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USING A CNC MILLING MACHINE FOR INCREMENTAL FORMING

Melania TERA[1,*], Radu BREAZ[2], Octavian BOLOGA[3], Gabriel RACZ[4]

[1)] Assist. Prof., PhD, Industrial Machines and Equipments Department, Faculty of Engineering, "Lucian Blaga" University of Sibiu, Romania
[2)] Prof., PhD, Industrial Machines and Equipments Department, Faculty of Engineering, "Lucian Blaga" University of Sibiu, Romania
[3)] Prof., PhD, Industrial Machines and Equipments Department, Faculty of Engineering, "Lucian Blaga" University of Sibiu, Romania
[4)] Prof., PhD, Industrial Machines and Equipments Department, Faculty of Engineering, "Lucian Blaga" University of Sibiu, Romania

Abstract: *The Asymmetric single point incremental forming (ASPIF) is a manufacturing technology with a high degree of novelty which has been widely recognized as a solution with great potential in manufacturing small batches or even single sheet metal parts. Machines for this specifically process are hardly are almost inexistent for that reason some solutions would be using CNC machines or industrial robots. The technological equipment used for the incremental forming is the CNC cutting milling machine-tools. The control system of the CNC equipment is tuned according the accuracy domain of the milling process, which lies within micrometers range. The control parameters are chosen in order to minimize the positioning errors and to deal with predictable and constant forces. This research presents an approach of re-tuning the control system of the CNC equipment for the requirements of the ASPIF process, a smaller accuracy, lying within millimeters range and unpredictable forces. In the last stage of the paper there was realized a comparative study of the parts' roughness function of the employed incremental forming process.*

Key words: *CNC milling machine, control parameters, incremental forming, roughness, simulation.*

1. INTRODUCTION

New manufacturing technologies are developed fast in order to keep up with the market demands, both in the field of metal cutting and metal forming. Asymmetric single point incremental forming (ASPIF) has been widely recognized as a solution with great potential in manufacturing small batches or even single sheet metal parts [1, 2]. A brief description of the ASPIF 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.

However, in spite of its great potential, the industry is still reluctant to apply the ASPIF process on a large scale [3, 4, and 5]. One of the reasons for that is the lack of a dedicated machine. The ASPIF process is now unfolded on CNC milling machines, robots and Stewart platforms and hexapods [1]. There are also in use some purpose built machines, but most of them are only prototypes [6, 7].

Common CNC milling machines are the most used technological equipment for manufacturing parts by ASPIF. However, there are some drawbacks related with their use. First of all, the technological forces are bigger than in normal cutting (milling) processes and moreover, their values cannot be estimated.

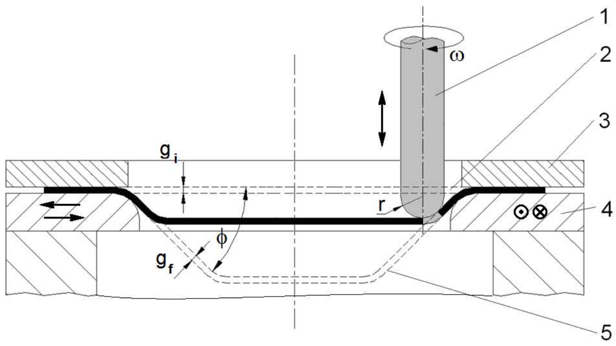


Fig. 1. The ASPIF process.

There are still no reliable relationships for calculating these forces, and the users are concerned about their effect upon the CNC machines. There are some special designed sensors able to measure the forces in the ASPIF process [7, 8] but measurement has to be done on-line and no estimation can be made before manufacturing the part. Usually, the CNC controllers have failsafe systems which protect the machine if the technological forces or toques exceed the maximum allowable values. However, using the machine at its limits is not recommendable, because such regimes could affect, in time, the machine's performance.

The control system of the CNC equipment is tuned according the accuracy domain of the milling process, which lies within micrometers range. The control parameters are chosen in order to minimize the positioning errors and to deal with predictable and constant forces. The

[*] Corresponding author: Faculty of Engineering, 4, Emil Cioran Street, Sibiu, 550025, România,
Tel.: 0269216062 ext.453
Fax: 0269217871
E-mail addresses: *melania.tera@ulbsibiu.ro* (M. Tera);

accuracy domain of the ASPIF process lies within millimeters range, while the technological forces, as stated before, are quite unpredictable.

Also, the main objective while processing a part by ASPIF on a CNC milling machine is to obtain an acceptable roughness.

The elastic springback of the part has a great influence upon the shape and dimensional accuracy, so it is not practically possible to obtain accuracies as higher as the ones obtained in the milling process.

2. TECHNOLOGICAL FORCES AND TORQUES

The feed drives of CNC machine tools control the positions and velocities of machine tool slides in accordance with commands generated by the CNC equipment. Basically, the feed drive is composed of a rotary servomotor as actuation device and a recirculating ball screw as the solution for converting the rotary motion of the servomotor into linear slide motion, its bearing taking up all axial forces of the slide. The servomotor and ball screw drive are usually directly coupled.

The total static torque for a horizontal feed drive within a CNC milling machine may be calculated with the following relationship:

$$M_{st} = \frac{[F_t + m(a + \mu g)]p}{2\pi\, i \eta_{tot}} + M_{pr}, \tag{1}$$

where: M_{st} – total static torque Nm; F_t – technological force, N; m – total mass (machine slide and workpiece), kg; a – linear acceleration, m/s^2; μ – friction coefficient; g – gravity acceleration, m/s^2; p – lead ball-screw step mm; i – transfer ratio between rotational motor and machine slide; η_{tot} – total efficiency of the mechanical transmission between rotational motor and machine slide and M_{pr} – pre-loading torque of the nut of the main ball-screw system.

Also, the total dynamic torque may be calculated as:

$$M_{dt} = J_t \cdot \varepsilon_M, \tag{2}$$

where: M_{dt} – total dynamic torque, Nm; J_t – equivalent moment of inertia of the feed drive, reduced at the rotational motor spindle, kgm^2; ε_M – angular acceleration of the rotational motor.

For a vertical feed drive, one has to take into consideration the following specific characteristics:

- weight of the vertical slide has to be introduced. Normally, at the heavy duty machine tools the weight force is compensated by means of a counterweight which balances the vertical slide mass. However, the small machine tools, as the one which was used for this research are not equipped with the counterweight system;
- effect of the friction force may be neglected, because its value is much smaller compared with the weight of the system;
- rotational motor of the vertical feed drive is equipped with a brake, which has its own moment of inertia, which has to be considered when calculating the equivalent moment of inertia of the feed drive, reduced at the rotational motor spindle.

Consequently, for a vertical feed drive, relation (1) has to be modified, as:

$$M_{st} = \frac{[F_t + m(a \pm g)]p}{2\pi\, i \eta_{tot}} + M_{pr}, \tag{3}$$

where the sign "+" stand for up movements and "–" for down movements.

As experimental layout, a Haas MiniMill vertical machining center was used (Fig. 3). Some characteristics of the machine are presented below:

- the step of the lead ball-screw on X, Y, Z axes, p = 6 mm pitch screw (25.4 / 6 mm), maximum feed force on X, Y, Z axes, $F_{maxX} = F_{maxY} = F_{maxZ}$ = 8 896 N (when these values are reached, all movements stop on every axis). Consequently, these are maximum forces which may appear during the machining process. Greater values of technological forces will lead to a process halt.

The servomotors on each feed drive are Yaskawa SGMGV 09ADA6C permanent magnet synchronous motors, with the following characteristics: nominal power P_n = 850 W; nominal torque M_n = 5.39 Nm; maximum torque M_{max} = 13.8 Nm; angular acceleration for X, Y axes motors ε_M = 3 880 rad/s^2; angular acceleration for the Z axis motor (equipped with brake) ε_{Mb} = 3 370 rad/s^2; moment of inertia $J_M = 13.9 \cdot 10^{-4}$ kgm^2; moment of inertia for the motor equipped with brake $J_M + J_b = 16 \cdot 10^{-4}$ kgm^2.

Taking into consideration the fact that the rotational motors are directly coupled with the lead screws (i = 0), the following relationships regarding the static torques on each axis may be written:

$$M_{stX} = \frac{[F_{tX} + m_X(a + \mu g)]p}{2\pi \eta_s} + M_{prX}, \tag{4}$$

$$M_{stY} = \frac{[F_{tY} + m_Y(a + \mu g)]p}{2\pi \eta_s} + M_{prY}, \tag{5}$$

$$M_{stZ} = \frac{[F_{tZ} + m_Z(a - g)]p}{2\pi \eta_s} + M_{prZ}, \tag{6}$$

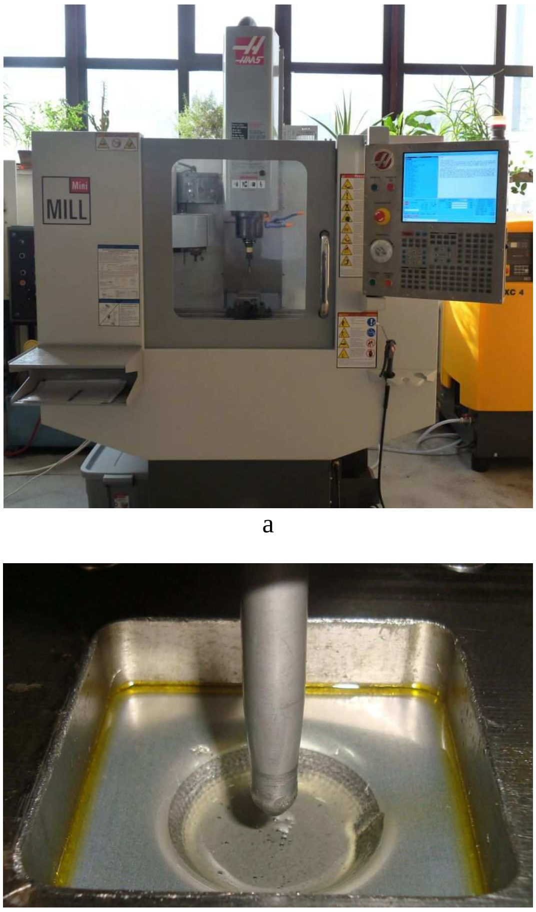
where: η_s – efficiency of the lead ball-screw transmission which is considered 0.9.

Expressing the left part of each of (4)–(6) equation by means of the maximum feed force on X, Y, Z axes, the following relationships may be written:

$$M_{st\max X} = \frac{F_{\max X} \cdot p}{2\pi \eta_{sb}} = \frac{8896 \cdot \frac{25.4}{6} \cdot 10^{-3}}{2 \cdot \pi \cdot 0.9} = 6.66 \text{ Nm}, \tag{7}$$

$$M_{st\max Y} = \frac{F_{\max Y} \cdot p}{2\pi \eta_{sb}} = \frac{8896 \cdot \frac{25.4}{6} \cdot 10^{-3}}{2 \cdot \pi \cdot 0.9} = 6.66 \text{ Nm}, \tag{8}$$

$$M_{st\max Z} = \frac{F_{\max Z} \cdot p}{2\pi \eta_{sb}} = \frac{8896 \cdot \frac{25.4}{6} \cdot 10^{-3}}{2 \cdot \pi \cdot 0.9} = 6.66 \text{ Nm}, \tag{9}$$



a

b

Fig. 3. Experimental layout: *a* – Haas Mini Mill CNC milling machine; *b* – example of processed part.

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

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.

3. SIMULATION

In order to simulate the behavior of a CNC drive a simulation diagram under Matlab and Simulink was build (Fig. 4). The diagram simulates the behavior of a position control system using a permanent magnet synchronous motor as actuating device. The subsystem which simulates the permanent magnet synchronous motor was adapted from the existing diagrams within Matlab and modified according to the Yaskawa SGMGV 09ADA6C motors characteristics.

The position loop which takes into consideration the mechanical transmission and the incremental encoder was introduced by the authors. The simulation diagram was also completed with a kinematic generator, which issues the kinematic inputs (space, velocity and acceleration) using a trapezoidal velocity profile. The kinematic inputs for a linear displacement are presented in Fig. 5.

The encoder is characterized by the encoder gain K_e, which appears in Fig. 4, defined as the number of pulses emitted for one rotation of the lead screw:

$$K_e = \frac{N_{imp}}{2\pi} \text{ pulses/rad}. \qquad (10)$$

According to the machine documentation, K_e = 8192/2π pulses/rad.

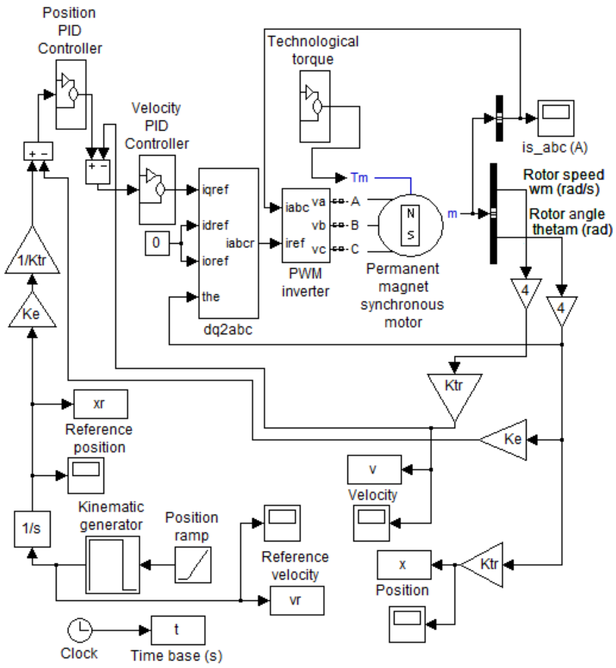


Fig. 4. Simulation diagram.

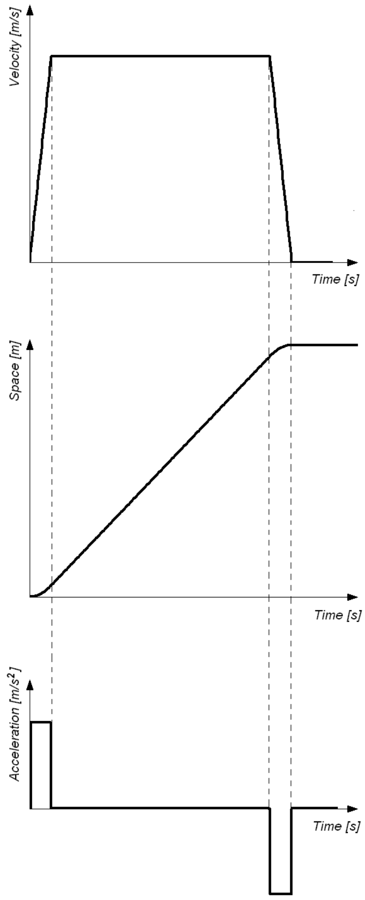


Fig. 5. Kinematic inputs for a linear displacement for a trapezoidal velocity profile.

Another input from Fig. 4 is the mechanical transmission constant, K_{tr}, defined as:

$$K_{tr} = \frac{p \cdot i}{2\pi} \text{ m/rad}. \quad (11)$$

where: p – step of the leadscrew m; i – gear reducer ratio.

For this particular machine tool, p = 0.004233 m and i = 1, so K_{tr} = 0.004233/2π m/rad.

The main controllers of the feed drive are the position and the velocity PID controllers. The tuning parameters of these controllers are presented in Table 1. Each parameter form Table 1 is also available at the operator panel of the CNC milling machine and can be changed by the user. The initial set of values (factory settings) for the control parameters are: K_{PP} = 40, K_{IP} = 64, K_{DP} = 500 and K_{PV} = 60, K_{IV} = 5.6549, K_{DV} = 0.1.

The initial set of control parameters were chosen by the machine manufacturer taken into consideration the main objective of milling process: part dimensional accuracy within micrometers range, which may be also expressed as small positioning errors, also in the micrometers range. The tuning strategy proposed in this paper is oriented to obtain a better quality of the part surface, instead of a small positioning error. In terms of control, it means that the velocity output should oscillate much less than in the initial situation.

The simulation process was unfolded for a linear displacement x = 2 mm, with a feedrate F = 240 mm/min, a linear acceleration a = 2.68 m/s^2 and an angular acceleration ε = 3 370 rad/s^2. The numerical character of the feed drive system was also taken into consideration, by introducing a sampling time of T =10^{-6} s. The PID controllers were introduced as discrete ones, according to the diagram presented in Fig. 6 for the position controller (the same structure was used for the velocity controller).

Table 1

Control parameters

PID Controller	Gains		
	Proportional gain	Integral gain	Derivative gain
Position	K_{PP}	K_{IP}	K_{DP}
Velocity	K_{PV}	K_{IV}	K_{DV}

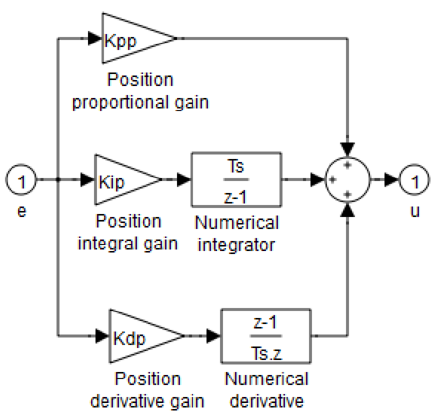


Fig. 6. Discrete position controller.

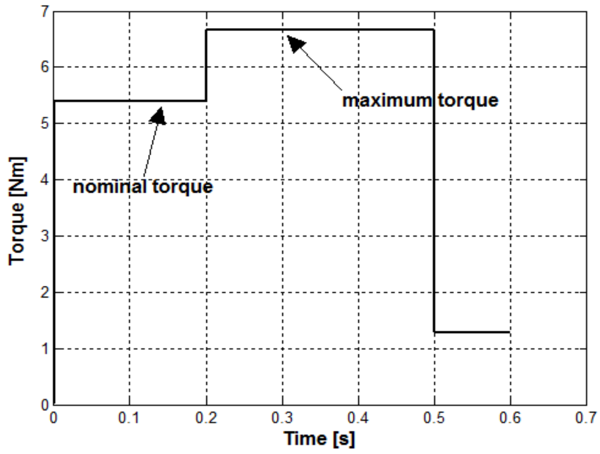


Fig. 7. Simulated technological torque.

The simulated technological torque was introduced according to the diagram presented in Fig. 7: at the beginning of the movement cycle the torque is equal to the nominal value M_n = 5.39 Nm and after 0.2 the value increases to M_{stmax} = 6.66 Nm. As presented above, any value greater that 6.66 Nm will lead to a stop in the movement of the feed drive.

Two sets of simulations were unfolded, the first one with the initial control parameters presented above and the second one with the following parameters: K_{PP} = 4, K_{IP} = 64, K_{DP} = 500 and K_{PV} = 15, K_{IV} = 0.3534, K_{DV} = 0.1. The first set of control parameters characterize a system “tuned for milling” while the second set characterize a system “tuned ASPIF”.

As it can be observed, changes occurred only at K_{PP}, K_{PV} and K_{IV} values. The tuning process was based partially on a trial and error process, partially on some analytic relationships recommended by the machine manufacturer

For the velocity controller, the integral time T_{IV} was introduced, together with the following relationships:

$$T_{IV} = \frac{10^{-3} \cdot 4}{2\pi \cdot K_{PV}}, \quad (12)$$

$$K_{IV} = \frac{K_{PV}}{T_{IV}}. \quad (13)$$

The value K_{PV} = 15 was recommended by the machine manufacturer for low-rigidity systems and K_{IV} was calculated according to equations (12) and (13).

In Fig. 8 the velocity step responses for the two systems are presented. It is here noticeable the fact that the system tuned for milling is faster than the one tuned for ASPIF. However, neither overshoot, nor steady state errors are present for both systems. Fig. 9 shows the simulated positioning errors for both systems. The error for the system tuned for milling is four times smaller than the error for the system tuned for ASPIF.

The velocity outputs are presented in Fig. 10. In order to show more accurate results, only a detail form the outputs are shown. One can notice that the velocity output oscillations are significantly greater fir the system tuned for milling than for the system tuned for ASPIF.

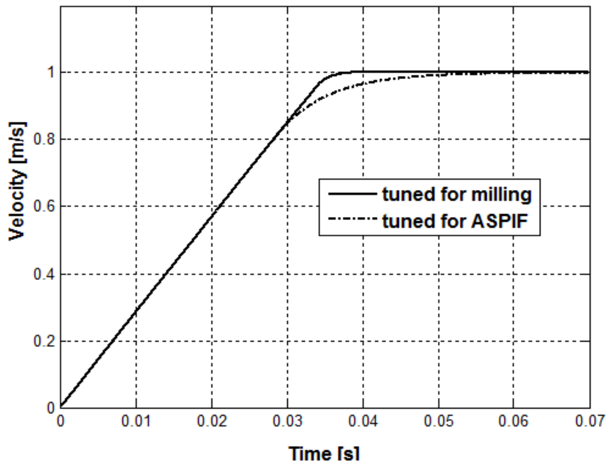


Fig. 8. Simulated step responses.

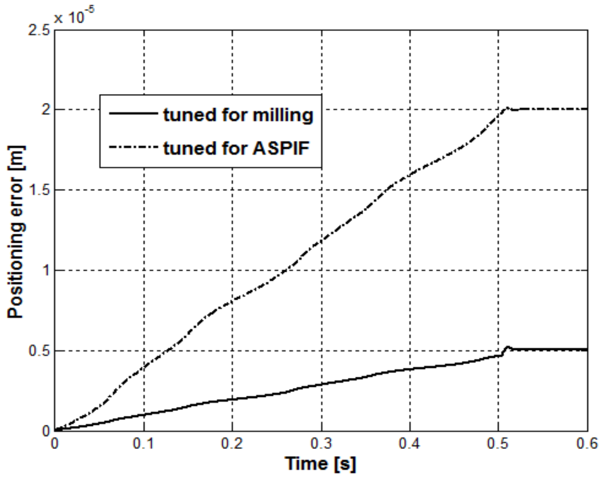


Fig. 9. Simulated positioning errors.

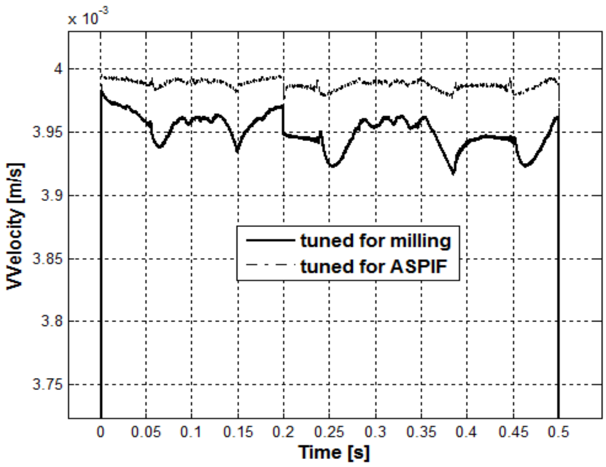


Fig. 10. Simulated velocity outputs (detail).

4. EXPERIMENTS

In order to validate the proposed control strategy a number of simple parts were processed by means of ASPIF process on the Haas MiniMill vertical CNC machining center. The same set of control parameters as the ones used for simulation were used during the machining process. The parameters were altered from the CNC operator panel.

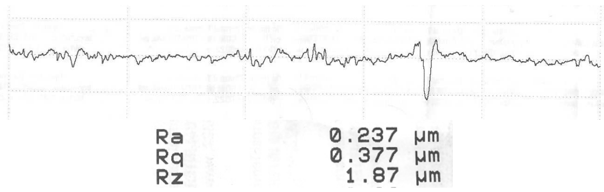


Fig. 11. Measured roughness for the system tuned for ASPIF

Table 2

Tuning for milling and ASPIF

Tuning	R_a µm
Tuned for milling	1.305
	1.164
	1.534
Tuned for ASPIF	0.568
	0.511
	0.445

Table 3

Roughness R_a for different processing methods

The processing methods	Accuracy classes	R_a µm
Rough turning	6 – 7	12.5 – 50
Finish turning	5 – 6	3.2 – 12.5
Rough milling	5 – 7	6.3 – 25
Finish milling	3 – 4	0.8 – 6.3
Grinding	1 – 2	0.1 – 0.8
Superfinishing	1	0.5 – 0.2

The parts were generated as hemispheres and simple circular trajectories in the horizontal *XY* plane, equally spaced between each other on the *Z* axis were used to obtain the shape of the parts.

Further experimental research studied the surface quality of machined parts, with different variants of the process of incremental forming.

The roughness of the parts was measured and one result is presented in Fig. 11. For example, the R_a value for this case was between 1.534 µm and 0.237 µm as shown in Table 2, where the most representative of these are presented. Surface roughness analyze is made using quality assessment criteria R_a.

In order to make a comparison of the surface roughness of parts made by incremental forming with cutting process in Table 3 was presented standard roughness classes R_a for several machining processes.

Among the criteria showed the highest accuracy is assured by roughness R_a, its evolution is shown in Fig. 12, where are presented seven different types of parts obtained through incremental forming.

It is noted that the type pieces hemisphere arithmetic mean deviation R_a irregularities values have values between 0.445 µm and 0.568 µm are equivalent with flat finish milling process.

For parts of type roughness hemisphere best variant obtained processing method which incorporates the complex contour spiral buoyancy completed circle.

Complex parts have values approximately 70% lower roughness R_a, and the obtained values fall within processing by grinding.

The lowest roughness value of 0.237 micrometres was obtained for complex song performed by optimized roughing and finishing.

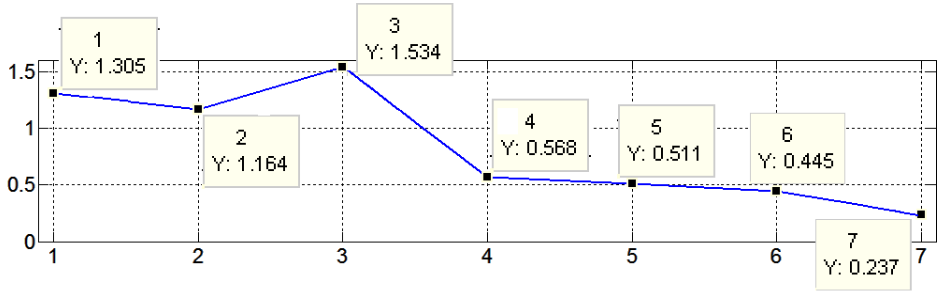


Fig. 12. Arithmetic average deviation of irregularities R_a µm.

5. CONCLUSIONS

The ASPIF process is still a new and promising manufacturing technology, yet it lacks of dedicated technological equipments. CNC milling machine are used for this purpose but the control parameters are chosen for a very different process, milling.

The work presented in this paper proposed some simulation tools, which were used for testing a new control strategy for the CNC feed drives used for the ASPIF process. Instead of focusing on the positioning accuracy, the CNC controller was tuned in order to reduce the oscillations of the velocity output, which consequently lead to a better surface quality of the processed parts.

The simulated control strategy was validated by experiments. The parts processed with the CNC equipment tuned specifically for the ASPIF process had shown a significantly smaller roughness as the parts processed with the initial tuning, specific for the milling process.

In the last stage of the paper there was realized a comparative study of the parts' roughness function of the employed incremental forming process.

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