METHOD FOR DETERMINING TECHNOLOGICAL FORCES ON MILLING AND INCREMENTAL FORMING PROCESSES USING MACHINE SENSORS

Melania TERA[1] and Radu-Eugen BREAZ[1]

ABSTRACT: Incremental forming technologies have a great potential in manufacturing. It is a well-known fact that there are no technological equipments dedicated for incremental forming process, it being unfolded in most cases on numerical controlled milling centers. These are expensive and complex equipments, the occurrence of resistive technological forces that would surpass the admissible values being able to deteriorate these equipments. The researches unfolded during the realizing of this paper have targeted the elaboration of an experimental-analytical method that would allow the determining of these forces in order to avoid the above-mentioned situation. The paper analyzes the theoretical and experimental of the forces occurred during the manufacturing through milling process and incremental forming.

KEY WORDS: incremental forming process; milling process.

1 INTRODUCTION

The incremental forming process has been widely recognized as a solution with great potential in manufacturing small batches or even single sheet metal parts [Jeswiet, Micari, Oleksik].

A brief description of the incremental forming process principle is presented in Fig. 1. The blank (2) is fixed by mean of the blank holder (3). In order to realize the shape of the sheet metal part, one of the active elements, usually the punch (1) has an axial feed movement on vertical direction, continuous or in steps s (incremental), while the other element, the active plate (4) carries out a plane horizontal movement. The most used technological equipment for incremental forming process is still the CNC (computer numerical control) milling machines, which clearly are not designed for this process [Ceretti].

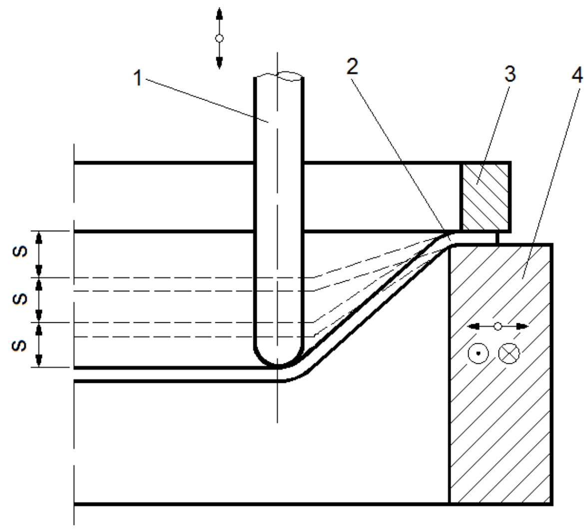

Fig. 1. Process principle of incremental forming

2 TECHNOLOGICAL FORCES ON MILLING PROCESS

In the experimental tests we used vertical machining center Haas CNC MiniMill that have the following characteristics: X axis stroke length, L_x = 406 [mm]; Y axis stroke length, L_y = 305 [mm]; Z axis stroke length, L_z = 254 [mm]; the step of driving screw of axis X, Y, Z, p_{sb} = 4.233 [mm].

The maximum feed force on the X axis, F_{maxX} = 8896 [N]; the maximum feed force on the Y axis, F_{maxY} = 8896 [N]; the maximum feed force on the Z axis, F_{maxZ} = 8896 [N]; cutting speed v_{avmax} = 12.7 [m/min].

Kinematic chains are using permanent magnet motors, Yaskawa SGMGV 09ADA6C having the following characteristics:

- nominal power P_n = 850 [W];
- nominal torque M_n = 5.39 [Nm];
- maximum torque M_{max} = 13.8 [Nm];
- nominal drive speed n_n = 1500 [rot/min];
- maximum drive speed n_{max} = 3000 [rot/min]
- nominal current I_n = 6.9 [A];
- maximum current I_{max} = 17 [A];

[1] "Lucian Blaga" University of Sibiu, Faculty of Engineering, Department of Industrial Machines and Equipments, Victoriei Blvd. 10, 550024 Sibiu, Romania

E-mail: melania.tera@ulbsibiu.ro; octavian.bologa@ulbsibiu.ro.

- torque constant K_m = 0.859 [Nm/A];

- angular acceleration ε_M = 3880 [rad/s^2];

- angular acceleration for the Z axis motor (equipped with brake) ε_{MF} = 3370 [rad/s^2];

- moment of inertia $J_M = 13.9 \bullet 10^{-4}$ [kgm^2];

- moment of inertia for the motor equipped with brake $J_M+J_F = 16 \bullet 10^{-4}$ [kgm^2].

The servomotors on Z axis feed drive are the same type of motor but with the difference that this engine is equipped with brake.

Starting with these data can be written relationships:

$$M_{stX} = \frac{[F_{rtX} + m_{sX}(a + \mu g)]\, p_{sb}}{2\pi\eta_{sb}} + M_{prX} \quad (1)$$

$$M_{stY} = \frac{[F_{rtY} + m_{sY}(a + \mu g)]\, p_{sb}}{2\pi\eta_{sb}} + M_{prY} \quad (2)$$

$$M_{stZ} = \frac{[F_{rtZ} + m_{sZ}(\mathrm{a} - g)]\, p_{sb}}{2\pi\eta_{sb}} + M_{prZ}\,. \quad (3)$$

By expressing the left hand side of relations (1)-(3) based on the maximum feed force each axis we can write:

$$M_{st\max X} = \frac{F_{\max X} \cdot p_{sb}}{2\pi\eta_{sb}} = 6.65 \quad [Nm]. \quad (4)$$

$$M_{st\max Y} = \frac{F_{\max Y} \cdot p_{sb}}{2\pi\eta_{sb}} = 6.65 \quad [Nm]. \quad (5)$$

$$M_{st\max Z} = \frac{F_{\max Z} \cdot p_{sb}}{2\pi\eta_{sb}} = 6.65 \quad [Nm]. \quad (6)$$

where: $M_{stmaxX,Y,Z}$ the maximum values of the static torques.

The efficiency factor for the screw nut assembly is η=0.9.

It is noticeable the fact that these values are in-between the values of the nominal torque (M_n = 5.39 [Nm]) and maximum torque (M_{max} = 13.8 [Nm]) of the motors used for kinematical chains.

To determine experimentally the technological forces occurred during milling we use the following method: it was measure of the static torque using the information displayed by transducers mounted on the machine, during the processing of a blank 16MnCr5with an end mill carbide tool with 4 teeth.

As a cutting condition was as follows: Effective cutting diameter: d = 8 [mm], speed n = 1000 [rot/min], cutting speed v_c=25 [m/min], feed rate f = 300 [mm/min], feed per tooth f_z = 0.08 [mm], axial depth of cut a_p = 2 [mm], radial width of cut a_e = 8 [mm].

In order to make a comparison with the forces during milling process it was used a milling cutting tool with same diameter as the punch used for incremental forming and the same technological parameters.

The only difference is that the blank a rectangular one and the cutting process that must begin outside the blank to the desired cutting depth as shown in Fig. 2, where is presented the blank and the tool before processing on the CNC milling centre HASS MiniMill.

Fig. 3 shows the part after three linear milling during which were taken data from the transducers of the machine on the axis X and axis Y and at a 45^o relative to these axes.

The material has a Brinell Hardness of 207 HB and a breaking strength 714 [N/mm^2].

The processed segments were 20 mm in the direction of X and Y axis, climb mill and conventional mill, and a depth of 2 mm. Also it was made a 45 degree segment. Another step was to read the data from the transducers for an empty run (without cutting).

In order to determine experimentally the forces at the machine's level which appear during the process, the following method was used: the measurement of static moments using the information displayed by the transducers mounted on the machine.

Fig. 2. The blank and the tool on CNC milling machine

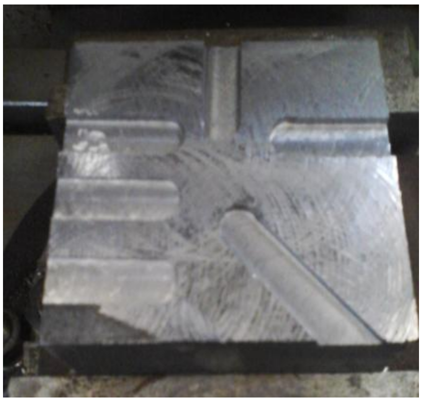

Fig. 3. The blank after milling process

For this, a linear segment with a length of 40 mm was processed along the X axis, on a final depth of 6 mm, in three passes, each pass having a depth of 2 mm on the direction of the Z axis.

The indications of the sensors on the machine (position transducers and torque transducers) were read using following methodology:

- there was realized a video file during the process, using a digital camera;

- the video file was converted from mpeg format into avi format, using a freeware conversion software;

- the video file was separated into frames, each frame being captured at an interval of a second. In order to separate the video file into frames there was used a Matlab routine presented in the annexes.

Fig. 4 presents an example of a frame obtained through the image capture during manufacturing process. The values are in continuing changing but there is enough to extract the information we need.

In Fig. 3 there can be seen the areas from which information of interest is being extracted:

- on the left side of the frame there are displayed information coming from the machine's motion/position transducers, which indicate the instantaneous position of the machine's sleds;

- on the right side of the frame there are displayed information coming from the machine's torque transducers, which indicate the value of the resistant moments, expressed as percentage function of the maximal resistant moment;

- on the rightmost side of the frame there are displayed information related to the time, starting from the starting moment of the process.

Two determinations were made, one for an empty run and one for working under load. The determined values are presented in Table 1.

Where: $m_{Xg,Zg}$ - torque on empty run (percentage of the maximum value of 6.65 [Nm]), $m_{Xs,Zs}$ - torque during processing (percentage of the maximum value of 6.65 [Nm]), $\Delta m_{X,Z}$ - difference between the empty run and load.

Table 1.

	Movement of 20 [mm] towards the feed on X axis	Movement of 20 [mm] towards the feed on X axis	Moveme nt of 20 [mm] towards the feed on X axis
m_{Xg} [%]	9	9	1
m_{Yg} [%]	5	5	13
m_{Xs} [%]	12	12	1
m_{Ys} [%]	5	5	16
Δm_x [%]	3	3	0
Δm_y [%]	0	0	3
ΔM_x [Nm]	0.1995	0.1995	0
ΔM_y [Nm]	0	0	0.1995

If we neglect the effect of dynamic resistance torque, we can express the values of $\Delta M_{X,Y,Z}$ with relations:

$$\Delta M_X = \frac{[F_{rtX} + m_{sX}(a+\mu g)]\,p_{sb}}{2\pi\eta_{sb}} + M_{prX} = = \left(\frac{[m_{sX}(a+\mu g)]\,p_{sb}}{2\pi\eta_{sb}} + M_{prX}\right) = \frac{F_{rtX}\quad p_{sb}}{2\pi\eta_{sb}} \quad . \tag{7}$$

$$\Delta M_Y = \frac{[F_{rtY} + m_{sY}(a+\mu g)]\,p_{sb}}{2\pi\eta_{sb}} + + M_{prY} == \left(\frac{[m_{sY}(a+\mu g)]\,p_{sb}}{2\pi\eta_{sb}} + M_{prY}\right) = = \frac{F_{rtY}\quad p_{sb}}{2\pi\eta_{sb}} \quad . \tag{8}$$

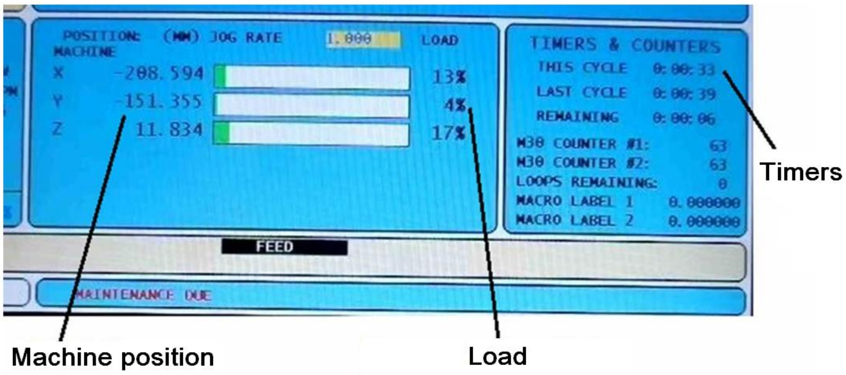

Fig. 4. Frame obtained through the image acquisition process

$$\Delta M_z = \frac{[F_{rtZ} + m_{sZ}(a \quad g)]\, p_{sb}}{2\pi\eta_{sb}} + M_{prZ} = $$
$$= (\frac{[m_{sZ}(a \quad g)]\, p_{sb}}{2\pi\eta_{sb}} + M_{prZ}) = \frac{F_{rtZ} \quad p_{sb}}{2\pi\eta_{sb}}. \quad (9)$$

Relations above allow calculation of forces resistant technological whose values are shown in Table 2.

Table 2.

	Movement of 20 [mm] towards the feed on X axis	Movement of 20 [mm] counter the feed on X axis	Movement of 20 [mm] on Y axis
F_{rt} X [N]	266.49	266.49	0
F_{rt} Y [N]	0	0	266.49

3 TECHNOLOGICAL FORCES OBTAINED THEORETICALLY

We performed this calculation and formulas according to technical documentation. For theoretical determination of machining power we start of the same characteristics of the blank, material and tool. The spindle speed can be calculated as [Vlase]:

$$n = \frac{1000 \cdot v}{\pi \cdot D} = 994.72 \quad [rot/\min]. \qquad (10)$$

where: v = cutting speed [m/min], D = effective cutting diameter .

The feed rate is obtained with the formula (11) with the specification that this is not a productivity formula:

$$v_f = s_d \cdot z \cdot n = 318.31 \quad [mm/\min]. \qquad (11)$$

where: v = spindle speed [rot/min], z = number of cutter of the end milling tool, ans sd = reduced feed per tooth (chip load at the cut).

$$q = s_d \cdot a_e = 0.16 \quad [mm/\min] \qquad (12)$$

where s_d = reduced feed per tooth [mm], and a_e = radial width of cut [mm].

Metal removal rate is presented in (13) [cm^3/min].

$$Q = v_f q = 318.31 \quad 0.16 = 50.929 \quad [cm^3/min]. \qquad (13)$$

Tangential cutting force:

$$F_A = \frac{K_p}{\pi \cdot 2^{\mu}(2-\mu)\cos\omega} \cdot z \cdot B^{u_F} \cdot u_z^{y_F} \cdot d^{-Q_F} \cdot t^{x_F} = 251.29 \quad [N]. \qquad (14)$$

where: K_p, μ, u_F, y_F, Q_F, x_F – constants, z - number of inserts/cutter, B - width of cut [mm], uz - feed per tooth [mm], d - effective cutting diameter [mm], ω - contact angle between the cutting edge and material.

It can be noticed quite a similarity between the experimentally determined value F_{rtX} = 266.49 [N] and the theoretical value calculated above F_A = 251.29 [N].

4 TECHNOLOGICAL FORCES ON INCREMENTAL FORMING PROCESSES

In order to determine experimentally the forces at the machine's level which appear during the incremental forming process, the method presented below was used: the measurement of the technological force on each movement axis using a dynamometric table and a data acquisition system Fig 5. There was used an internal data acquisition device Keitley Metrabyte KPCI 3018, connected by means of a PCI interface, with a maximum sampling frequency of 333 kHz.

On the incremental process we use the same strategy as for milling. So the processed segments were 20 mm in the direction of X and Y axis, in the sense and the counter the feed, and a depth of 2 mm. Also it was made a 45 degree segment are presented in Fig. 6. The step for the incremental forming was also equivalent with the milling depth and equal to 2 [mm].

In Fig. 7 is presented the technological force obtained by means of the data acquisition system. It can be noticed that also through this method the value for technological force is the same. Consequently, using these methods one can estimate the forces appearing during incremental forming.

Fig. 5. The data acquisition system

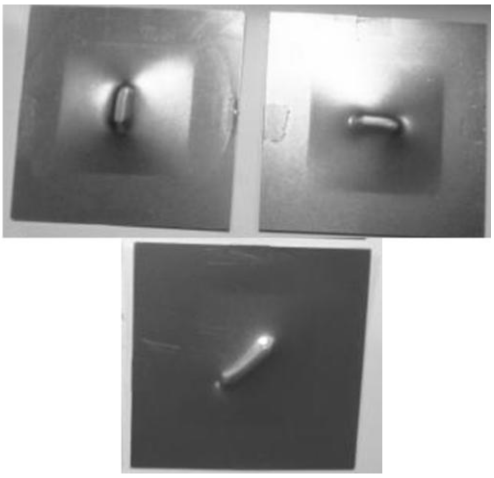

Fig. 6. The parts obtained through incremental forming

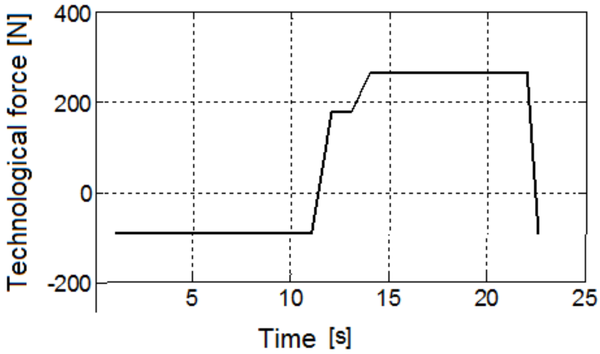

Fig. 7. Technological farce obtain during incremental

5 SUMMARY

The researches unfolded during the realizing of this paper have targeted the elaboration of an experimental-analytical method that would allow the determining of the technological forces in order to avoid damage the CNC milling machine.

First of all the paper presents the determination technological forces obtained during the milling process.

The next step presents the technological forces obtained theoretically.

Finally technological forces on incremental forming processes were determined.

A method was elaborated that allows the determination the technological resistant forces that use only the equipment from the machine.

Following the comparison of the theoretical and experimental results we can validate the experimental-analytical method.

This method can provide a secure use of CNC milling machines in case incremental forming process and also provides a fast way of determination the forces during milling.

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