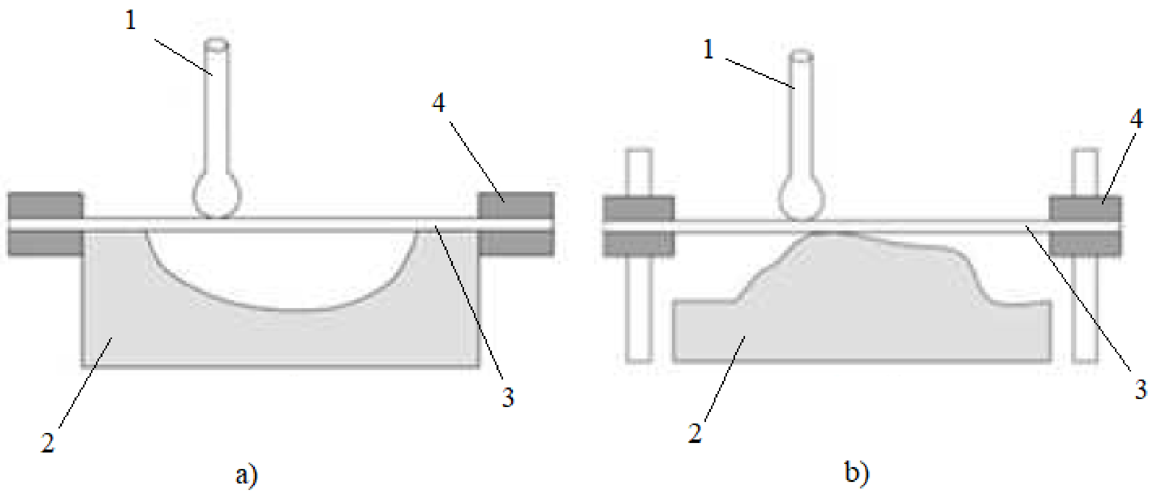

Fig. 3. Incremental forming, [12]: a-negative; b-positive; 1 – incremental forming tool; 2 – negative or positive counter form; 3 – sheet/base material; 4 – clamping device.

The main characteristics of incremental forming technologies are:
- the incremental forming process does not require a mold, but requires a system for fixing the semi-finished product, various tool sizes, forming rollers, active plates, etc.;
- the incremental forming process has a lower productivity compared to conventional forming, but does not require high equipment costs;
- the incremental forming process is flexible, the same equipment can be used to make different part geometries;
- the forming angle is obtained higher than with conventional forming, this makes it suitable for the processing of various materials that are difficult to form;
- the arching effect of the material reduces the processing precision in the case of conventional forming, but using the incremental forming process removes this disadvantage, [7].
The main incremental forming technologies are presented below.

➢ *Hammer blow*: One of the oldest incremental forming processes is hammering, Figure 4. This process was initially done manually, but with the development of technology it can also be done with the help of industrial robots. The advantage of using industrial robots is that the robot arm controls the movement of the tool and the strokes applied to the blank. The semi-finished product is clamped in the clamping device, where another circular descent trajectory will be made step by step at each pass, [13].

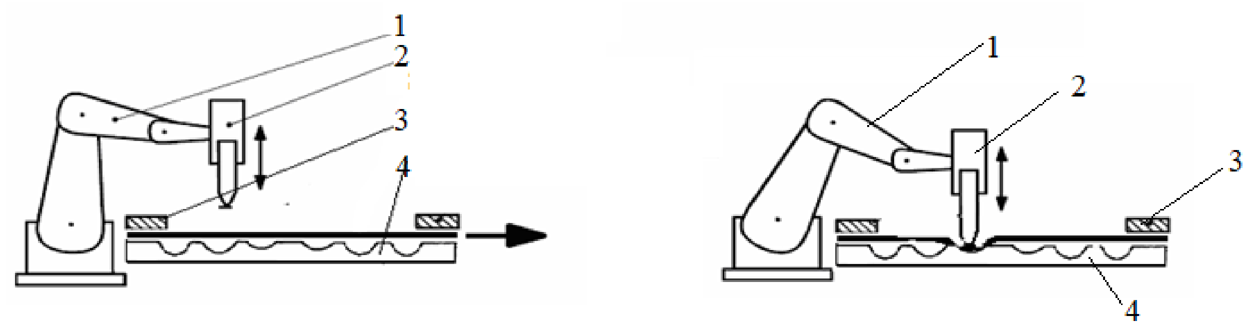

Fig. 4. The hammer blow performed by an industrial robot, [14]: 1 – industrial robot; 2 – semi-finished tool; 3 – clamping device; 4 – support frame

➢ *Multi-point forming*: Multi-point forming, Figure 5, is a technology similar to the solid die forming process. In this process, two opposite molds are used pressed on the semi-finished plate to obtain a certain geometry. Multi-point forming replaces the solid mold with a mold with several punches having specific geometries adjustable in height with the help of linear motors, in order to use the process to obtain various shapes in a short period of time, [13].

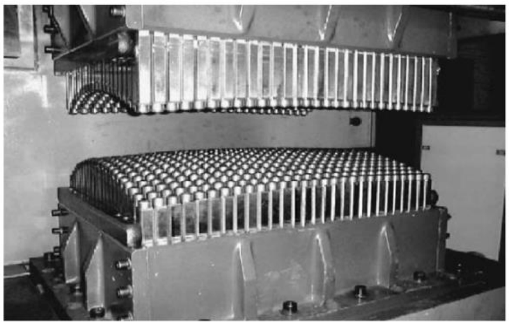

Fig. 5. Multi point forming, [13]

➢ *Laser forming process*: The laser forming process, Figure 6, is based on the thermal stresses induced in the structure of the semi-finished material by the laser radiation. The thermal demands induce plastic deformations resulting in bending of the material. This process can be used to repair or modify sheet metal components, [13].

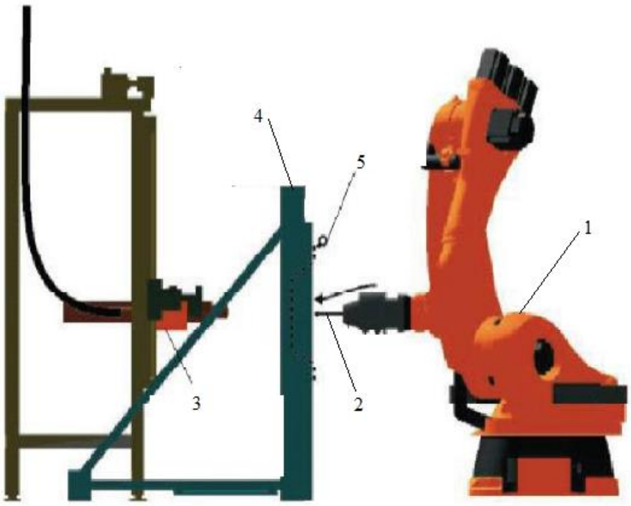

Fig. 6. Forming with laser beam, [13]:1 – robot with 6 axes; 2 – incremental forming tool; 3 – 3-axis laser beam positioning system; 4 – vertical table with clamping system; 5 – coolant circuit

➢ *Water jet forming*: Water jet forming is similar to laser beam forming, with the water jet replacing the laser. The advantages of this process are the following: flexibility; low equipment costs and low impact on the environment.
Among the disadvantages of the procedure, the following can be listed: low precision; high energy consumption and high processing time compared to other incremental forming processes, [13, 15].

➢ *Spinning*: The spinning process is divided into two categories: conventional spinning, Figure 7a, and shear spinning, Figure 7b.

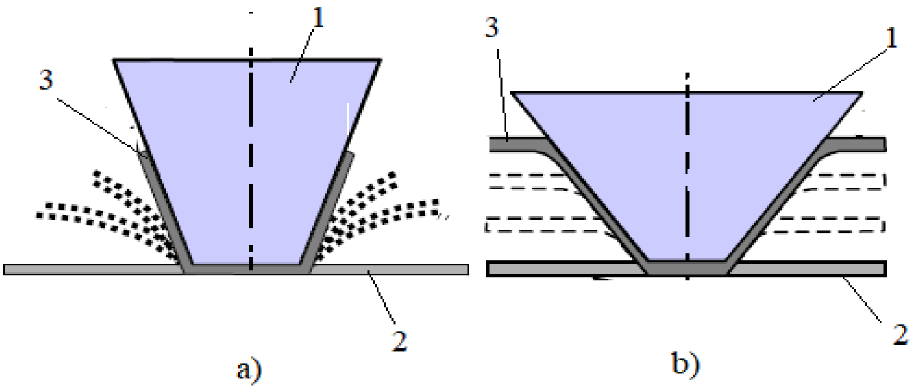

Fig. 7. Variants of the spinning technological process: a) conventional spinning of a cone; b) shear spinning of a cone, [16]: 1 – rotating mandrel; 2 – semi-finished product; 3 – final piece

In conventional spinning (Figure 7a), the pieces (3) are formed gradually, with the help of a rotating mandrel (1). The tool produces local pressure in order to deform the semi-finished product through axial and radial movements on the surface of the piece. The tool can be operated manually or mechanically, the manufacturing costs for the tool are reduced, being suitable for small series production, as it involves several passes, [16]. Shear spinning, Figure 7b, is similar to conventional spinning, the difference being that the process of stretching the material is used versus conventional spinning, which uses material bending. This factor has a major influence on the thickness variation along the wall, [13, 16].

The spinning process is limited by the angle α, Figure 8, and the final thickness of the sheet t is determined by the relationship between the angle α and the initial thickness of the sheet t_i (equation 1). The schematic representation of the sine law, respectively the deformation of the material during shear spinning, which is presented in Figure 8, [13].

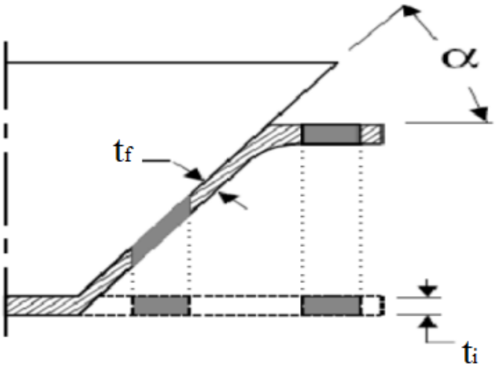

Fig. 8. Material deformation during shear spinning of a cone, [16]

$$t_f = t_i \sin\alpha \tag{1}$$

where: t_f is the final thickness of the plate, [mm]; α represents the angle of the wall, [^{0}], and t is the initial thickness of the plate, [mm].

➢ *Single point incremental forming*: Single-point incremental forming, Figure 9, represents a developed method of incremental forming over spinning. The process is performed on a CNC milling machine. The semi-finished sheet metal is fixed in the clamping device and the tool with the hemispherical tip will print the desired geometric shape. The tool has a rotary motion and can have a helical trajectory, [13, 16, 17].

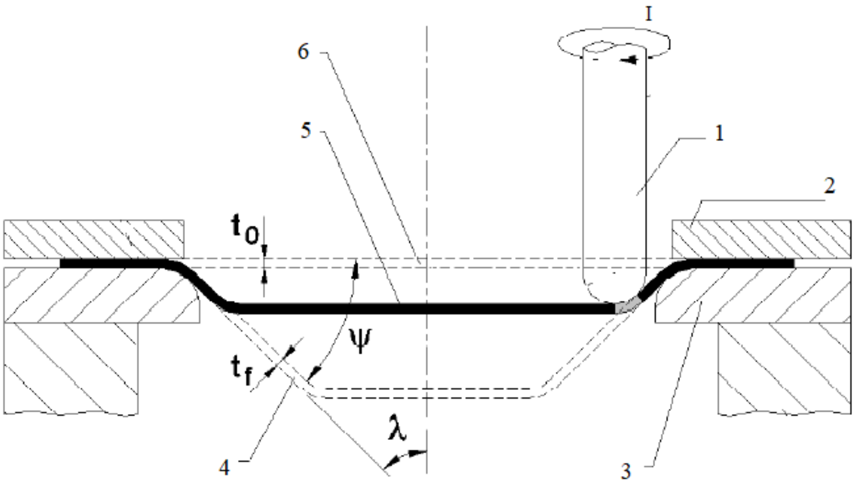

Fig. 9. Schematic representation of the incremental forming process in a single point, [13]: 1 – the forming tool; 2 – clamping device; 3 – support plate; 4 – final piece; 5 – the intermediate shape of the part; 6 – semi-finished sheet metal; I – rotational movement of the tool

➢ *Incremental forming with counter tool*: Incremental forming with counter tool (Figure 10), is a variant of incremental forming in a single point, but uses a counter tool that follows the same trajectory as the main tool, [13].

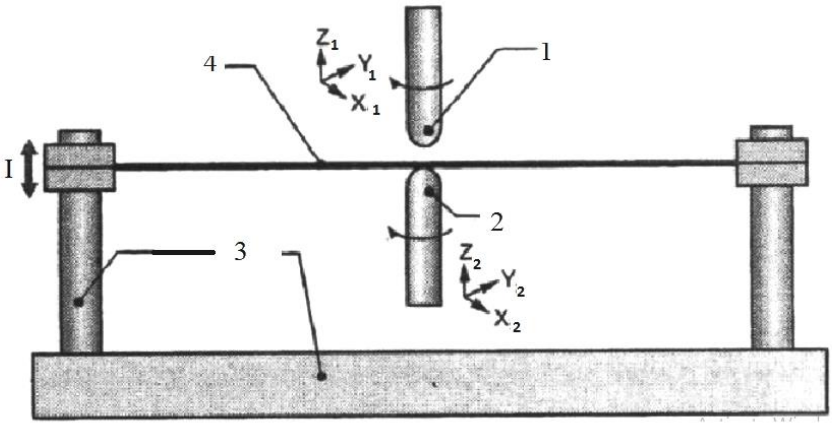

Fig. 10. Schematic representation of incremental forming with counter tool, [13]: 1 – main tool; 2 – auxiliary tool; 3 – semi-finished fixing device; 4 - semi-finished product; I – the penetration movement of the tool in the direction of the Z axis

➢ *Two-point incremental forming*: In two-point incremental forming, Figure 11, the process is identical to that of single-point forming, except that in addition to the main tool, a support plate is also used. The blank is clamped in the clamping device and can be adjusted in height in the direction of the Z axis. The tool is similar to the tool from the single-point forming process and performs a geometric path from top to bottom. Incremental forming in two points can be with: tool having spherical tip and partial die, [13], and tool having spherical tip and full die, Figure 12, [13].

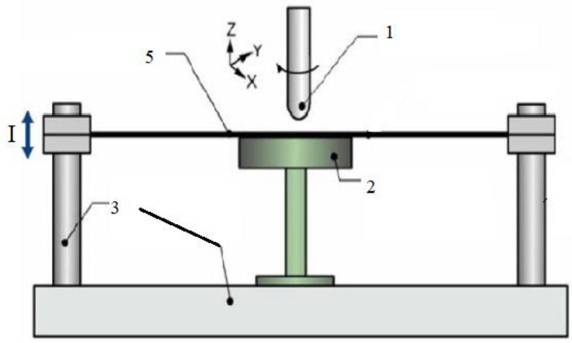

Fig. 11. Incremental two-point forming with spherical tip tool and partial die, [13]:1 – main tool; 2 – non-specific support; 3 – fixture; 4 – semi-finished product; I – tool penetration movement in the direction of the Z axis

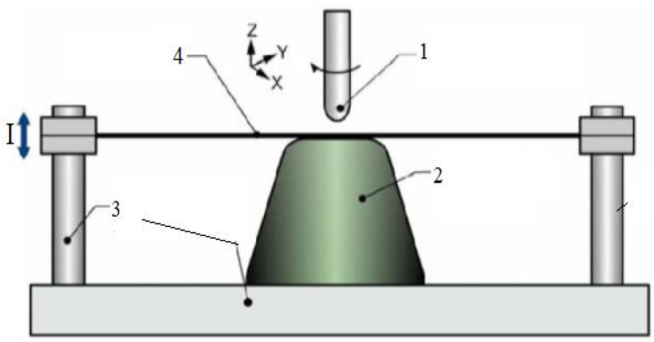

Fig. 12. Incremental two-point forming with ball tip tool and partial die, [13]:1 – main tool; 2 – specific support; 3 – fixture; 4 – semi-finished; I – tool penetration movement in the direction of the Z axis

➢ *Multi-stage incremental forming*: When forming in several steps (Figure 13), it is important to know the maximum angle of forming, for each material with a specific thickness. To establish the maximum angle of forming, a series of tests are performed using as parameters the diameter of the tool, the number of passes and tool trajectory, [13].

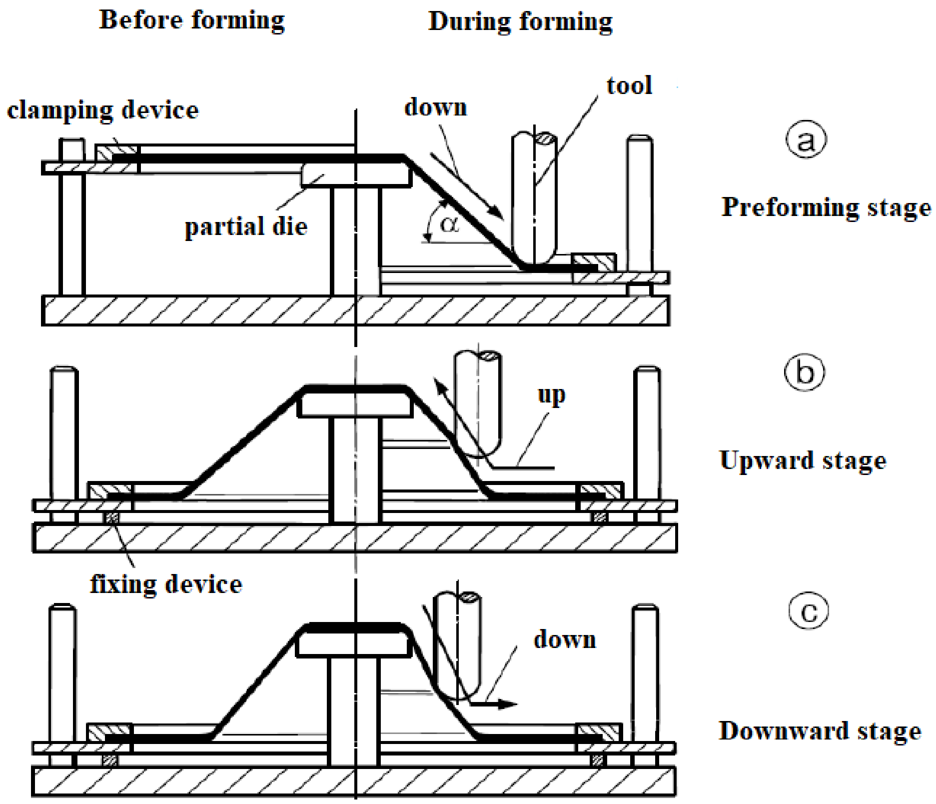

Fig. 13. Multi-stage incremental forming, [13, 18]

➢*Hybrid forming processes*: One of the limitations of incremental forming is manufacturing time. An example of a hybrid incremental forming technique, Figure 14, is the combination of stretch forming and incremental forming. Different forming strategies are used for each part geometry, [19, 20].

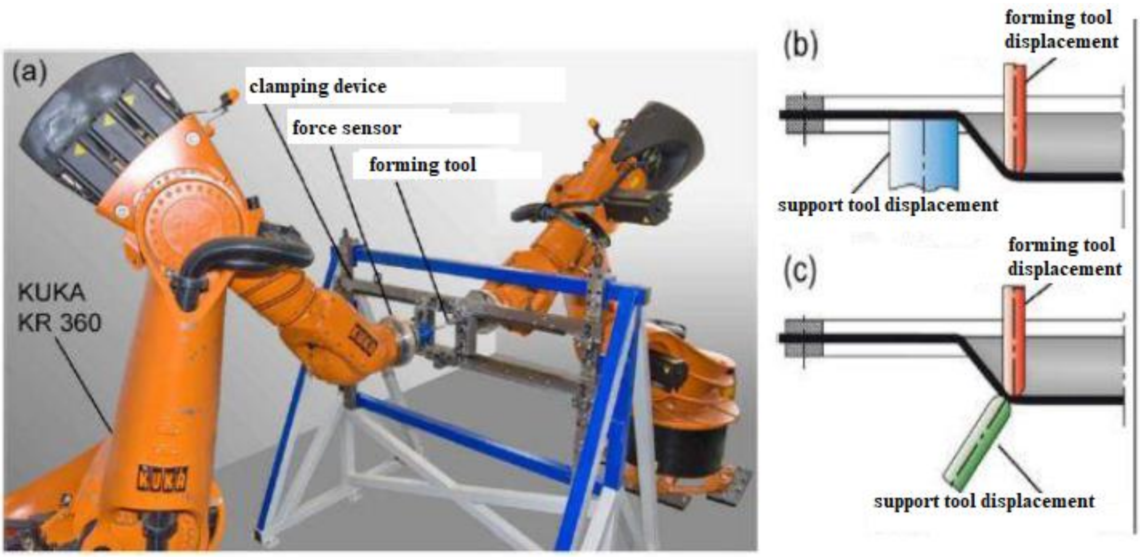

Fig. 14. Hybrid forming processes, [20]

Figure 14 shows a hybrid forming equipment that consists of two industrial robots, forming tools and the semi-finished clamping device. Each industrial robot has placed force sensors to know and maintain the incremental forming force during the process. One industrial robot actually executes the incremental forming process, and the other, positioned on the opposite side, has the same displacement as the first robot contributing to the execution of the incremental forming process.

3. GENERAL ASPECTS OF TECHNICAL-ECONOMIC CALCULATION OF CONVENTIONAL AND INCREMENTAL FORMING

Carrying out plastic deformation activities in a company from the purchase stage to delivery, there is an influence of factors such as the deformation process carried out, the technology available, production management, the types of parts obtained, the actual manufacturing time, [21]. However influential these factors may be, the determination of costs is carried out as the ratio between the company's expenses and the quantity of the products obtained, of the works performed and of the services provided, [21]. The expenses can be classified according to the economic nature in: expenses with salaries, social insurance and expenses with materialized work such as: material expenses, expenses with the works and services performed by collaborators, as well as taxes and fees, [22]. The expenses can be classified according to the connection they have with the technological process and can be technological expenses and overhead expenses. Technological expenses are dependent on the manufacturing process. These expenses include: consumption of raw materials, direct materials, fuel, energy, water, salaries of directly productive personnel, etc.
Overhead expenses are the expenses that do not directly depend on the manufacturing process, they are spent on the administration, organization and management of the manufacturing process, [22].
Technological expenses in general are direct and variable expenses, while overhead expenses are indirect, some of them being fixed expenses and others variable, [22].
To calculate the total execution price of a conventional stamping die, it is necessary to use equation (2) and (3) respectively:

$$C_t=C_{man}+C_{pm}+C_{mp}+C_p+C_a \quad (2)$$

unde: C_t - represents the total cost of the conventional forming die, [€]; C_{man} - represents the management cost, [€]; C_{pm}- Mold production cost, [€].

Mold price = Management cost + Mold design cost + Raw material cost + Mold production cost + Administrative cost (3)

Cost structure: 1. acquisition costs; 2. production costs and 3. processing costs.
The cost of stocks must include all costs related to acquisition, production, processing, as well as other costs incurred to bring the goods, works, services in the form and place where they are currently.
The purchase cost of the goods includes the purchase price, import taxes and other taxes (except those that the company can recover from the tax authorities), transport, handling and other expenses that can be directly attributed to the purchase of the respective goods. Discounts commercial, rebates and other similar elements are not included in the purchase cost.
The production cost includes the direct expenses related to production, namely:
- direct materials;
- energy consumed for technological purposes;
- direct labor;

The processing cost includes labor and other expenses related to the personnel directly engaged in providing the services, including the personnel in charge of supervision, as well as the corresponding indirect expenses (royalties).

3.1 Main component of the price

The price calculation of a conventional forming die is calculated according to equation (4):

Mold price = Management cost + Mold design cost + Raw material cost + Mold production cost + Administrative cost (4)

Cost management = 10% of the total price
Mold design cost = 10% of the total price
Raw material cost = 35% of the total price
Mold production cost = 40% of total price
Administrative cost = 5% of the total price

Establishing the research methodology and the experimental plan to meet criteria such as: ease of data acquisition; reducing the number of attempts, respectively the price of experimentation; achieving very good accuracy;
Design and execution of tools used in the incremental forming process;

The design and execution of the devices for fixing the semi-finished product in the incremental forming process;
Determination of the Erichsen index of the EN AW-3003 aluminum alloy material according to the Erichsen method in accordance with STAS 2112-86;
Realization of the numerical simulation of the incremental forming process of a pyramid trunk piece;
Carrying out the experimental tests according to the proposed experimental plan. The process parameters taken into account will be: the forming tool, the advance speed and the forming depth, the 3 parameters varying on two levels;
Establishing the limitations of the incremental deformation process, for the EN AW-3003 aluminum alloy material:
- The influence of the tool path on the geometric precision of the part;
- The influence of experimental parameters on deformations and material thickness reduction;
- The influence of the tool trajectory on the surface roughness, respectively on the geometric precision of the part;
- The influence of forming forces on the realization of parts incremental forming process.

4. CONCLUSIONS

The process of machining metal known as incremental forming is one that does not require the use of dies and can be applied to the manufacture of a wide range of products in small quantities. When compared to traditional metalworking processes (like spinning or die casting), this method offers a number of benefits, including a reduction in cost and an improvement in lead time.
The deformation process that is carried out, the technology that is available, production management, the types of parts that are obtained, and the actual manufacturing time all have an impact on the incremental forming activities that are carried out in an organization from the stage of purchase all the way through to the stage of delivery. According to the economic nature of the expenditures, they can be categorized as follows: expenses with salaries, social insurance and expenses with materialized work such as: material expenses, expenses with the works and services performed by collaborators, as well as taxes and fees. Expenses with materialized work include: material expenses, social insurance and expenses with materialized work. These costs include, but are not limited to, the consumption of raw materials, direct materials, fuel, energy, water, salaries of directly productive personnel, and so on.

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