Quest Journals
Journal of Research in Mechanical Engineering
Volume 9 ~ Issue 6 (2023) pp: 01-08
ISSN(Online):2321-8185
www.questjournals.org

Research Paper

A design of mini CNC machine applying to incremental sheet forming processes

Ngoc-Tuan La[1,*], Khac-Binh Le[1], Thanh-Son Nguyen[1], Hai-Chung Luong[1], Van-Giang Ngo[1], Van-Thong Pham[1], Chien-Thang Nguyen[2]
[1]*Vinh University Technology of Education, Vietnam*
[2]*The German-Vietnamses College of Nghe An, Vietnam*

ABSTRACT: *Incremental sheet forming (ISF) has been attracting many scientists around the world to research in order to partially replace the cold sheet drawing technology. Recent publications show that studies focus on aspects such as the influence of forming parameters and technological parameters on plastic deformation force, deformation capacity, product quality... This paper presents results of designing and manufacturing a mini CNC machines for ISF processing research. On the basis of determining the deformation force components at the most unfavorable conditions, the structure of the modules is designed independently and incorporated in the overall design. After designing, the machine was tested for programming ability, the ability to perform ISF technology with sheets of Al 5052 aluminum alloy. The results showed that the mini CNC machine was designed and manufactured to ensure rigidity and satisfy the requirements of movement and interpolation in 3 axes x, y, z to create simple or complex shapes. This mini CNC machines can serve the implementation of ISF processing research or expand the application for other cutting and processing technologies, such as milling, drilling....*

KEYWORDS: *ISF, Design, Mini CNC, Manufacture.*

R*eceived 25 May, 2023;* ***R****evised 03 June, 2023;* ***A****ccepted 05 June, 2023 © The author(s) 2023.*
P*ublished with open access at* ***www.questjournals.org***

I. INTRODUCTION

Incremental sheet forming (ISF) processes, also known as continuous local plastic deformation processes, was first announced by Leszak in 1967 [1], [2]. This is considered an ideal processing method for forming products with concave pots or products with embossed edges and complex profiles from sheet blanks without the need for a mold. During the forming process, only part of the metal at the point of contact with the tool deforms locally, and this plastic deformation zone moves over the entire area to be formed until the product is finished [3], [4].

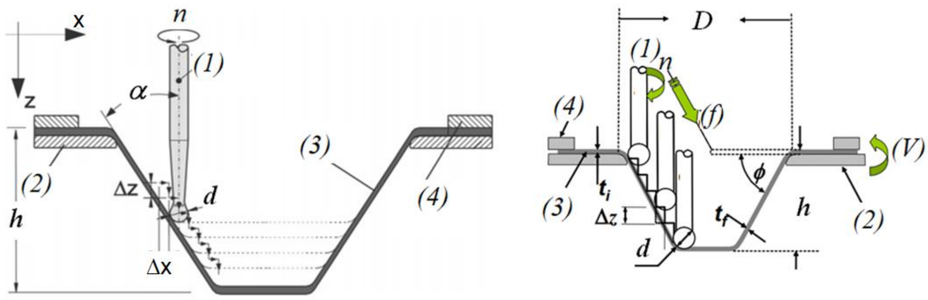


Figure 1. Diagram of ISF processing

Geometric and forming parameters in ISF processing are illustrated in Figures 1 [3], [4]. Before forming, the plate blank (3) is placed on the backing plate (2) and clamped by clamps (4). During the forming process, the tool (1) moves downwards along the z-axis with a step *Δz* to create a plastic deformation process. At the same time, the deformation tool performs motion *V* according to the contour to be deformed until the end of the surface profile to be formed. At the end of a deformation stroke with depth Δz as above, the tool performs a horizontal movement towards the center of the workpiece by an amount Δx and then continues to deepen plastic deformation by an additional amount of Δz. This plastic deformation process is carried out continuously until the depth to be formed h is exhausted. Summarizing the two motions Δx and Δz to get the tool advance f. Note that, during ISF processing, the plastic deformation tool can either rotate around its axis (with a rotation speed n) or not rotate at all.

Unlike the spinning method which is usually only used to form axially symmetrical products, the ISF process has a more diverse product range and more complex profiles. In addition, because the contact area between the tool and the workpiece when deforming by ISF process is quite small [3], the force required for plastic deformation in the ISF process is much smaller comparing with the compared with traditional cold drawing sheet or embossing process. Therefore, the ISF method has many application prospects to replace the traditional cold drawing sheet, such as in the production technology of car panel products [5], [6], [7], [8]. Besides, this process is also used in other fields, such as manufacturing products in the field of rapid prototyping ... [7], [9]. Figure 2 shows some typical products formed using ISF process.

Figure 2. Typical products formed by ISF process

The outstanding feature of the ISF process is that it is possible to use a variety of machining machines, such as conventional or CNC lathes [10], conventional or CNC milling machines [5], [11], [12] or specialized machines [13], or industrial robots [5]. Besides, a number of research groups have designed and manufactured mini CNC machines to save investment costs as well as be proactive in terms of structure and technology [5], [14], [15].

This paper presents some results of designing and manufacturing a mini CNC machine and deploying the plastic deformation test of Al 5052 aluminum alloy sheet to evaluate the stability of the machine. This design and manufacturing result will help the team continue to conduct research to gradually apply ISF method to production life.

II. DESIGN MINI CNC APPLYING TO ISF PROCESS

2.1. Determine forces deformation

Applying the model to determine the maximum deformation force at the end of the forming process, according to Allwood et al. [15], the vertical force F_z and the horizontal force F_y (see Figure 3) are determined as follows:

$$F_z = \pi \times r \times t \times \sigma_y \times \sin\alpha \quad (1)$$

$$F_y = r \times t \times \sigma_y \times (\sin\alpha + 1 - \cos\alpha) \quad (2)$$

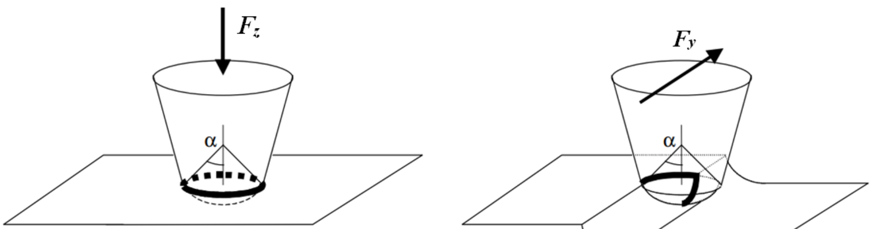


Figure 3. the model to determine the maximum deformation at the end of ISF process

Selected billets for forming are deformed aluminum alloys or low-carbon steel plates in annealed state, these materials have yield strength σ_y < 350MPa. The maximum thickness limit for forming is $t_i \leq$ 1.0mm. Assume that the deformation process will be done with the largest wall angle $\phi = 2\alpha = 60°$. The plastic deformation tool is a high-speed steel with a spherical tip, maximum diameter d = 12mm (i.e. r = 6.0mm). Applying expression (2), the maximum vertical force $F_{z\max}$ can be determined as:

$$F_{z\max} = 3.14 \times 6 \times 1.0 \times 350 \times \sin 30° \approx 3300N = 3.3kN \quad (3)$$

Similar to F_{zmax}, using expression (2) to determine the maximum force acting on the horizontal F_{ymax} as follows:

$$F_{y\max} = 6 \times 1.0 \times 350 \times (\sin 30° + 1 - c\text{os}30°) \approx 0.55\,\text{kN} \quad (4)$$

2.2. Choosing the spindle

Spindle of the CNC machine is responsible for clamping the tool and creating rotation around the axis to reduce contact friction during the forming process. The spindle speed n must be controllable in order to diversify the application of the machine when finished. In this work, the research team selected a commercial Spindle GDZ93X82-2.2 of THD Company (see Figure 4), with a capacity of 2.2-3.7kW.

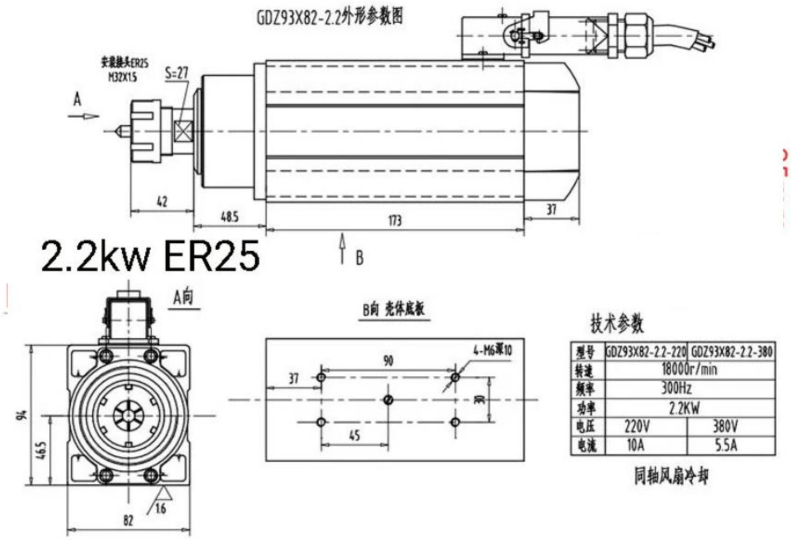


Figure 4. Dimensional parameters of the spindle GDZ93X82-2.2

2.3. Designing the drive system for 3 axes of mini CNC

Design of the CNC machine table drive system moving in the x horizontal direction: The drive system of the table, as shown in Figure 5, includes a ball screw (diameter d = 15mm; screw pitch p = 10mm) driven by a hybrid servo motor with 12N.m torque. The entire table can be moved horizontally on two ball sliding rails.

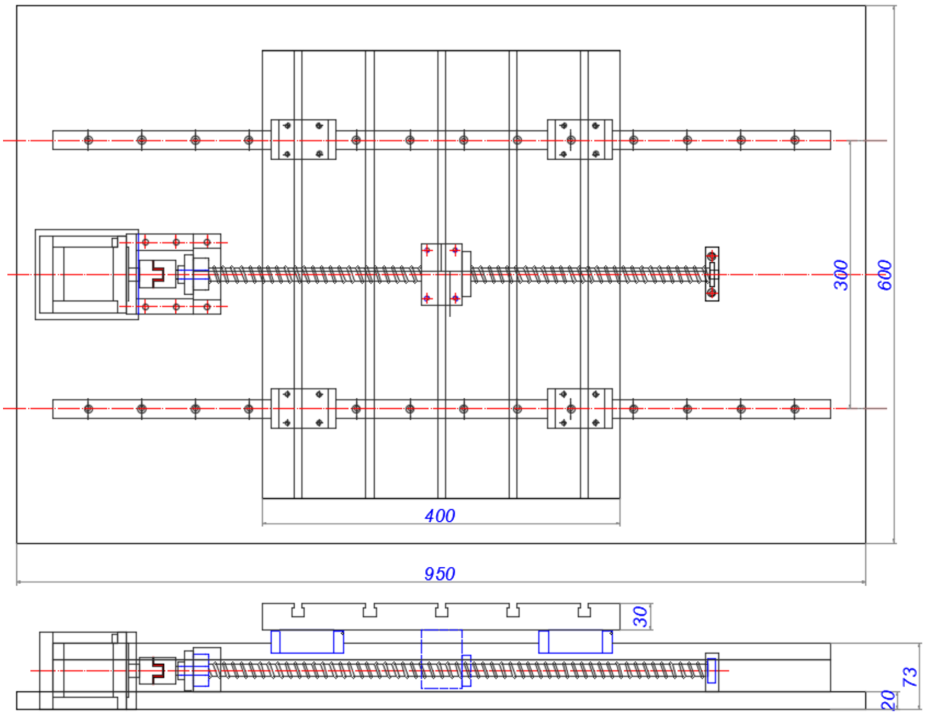


Figure 5. Diagram design of drive system of table machine (moving in x horizontal direction)

From the diagram design, it can be seen that drive motor is affected by the force component F_{zmax} through the friction in the ball rail system and the ball screw-nut, and at the same time is under the effect of the horizontal force F_{ymax} (in the most unfavorable conditions). Select the coefficient of friction in the ball rail system to be 0.01; the maximum horizontal force in the most unfavorable conditions is F_{ymax} = 0.55kN = 550N; then, the ball screw-nut is subjected to the following total load:

$$F_{sx} = F_{zmax} \times 0.01 + F_{ymax} = 3330N \times 0.01 + 550N = 583.3N$$

Compared with the static load capacity (C_0 = 24010N) and dynamic load capacity (C_a = 11030N) of the ball nut, it can be seen that the selected ball screw-nut transmission fully meets the working requirements.

$$T_{sx} = F_{sx} \times d_{mid} \times \tan(\lambda+\varphi_t)/(2 \times \eta)$$

Where: $F_{sx} = 583.3N$; $d_{mid} \approx 15mm = 0.015m$; $\lambda = \arctan(p/\pi d_{mid}) = 11.98°$; $\varphi_t = 2.5°$; $\eta = 0.99$. Substituting in the above expression we have:

$$T_{sx} = 583.3N \times 0.015m \times \tan(11.98° + 2.5°)/(2 \times 0.99) = 1.14N.m$$

To drive ball screw of x direction, Leadshine hybrid servo electric motor (code 86CME120-1000) with maximum torque of 12N.m was chosen. Compared with the required torque when working (T_{sx} = 1.14N.m), it can be seen that this motor completely meets the requirements.

Design of spindle drive system moving in z vertical direction: Similar to table drive system, spindle drive system in *z* vertical direction includes one ball screw-nut (diameter d = 15mm; screw pitch p = 10mm) driven by a Leadshine hybrid servo motor (code 86CME120-1000). The motor has a maximum torque of 12N.m. The entire spindle and tool can be moved vertical along two rails (see Figure 6).

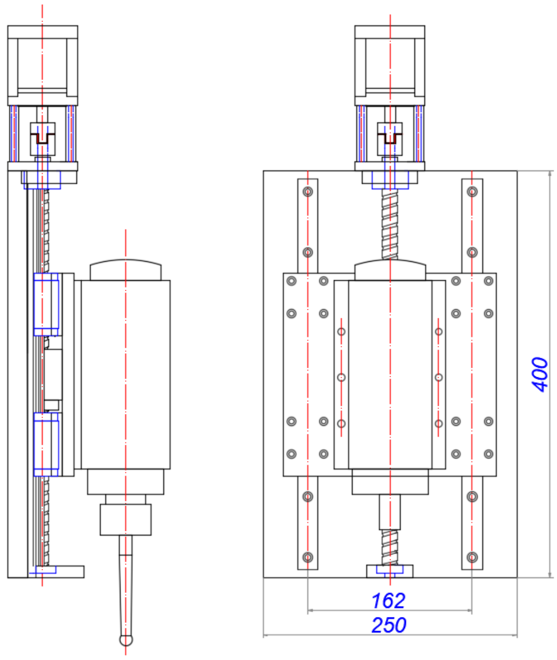


Figure 6. Diagram drive system of spindle of machine (moving in z vertical direction)

During the working process, the spindle and tool will move from top to bottom or vice versa, as shown in Figure 6. To implement the forming process, the driving motor must overcome the force F_{zmax} and the friction force of the system due to the force component F_{zmax} induced on the ball screw-nut and the force F_{ymax} induced on the ball slide. Assuming the coefficient of friction in the ball slide is μ = 0.01, the drive efficiency of the system is 99% (i.e. η = 0.99). Then the torque required for plastic deformation of the workpiece acting on the ball screw-nut is determined by the expression:

$$T_{sz} = F_{sz} \times d_{mid} \times \tan(\lambda+\varphi_t)/(2 \times \eta)$$

Where:

$$F_{sz} = F_{zmax} + F_{ymax} \times 0.01 = 3300 + 550 \times 0.01 = 3305.5\ N$$

Substituting in the above expression we have:

$$T_{sz} = 3305.5N \times 0.015m \times \tan(11.98^\circ + 2.5^\circ)/(2 \times 0.99) = 6.47N.m$$

Obviously, the torque produced by the electric motor (12 N.m) is much larger than the torque required at the most unfavorable operating conditions. In addition, the ball screw-nut transmission is subjected to longitudinal forces F_{sz} = 3305.5N. It can be seen that the load acting on the ball nut (3355N) is much smaller than the load capacity of the selected ball nut with static load (C_0 = 24010N) and dynamic load (C_a = 11030N). Through this, it can be seen that the *z* vertical direction drive system completely meets the working requirements.

Design of spindle drive system moving in y horizontal direction: Similar to the design of machine table drive system with horizontal movement in the *x* direction and the design of spindle drive with a vertical movement in the z direction, spindle drive system in horizontal direction y is selected including one ball screw-nut (screw pitch *p* = 10mm; diameter *d* = 15mm). The screw is driven by a Leadshine hybrid servo motor (code 86CME120-1000) with maximum torque of 12N.m. The whole system can move horizontally on two ball rails as shown in Figure 7.

From the diagram design, it can be seen that the lead screw-ball nut is simultaneously affected by the force component F_{zmax} through the friction in the ball slide rail system, in the ball screw-nut and at the same time under the force of the horizontal force F_{ymax} (in the most unfavorable case). Ignoring the influence of the system's gravity component, it can be seen that when selecting components of the same drive system that drives the machine table to move in the *x* horizontal direction, these components all meet the working requirements.

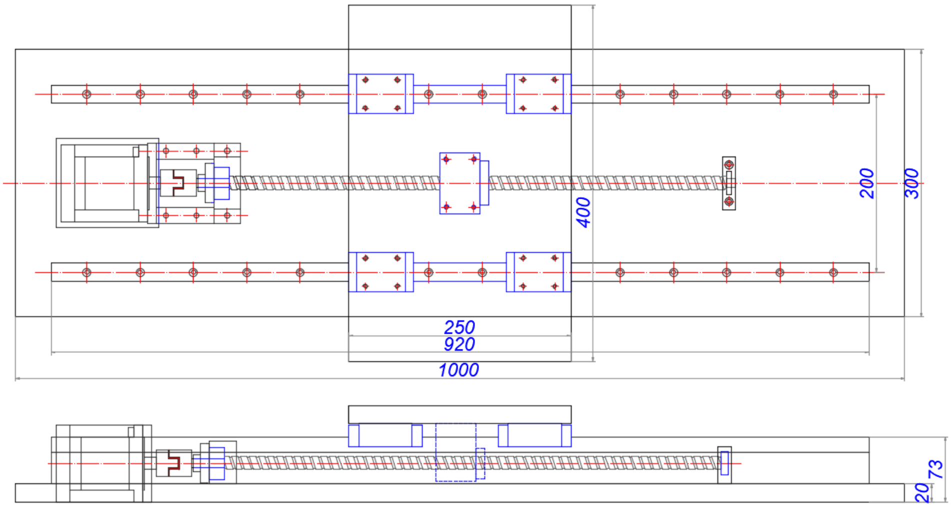


Figure 7. Diagram drive system of spindle of machine (moving in y horizontal direction)

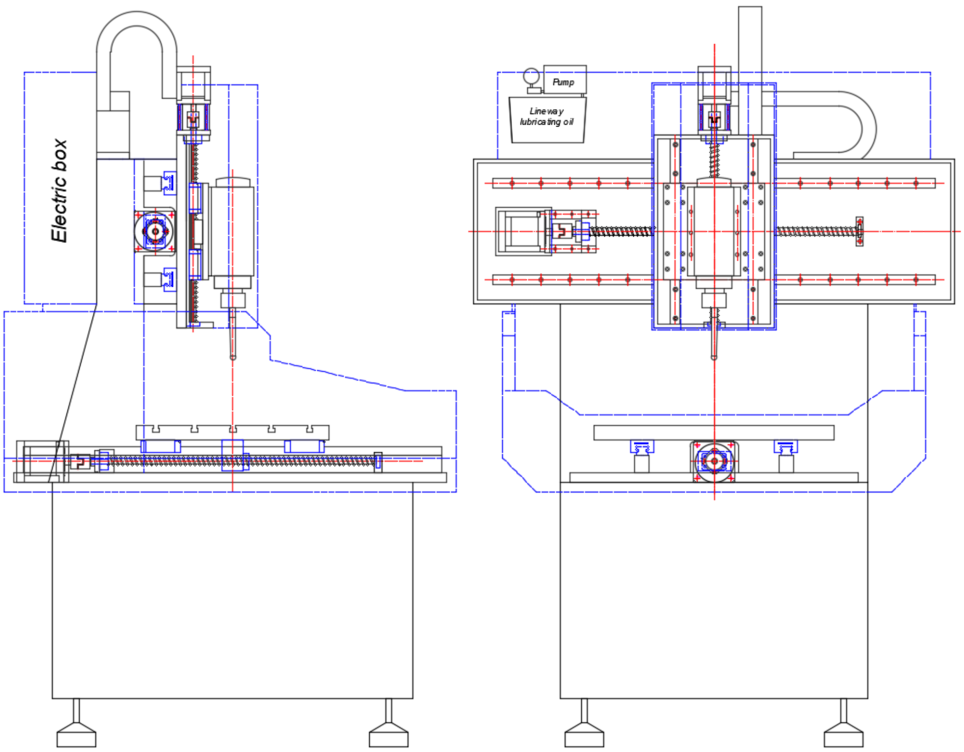


Figure 8. Assembly drawing of mini CNC machine after design

After designing the 3 modules, the overall structure of the mini CNC machine is shown in Figure 8 below. XC809D 3-axis CNC machine controller specialized for use in CNC machining centers was chosen for this machine. This controller adopts 32-bit high-performance microprocessor, using real-time multi-tasking control technology and hardware interpolation technology, full linkage, high-speed small line forwarding algorithm. This controller gives an interpolation accuracy of 0.001mm, the highest machining speed is 30m/min.

III. EVALUATING DESIGN BY EXPERIMENTAL ISF PROCESSES

Selecting experimental initial plates: The initial plates used to evaluate the machine's ability to work is Al 5052 aluminum alloy sheet with t_i = 0.5mm and t_i = 1.0mm thickness, length of 250 mm and 250mm width. The properties of this aluminum alloy are detailed in the Table 1 and Table 2 as followed.

Table 1. Typically chemical of 5052 Aluminum

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other-Each	Other-Total	Al
Al 5052	0.25	0.4	0.10	0.10	2.2-2.8	0.15-0.35	0.10	-	0.05	0.15	Remainder

*Corresponding Author: Ngoc-Tuan La

Table 2. Mechanical properties of Al 5052 aluminum alloy

Parameters	Notation	Value	Unit
Ultimate tensile strength	σ_{uts}	228	MPa
Tensile yield strength	σ_y	193	MPa
Shear strength	τ	138	MPa
Modulus of elasticity	E	70.3	GPa
Shear modulus	G	25.9	GPa

Choosing plastic deformation tool: Selection of materials for plastic deformation tools are high-speed steel, quenched and tempered to achieve a hardness of 60-62 HRC. The tool tip, which is in contact with the plate workpiece, is spherical with a diameter of d = 12 mm. This diameter is also the largest diameter used to design the machine. When forming, the tool is clamped on the collet of the spindle. The dimensions of the plastic deformation tool are as shown in Figure 9.

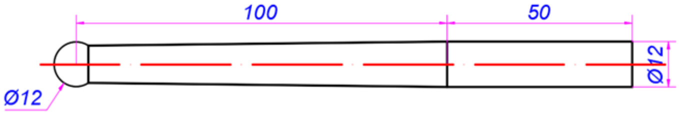


Figure 9. The dimensions of the plastic deformation tool

Designing workpiece clamping mold: The workpiece clamping mold has the structure as shown in Figure 10. The workpiece is clamped onto the mold by nuts as shown in Figure 11.

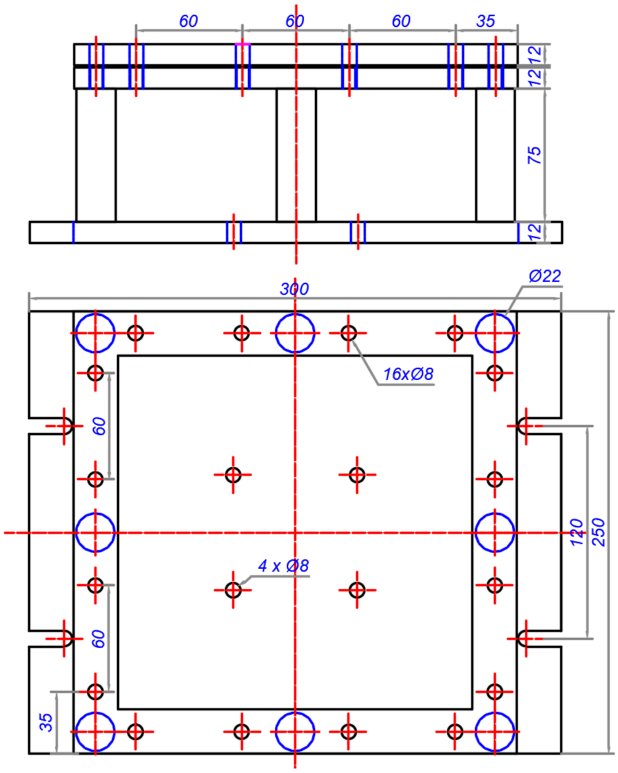


Figure 10. The structure clamping mold

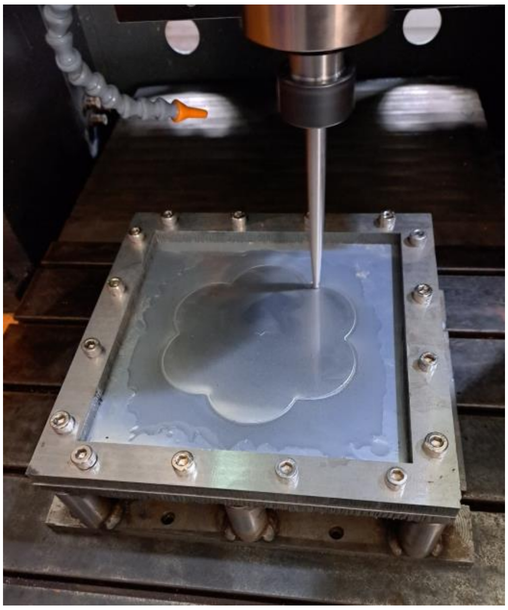


Figure 11. Photo of mold clamping workpiece

Selecting the deformation condition: To test the machine design results, in this study, the plastic deformation tool advancement trajectory is selected as shown in the Figure 12. During testing, we programmed with step Δz = 0.5mm for all runs. The results show that the product is shaped according to the design profile with the error of shape and size to meet the requirements, as shown in Figure 11 and Figure 13. Operation results show that the design machine can move in all 3 directions x, y, z. The interpolation algorithm of the controller works to guarantee the processing of complex or simple profiles. The machine can process products according to design requirements with small errors.

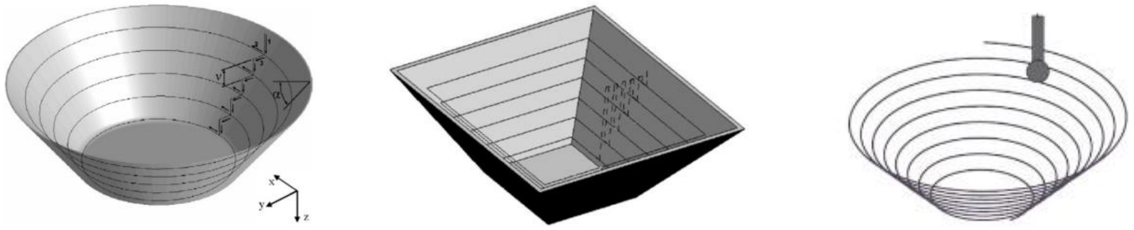
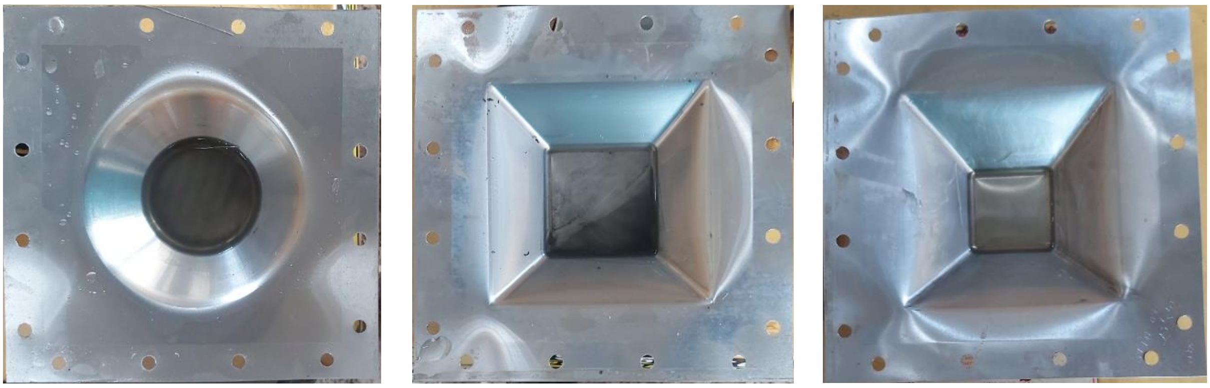


Figure 12. The plastic deformation tool paths



Truncated cone shape *Truncated prismatic profile* *Truncated prismatic profile*

Figure 13. Product photos after ISF processing

IV. CONCLUSION

On the basis of determining the deformation force components at the most unfavorable conditions, a mini CNC machines for ISF processing research was designed and manufactured. Operation results show that the mini CNC machine can move in all 3 directions x, y, z to create simple or complex shapes. The interpolation algorithm of the controller works to guarantee the processing of complex or simple profiles. The mini CNC machine can process products according to design requirements with small errors. This mini CNC machines can serve the implementation of ISF processing research or expand the application for other cutting and processing technologies, such as milling, drilling....

REFERENCES

[1]. Gallego-Juarez, J. and K.F. Graff, Power Ultrasonics: Applications of High-Intensity Ultrasound. 2014: Woodhead Publishing.

[2]. Edward, L., Apparatus and process for incremental dieless forming. Patent: US3342051, 1967.

[3]. Gatea, S., H. Ou, and G. McCartney, Review on the influence of process parameters in incremental sheet forming. The International Journal of Advanced Manufacturing Technology, 2016. **87**(1-4): p. 479-499.

[4]. Ham, M. and J. Jeswiet, Single Point Incremental Forming and the Forming Criteria for AA3003. Cirp Annals-manufacturing Technology - CIRP ANN-MANUF TECHNOL, 2006. **55**: p. 241-244.

[5]. Li, Y., et al., A review on the recent development of incremental sheet-forming process. The International Journal of Advanced Manufacturing Technology, 2017. **92**(5-8): p. 2439-2462.

[6]. Rosenthal, S., et al., Lightweight in Automotive Components by Forming Technology. Automotive Innovation, 2020. **3**(3): p. 195-209.

[7]. Koh, K.H., J.-G. Kang, and J.-Y. Jung, The Analysis of Forming Forces in Single Point Incremental Forming. MATEC Web of Conferences, 2016. **81**: p. 05004.

[8]. Hirt, G., J. Ames, and M. Bambach, A New Forming Strategy to Realise Parts Designed for Deep-drawing by Incremental CNC Sheet Forming. steel research international, 2005. **76**(2-3): p. 160-166.

[9]. Afonso, D., et al., Incremental Forming as a Rapid Tooling Process. SpringerBriefs in Applied Sciences and Technology, 2019.

[10]. Ambrogio, G., L. Filice, and F. Gagliardi, Improving industrial suitability of incremental sheet forming process. International Journal of Advanced Manufacturing Technology - INT J ADV MANUF TECHNOL, 2012. **58**.

[11]. Siddiqi, M., et al., Design and Assessment of Rotating Tool for Incremental Sheet Forming. 2016.

[12]. Jeswiet, J., et al., Asymmetric Single Point Incremental Forming of Sheet Metal. CIRP Annals, 2005. **54**(2): p. 88-114.

[13]. Li, Y.L., et al., Experimental Study and Efficient Prediction on Forming Forces in Incremental Sheet Forming. Advanced Materials Research, 2014. **939**: p. 313-321.

[14]. Kumar, Y. and S. Kumar, Design and Development of Single Point Incremental Sheet Forming. 5th International and 26th All India Manufacturing Technology, Design and Research Conference AIMTDR 2014. 2014.

[15]. Allwood, J., N. Houghton, and K. Jackson, The Design of an Incremental Sheet Forming Machine. Advanced Materials Research, 2005. **6-8**: p. 471-478.

*Corresponding Author: Ngoc-Tuan La