A DESIGN OF SPECIALIZED SHEET FORMING MACHINE BY ISF TECHNOLOGY

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ABSTRACT: *This paper presents the design of a machine using for incremental sheet forming (ISF) technology. Mechanical design has differences compared with conventional CNC machine which has enough rigidity to match the high value of axial force when processing by ISF technology. The machine is manufactured successfully and operates stably when forming steel sheet of 210mm square and thickness of 1.5mm. It shows that the control and mechanical design presented shows appropriate and capable of manufacturing a machine with larger machining size to use for the actual sheet products in industries*.

Keywords: *SPIF, ISF, Die-less NC forming machine, Amino sheet forming machine,...*

1. INTRODUCTION

In recent years, rapid prototyping methods have developed quickly. These methods are better at accuracy, which is accompanied by increased ability to create model with more complex shapes while the sample time is shortened. Besides the improvement of traditional rapid prototyping methods, new methods were also developed. Single point incremental forming technology (SPIF) is one of the new methods is referred as a promising technology in this area [1].

In SPIF technology, a spherical tool tip is controlled by a digital control milling machines with a preset program and sheet metal will gradually be deformed. By forming the product by slices and gradually deform at the position of the metal in contact with the sheet, this increases the ability of material deformation the rather than the instantaneous one as in the stamping method [2].

The product using SPIF technology can be made without either molds or complex fixtures. The shape can also be changed easily by vary the CAD model. Therefore, SPIF technology has shortened the time to create models significantly. It also reduces the cost of research and original design quite clear.

Single point incremental forming technology registered in 1967 by Leszak but not included in application until recent years, one of the reasons is the development of CNC machine. When digital controlling technology developed, creating modern CNC machines, SPIF technology as well as that continuous development [3]. But it was quickly realized that the existing CNC machines, which are designed for metal cutting process, still can not fully meet the technological needs of SPIF. The main reason is two different processes of cutting and metal deformation. In the metal cutting process, the x and y-direction force act mainly on cutting tools and it is larger than the z-direction force. For processing, the deformation in SPIF process took place contrary: the z-direction force is the greatest [4].

For this reason, the development of a new device suitable for SPIF method is an existing demand. This device needs to combine the precious controlling of a CNC machine and the stability of the spindle on tool step direction.

2. MECHANICAL DESIGN AND CALCULATION

2.1. The frame of machine

The frame of machine is an important factor to the stability of the device. The traditional spindle structure of a CNC machine is console and the machine table follows the x-y direction. When processing SPIF technology, the console structure of the spindle is not suitable because it decreases the system stability with high value of z-force.

There is another design that spindle is supported by two pillars. They slide follow one direction together with the spindle. The other x-y direction is made by the machine table. This design will promote the ability of spindle bearing on z-direction by avoiding the console structure. However this follows with the inaccuracy because of the spindle movement (Fig.1)

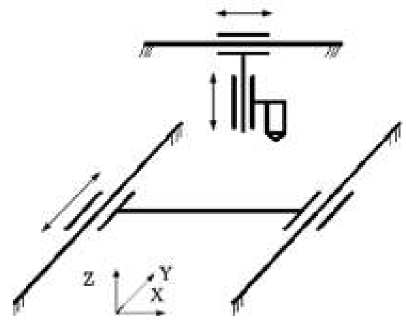

Figure 1. The design of frame movement.

From the previous discussion, the structure with a rigid spindle and machine table follow x-y direction is suitable. This frame includes four pillars support between the up and down part of the machine (Fig.2). Compare with the traditional CNC machine console structure, this design improves the ability of force bearing on z-direction. Moreover, it decreases the dimension error and not prevents the movement on x-y direction.

Figure 2. The design of machine

2.2. Tool mount

Forming tool used for the SPIF technology has a spherical tip. While processing, forming tool has spin and move along the axis x, y, z. Tool mount are designed specifically for machine includes three diameter values most often used as D5, D10 and D15 (Fig.3).

Figure 3. Three forming tools designed specifically for the machine.

Tool is designed to expand the types of processing equipment having different diameters. Besides processing SPIF technology, this tool mount allows clamping various milling tools (Fig.4). It makes the machine more flexible as well as the ability of manufacturing with the two points incremental forming (TPIF) method, which needs a milling template.

Figure 4. The multi-use tool mount.

2.3. Motor type used

The x, y, z axis of the machine is controlled by two servo motors using two-phase current. Motor power of x, y -axis is 400W and 900W for z-axis. Motor of rotation axis uses 3-phase source and is a conventional electric motor with the power of 1.75 kW. In traditional CNC machines, rotating spindle speed is infinitely controlled and regulated by the G-code output from the CAM program. However when working with SPIF technology, it can simplify as spindle speed affects the output parameters of the product (roughness, the angle of largest deformation, the size error...) only when it changes in a wide range with steps of about 100rpm. Thus the structure of spindle motor is driven by the multi-level pulley, providing a wide range of spindle speed from 900 to 4500 rpm.

3. STRESS ANALYSIS

3.1. Modeling the force analysis

A capacity analysis model is proposed to determine the chassis durable and necessary capacity of the engine. Considering the gradual deformation of sheet metal in SPIF technology consists of two main steps. First, forming tool press the sheet metal surface with a step Δz down. Then it moves along x-y axis and creates distortions at that surface elevation in the plate. In the first step, the sheet is deformed into a concave shape with tool diameter. If the tool radius is called the radius R, the elastic limit is σ_y, material thickness is t, the half-angle cone $\alpha_c/2$ is limited by contact between tool and sheet wall. Axial force F_Z is evaluated according to [4] is:

$$F_z = \pi R t \sigma_y \sin(\alpha / 2) \quad (1)$$

And the force F_x on the planar place is:

$$F_x = R t \sigma_y (\sin\alpha / 2 + 1 - \cos\alpha / 2) \quad (2)$$

3.2. The parameter of design problems

The technological requirements for SPIF determine specific values for each parameter of the design problem. As originally defined, machinery characterized SPIF can withstand large axial forces. Such design must ensure F_Z force bearing capacity of the machine with the parameters t plate thickness, tool diameter D and material parameters representative σ_y request of the technology SPIF. Material demand for rapid prototyping on the sheet metal usually is aluminum or mild steel plates with thickness between 1-2mm. Tool diameter can vary from low (less than 5mm) or high (above 15 mm) depend on surface quality requirements. However with diameter over 15mm, the surface quality improve not clearly while the deformation angle α_{max} will drop quickly and will destroy the material. So machine design should meet the following conditions:

Materials: the hardest material is selected for the mild steel, 1.6mm thickness, yield stress σ_y=350N/mm^2. This material is often used to manufacture the car frame.

Withstanding force of forming tool: the tool hardness and tool diameter must be large enough to ensure the ability of SPIF process. The suitable tool diameter values is 5mm, 10mm, 15mm which is most used for appliances. Tool material is high speed steel, hardness 65HRC.

The half-angle cone $\alpha_c/2$ is selected at the highest value, at 40 degree. This is the largest value of the cone angle in all the case of tool diameter D=15mm and sheet thickness t=1.6mm.

Specific parameter values required on the stability capabilities of the z-axis:

Table 1. The required values to determine the z-force

Yield stress σ_y N/mm^2	Sheet metal thickness t (mm)	Tool diameter D (mm)	Cone angle α_c (degree)
350	1.5	15	40

Besides the design requirements on the z axis, other factors relating to the capable of forming technology was also considered such as feed rate F_{xy} *(mm/min)* and the working area of the machine on three axis *x, y* and *z*.

Feed rate F_{xy}: designed to ensure the servo motor can withstand axial force from (1), (2) with parameter value in *table 1* when moving along the *x-y* direction at the feed rate suitable for SPIF of 400 – 3000rpm.

Working area: working area is designed at 225x210x140mm relative with XxYxZ. This value ensures the processing of such products on a small size of CNC machine (Tab.2).

Thus based on the actual needs of technology SPIF and calculations by the formula (1) and (2) determine the maximum force exerted on forming tool and processing characteristics of machine as follows:

Table 2. Process characteristics of the machine

Working area – X, Y travel	**210x210 mm**
Working area - Z travel	140 mm
Hardest material	Mild Steel, thickness of 1.6 mm
Force F_z	8480 N
Force F_{xy}	3682 N
Tool diameter	5-15 mm
Dimension acuracy	0.05 mm

4. DESIGN OF CONTROL SYSTEMS

The control system consists of three clusters corresponding to each driver servo motor of *x, y, z* axis. To ensure the elimination of signal interference when having more than two servo motors, a noise filter system is integrated on the signal transmission. The whole control system is assembled together with the engine driver to ensure a operation synchronization between axes. Driver is controlled from signal output of the CNC control-software through Parallel port of a desktop computer. Mach 3 is software which helps to interpolate and output control signals to the peripherals with G-code input.

Control signal from the Mach 3 software has the pulse number and frequency matches the type of driver and motor used. There are many ways to determine the appropriate number of pulses: via the driver manufacturer's manual or by means of processing test and measurement precision for each level of pulse number and different frequencies. The machines are designed using both methods. After calculations and tests, it showed that the most appropriate value for frequency is 75000 Hz, the number of pulse to the *x-y* axis and *z* axis respectively 3900 and 4300 pulses. With these values to achieve accuracy is 0.05 mm over 210 mm of travel.

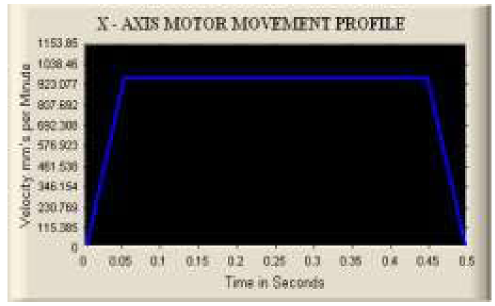

Figure 4. Chart of pulse number x-axis

However, for each number of pulses set to one axis, it has a speed limit of feed rate along that axis. Moreover there is a linear relation between number of pulse and dimension of the model processed. This means when the number of pulse is set higher than 3900, the real model is bigger than the CAD model. For example in Fig.4: when setting parameters on *x*-axis at the pulse number of 3900, the maximum feed rate is limited to 1153 mm/min and the model dimension is accuracy but with the value of 3000, maximum feed rate is 1500 mm/min, coming along with the decreasing of model size. It is possible to overcome this problem by scaling the CAD model. When processing with the other number of pulse which provide the feed rate F_{xy} needed, CAD model is scaled with the rate:

$$r = \frac{3900}{\text{Pulse provide } F_{xy} \text{ needed}} \quad (3)$$

This rate can be filled in the panel “Scale” of Mach 3 software.

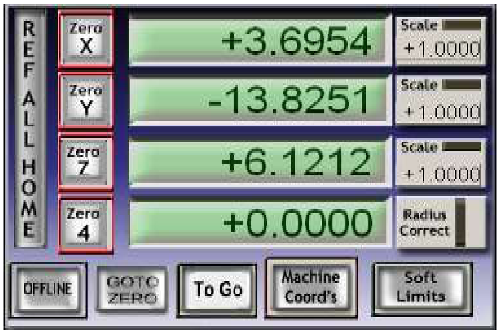

Figure 5. The scale is +1 when using the number of pulse for x-y axis of 3900 and z axis of 4300.

When the machine table moves to the boundary position, the system will have two methods to interrupt the signal from drivers to stop moving of the machine table. The first method is called soft limit which are specified in the Mach 3 software. This method stops the movement of the machine table in case of over-travel. Coordinates on the display screen would stop at the same time and the location is stored without need of re-establish the origin. The second method uses a position sensor to detect if machine table is over-travel and then break the signal down. This second method helps to ensure safety if the soft limit parameters in the Mach 3 software was accidentally changed.

Flowchart presents how the control system works:

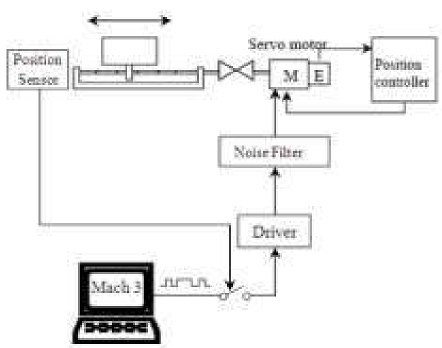

Figure 6. Working of the control system

The machine is also designed with a current relay. It shuts down system and protects electronic equipments in case of an overload.

In addition to monitoring the load on the axis, an indicator of current and voltage are also installed in the system. This helps to monitor and compare the computing power with real power which is influenced by many parameters.

5. MANUFACTURING AND TESTING MACHINE

SPIF machine are designed based on the parameters mentioned in the previous section with the goal of creating a device suitable for processing sheet metal by SPIF technology. Specifically, it can withstand the vertical axis force larger than the traditional CNC milling machine. This design allows SPIF machine process mild-steel sheet with thickness up to 1.6mm and tool diameter of 15mm. Finally, to test the actual ability of the machine with the design parameters, a series of experiments were conducted on the machine. A human model was also tested on material AA-1050H14 to show the milling ability and flexibility of the machine.

There are some model with input parameters tested on the machine:

Table 3. Tested models.

Material	Sheet thickness t (mm)	Spinde speed n (rpm)	Tool diameter D(mm)	Feed rate F_{xy} (mm/min)	Step depth Δz (mm)
A1050 -H14	1	1000	10	400	0.3
	1	1000	10	400	1
	1	1000	10	800	1
	1	1000	10	1000	0.5

Mild steel	1	1000	10	2000	1
	1	1000	10	3000	1
	0.3	1000	10	1500	0.3
	0.5	1000	10	1500	0.3
	0.7	1000	10	1500	0.5

When performing the test sample with parameter in Tab.3, the machine running smoothly with low vibration. This is proved by the surface quality of the product is improved. Dimension error is in the range of design allows of 0.05mm. Geometry of the product is not distorted, it means that the interpolation process is done well and the parameters set in the Mach 3 software is appropriate. Fig.7 shows some of SPIF model tested.

Figure 7. Some of SPIF models tested

In addition to test the flexibility of the machine on milling support for TPIF processing method, a complex geometric model is also conducted. The entire process of CAD/CAM is done similar with the conventional CNC milling machine. G-Code is put into Mach 3 software. The SPIF forming tool can easily be replaced by a milling tool. Then now the milling process are ready. Especially milling processing using the interpolation method in *x, y, z* coordinate at the same time and with high speed (1000mm/min) but the machine is running smoothly and without vibration.

Figure 8. The milling process of a human face.

Through the experiment showed that the design criteria were achieved: the size accuracy with dimension error less than 0.05mm, geometric accuracy and stability without distortion, good surface quality demonstrated high rugged of when working with cutting mode.

Discussion:

The article points out the reasons need to design a mechanical system differs from traditional CNC machine which can process technology SPIF. Great force on z-direction causes a console structure not stable enough.

By comparing many structures, it showed that four-cylindrical structure supporting the spindle and table is a logical structure for SPIF technology. Besides the machine is also design to become a conditional CNC milling machine and therefore can support the two point incremental technology which needs a mill processing. Machine is controlled by Mach 3 software via the driver and the integrated noise reduction. Simple control structure and standardization is also applied to make the machine easy to use even for first-time.

6. CONCLUSIONS

Single point incremental forming is a potential technology. The introduction of machinery and equipment specialized for SPIF process will promote the development of technology.

The machine is manufactured successfully and operates stably when forming steel plates 210mm square and thickness of 1.5mm. It shows that the control and mechanical design presented is appropriate and capable of manufacturing a larger machining size to use for the actual sheet products in industries.

The SPIF machine is designed with the purpose of playing a part on developing of SPIF technology - a promising technology for the future of rapid prototyping industry in Vietnam.

MỘT THIẾT KẾ MÁY TẠO HÌNH TẤM CHUYÊN DÙNG BẰNG CÔNG NGHỆ ISF

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TÓM TẮT: *Bài báo trình bày một thiết kế máy chuyên dùng trong tạo hình tấm bằng công nghệ biến dạng cục bộ liên tục (ISF). Thiết kế cơ khí máy có nhiều khác biệt so với các máy phay CNC thông thường nhằm tạo ra sự cứng vững cần thiết, phù hợp với đặc thù có lực dọc trục rất lớn của quá trình tạo hình tấm bằng công nghệ ISF. Máy được chế tạo thành công và hoạt động ổn định khi tạo hình thép tấm có kích thước vuông 210 mm và dày 1.5 mm cho thấy phương án thiết kế đã trình bày là phù hợp và khả năng chế tạo máy có kích thước lớn hơn để phục vụ nhu cầu tạo hình các sản phẩm tấm thực tế trong công nghiệp.*

Keywords: *SPIF, ISF, Dieless NC forming machine, Amino sheet forming machine,...*

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