Comparative study regarding the generation of circular profiles through cutting

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1. Testing the positioning precision using as actuator a performance synchronous permanent magnet motor

On a CNC machine PULLMAX Pullmatic PX- 12, from an OL 37 steel sheet with a thickness of 1.2 mm some pockets were machined both horizontally and vertically, with a nominal distance of 5 mm between them.

A rectangular punch with rounded ends with a length of 55.5 mm and a width of 5 mm was used for stamping.

To verify the accuracy of positioning the distances between the pockets were measured on a Zeiss coordinate measuring machine GageMax Prismo 7 S-ACC manufactured by Carl Zeiss GmbH in Germany. Figure 1 presents some snapshots during the measurements.

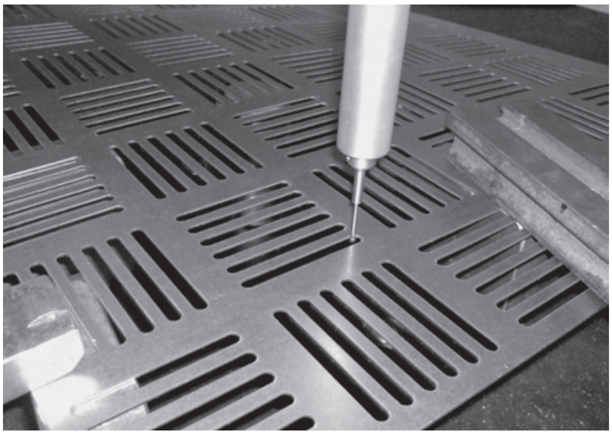

Figure 1. Snapshot during measurement on Prismo 7 S-ACC

For proper interpretation of measurement data, and graphical representation of the measured elements, the machine is equipped with a specialized software system, CALYPSO. This program operates under Microsoft Windows NT and allows both the precise data acquisition of the measurement data and comparison of these data with the original design, introduced in the form of IGES or DXF files.

Unlike other measurement systems, coordinate measuring machine provides the advantage of automated measurement, of an extremely high accuracy and the possibility to simulate, via integrated software packages, different measurement methods.

Prismo 7 S-ACC is a portal type coordinate measuring machine, manufactured by Zeiss Germany.

The representation of the measured area as it appears in the CALYPSO program is shown in Figure 2. To test the accuracy of positioning, the relative positions of the six slots located at a nominal distance of 5 mm apart were measured.

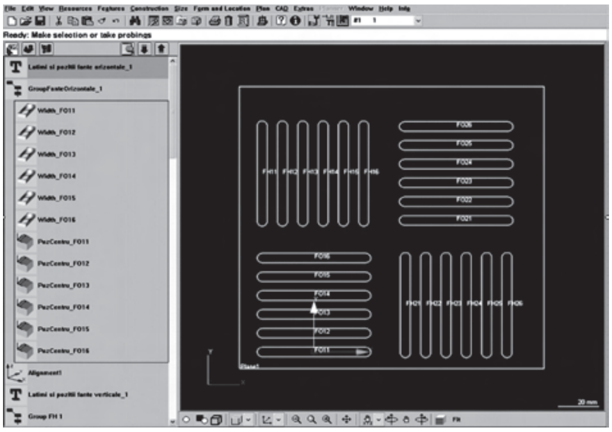

Figure 2. CALYPSO interface

For each set of measurements were obtained five results that we considered to be sufficient to draw the necessary conclusions.

In Table 1 the desired positions and the achieved positions for the horizontal slots are presented. In this case the regulator for the control of the numerical coordinate axis is not tuned. This first set of measurements was made for uncompensated system parameters (which were found the CNC in original condition): $K_{PP} = 1.32$; $K_{ip} = 0.5$; $K_{DP} = 0$.

Table 1. Measurements for uncompensated system parameters

j	x_{Pj}	x^i_{Rj}				
1	10.00	10.16	10.18	10.27	10.31	10.21
2	20.00	19.69	19.76	19.68	19.75	20.06
3	30.00	29.86	29.79	29.72	29.87	29.91
4	40.00	39.86	39.78	39.82	39.84	39.86
5	50.00	49.79	49.81	49.76	49.87	49.78
1	10.00	10.09	10.21	10.18	10.15	10.22
2	20.00	19.68	19.72	19.78	19.80	19.75
3	30.00	29.86	29.82	29.81	29.90	29.79
4	40.00	39.83	39.75	39.82	39.79	39.88
5	50.00	49.90	49.72	49.78	49.85	49.83

Measurements were repeated after the compensation of the numerical axis, with parameters: $K_{PP} = 0.3535$; $K_{ip} = 0$; $K_{DP} = 0.01$ obtained from a MATLAB simulation of the numerical axis model. In Table 2 the required positions and the actual positions for the horizontal slots are presented. In this case the controller is tuned with the above parameters.

Table 2. Measurements for compensated system parameters

j	x_{Pj}	x^i_{Rj}				
1	10.00	10.06	10.08	10.07	10.11	10.01
2	20.00	19.98	19.96	20.03	20.01	19.97
3	30.00	29.96	30.01	29.97	29.98	30.03
4	40.00	40.01	39.98	40.02	39.92	39.89
5	50.00	49.97	50.03	50.02	49.98	49.97
1	10.00	10.03	10.05	10.09	10.05	10.10
2	20.00	19.96	20.05	20.04	19.92	19.95
3	30.00	29.95	29.93	30.02	30.05	29.97
4	40.00	39.92	40.02	40.01	39.95	39.88
5	50.00	49.90	50.01	49.95	50.01	49.96

Based on the measurements above each position deviation, average deviation, wide dispersion, average spreading width, standard deviation was calculated.

Below the relations for calculating these quantities are presented. This data is required for a better tuning of the system.

Deviation Δx^i_j for each position is calculated by the relationship:

$$\Delta x^i_j = x^i_{Rj} - x_{Pj} \quad (1)$$

were x^i_{Rj} represents the real position, x_{Pj} represents the desired position.

Average deviation $\overline{\Delta}x_j$ for each position "j" and each direction is calculated with the formula:

$$\overline{\Delta}x_j = \frac{1}{n}\sum_{i=1}^{n} \Delta x^i_j \quad (2)$$

The spreading width D_j for each position "j" and for each direction is calculated with the relationship:

$$D_j = \max \Delta x^i_j - \min \Delta x^i_j \quad (3)$$

Average spreading width $\overline{D}_j$, separately for each direction of travel is calculated by relations:

$$\begin{cases} \overline{D}_j = (D_1 + D_2)/2, \ j = 1 \\ \overline{D}_j = (D_{j-1} + D_j + D_{j+1})/3, \ 2 \leq j \leq m-1 \\ \overline{D}_j = (D_{m-1} + D_m)/2, \ j = m \end{cases} \quad (4)$$

The standard deviation S_j, separately for each direction of travel is calculated by the relationship:

$$S_j = a_i \times \overline{D}_j \quad 10 \geq i \geq 5 \quad (5)$$

According to norm recalled, $a_5 = 0.4299$. Maximum spreading width, R_j, also called repeatability for each direction of travel is calculated by the relationship:

$$R_j = 6\, S_j \quad (6)$$

Next, a curve is drawn for each average deviation $\overline{\Delta}x_j\uparrow$, $\overline{\Delta}x_j\downarrow$ to verify the accuracy of positioning, using the values obtained with the formulas above. Two curves are drawn or a pair of curves for each direction by joining all the points situated at the distance ± $3S_j$ against the curves $\overline{\Delta}x_j$.

The tolerance M is determined with the relationship:

$$M = \max(\overline{\Delta}x_j + 3S)\uparrow or\downarrow - \min(\overline{\Delta}x_j - 3S)\uparrow or\downarrow \quad (7)$$

Insensitivity, N is determined by the relationship:

$$N = \max(\overline{\Delta}x_j\uparrow - \overline{\Delta}x_j\downarrow) \quad (8)$$

Measurement results show that after compensation, the precision of positioning of the CNC punching machine improves significantly, which validates the assumptions and strategies heavily outlined in the study and in the simulation.

2. The Renishaw QC10 ballbar

Renishaw QC10 ballbar and its software are being used to measure the errors of positioning of a CNC machine in case of circular interpolation mode.

QC10 ball bar is an extremely versatile tool designed for use on a variety of machines. The standard system can be used to test 3-axis CNC machines such as horizontal and vertical machining centers.

The data is captured, stored and analyzed while the machine performs a circular test. This requires the machine to move simultaneously on two linear axes of movement which, combined, generate a circular arc. This is easily programmed on most CNC machines.

A 100 mm ballbar transducer was used for measurements to evaluate the errors in the XY plane of a CNC milling machine with 3 axes.

During the data acquisition session, the transducer moves in clockwise and counterclockwise direction.

In a first phase measurements were made on a CNC milling machine, without adjusting the positioning controller of the axis showed in Figure 3.

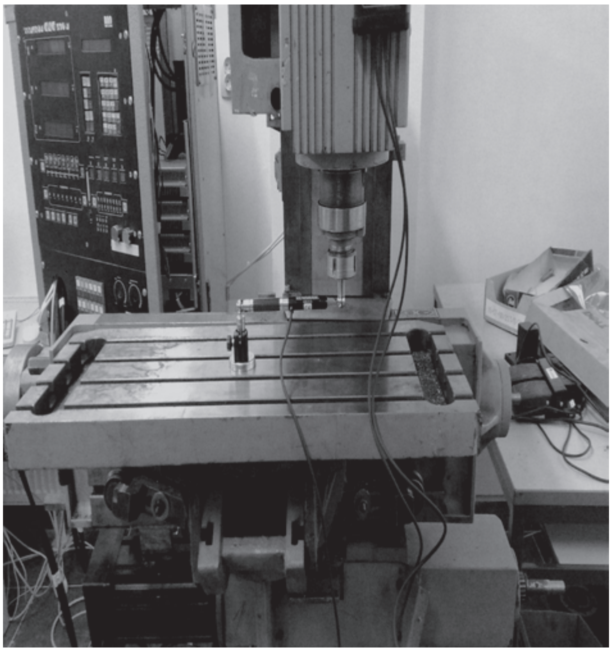

Figure 3. Ballbar QC10 system

Another test was made after adjusting the mechanical structure and after the adjustment of the controller. The controller setups were based on the simulations models realized in MATLAB.

Measurement results indicate a qualitative improvement in performance, which validates the mathematical models and diagrams of the proposed simulation.

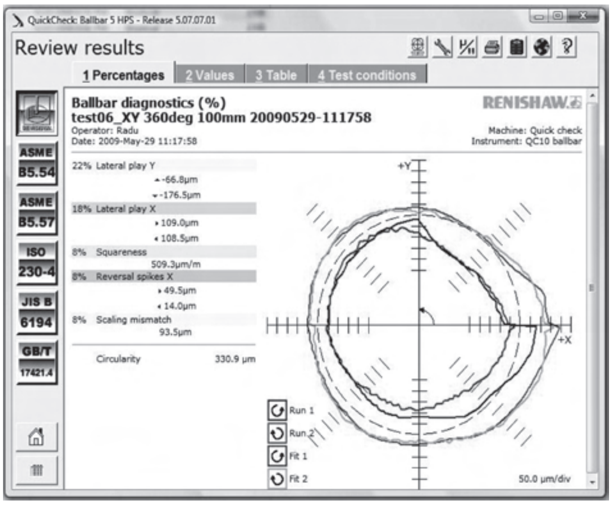

Figure 4. QC10 ball diagram without the NC axis

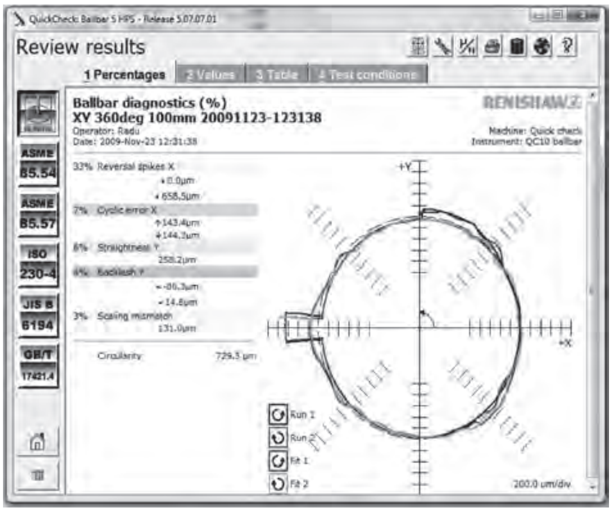

Figure 5. QC10 ball diagram with the NC axis tuned controller

In Figures 4 and 5 are presented the diagrams and the results of the circular interpolation both with and without tuning the positioning controller.

3. Experimental study of the circular profile generation by laser cutting on a CNC machine

Experimental determinations were made regarding precise generation by laser cutting, of circular profiles and the influence of parameters changes of the structure of the CNC machine. Real contour of the machined parts was determined by co-ordinate measuring with ZEISS PRISMO 7 S-ACC, machine.

The main influence factors of the dynamic behavior of motion control systems are:

- Setting parameters of position control system on each axis of movement (represented by the amplification factors K_{PD});
- Speed component on the axis.

Research has shown that differences appear in the accuracy of parts produced according to the type of cutting and the input parameters of the system.

Figure 6 and Figure 7 present the results after measuring the deviations from circularity for experimental generation of a full circle with a radius of 30 mm.

The material used was steel S355JR with thickness of 6 mm, using an amplification factor of the loop position K_{PD} = 38.38, equal on both axes, but with different cutting speeds.

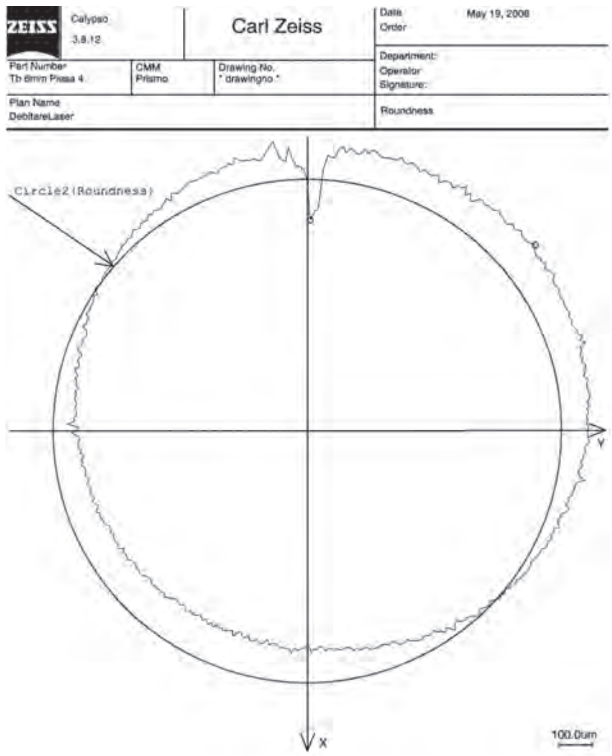

Figure 6. Errors for speed of 1500 mm/min and K_{PD}=38.38

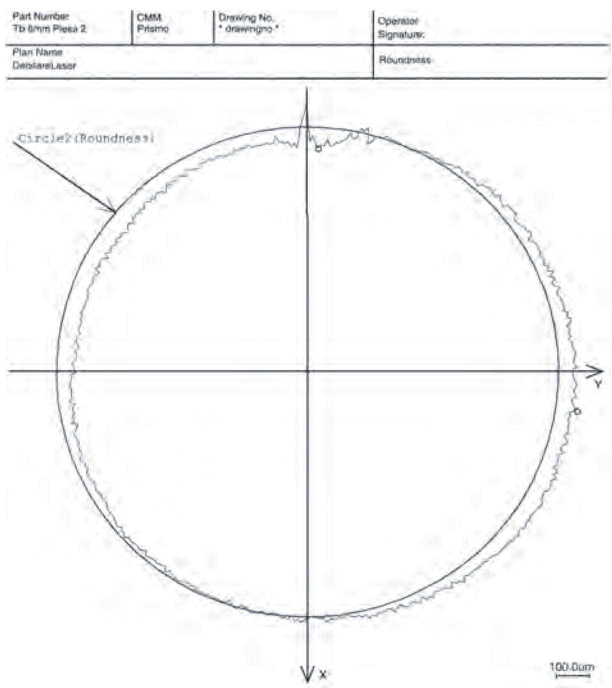

Figure 7. Errors for speed of 800 mm/min and

Figure 8 summarizes experimental generation of a full circle with the loop amplification factor K_{PD} = 19.69, equal on both axes, and a cutting speed of 1500 mm/min.

Figure 9 summarizes experimental generation of a full circle with different loop amplification factor on each axis.

One can see an improvement in correcting deviations from circularity to the previous cases.

Comparing the above figures and the simulations results from MATLAB included in the theoretical research stages one can observe that experimental results confirm the results obtained by simulation.

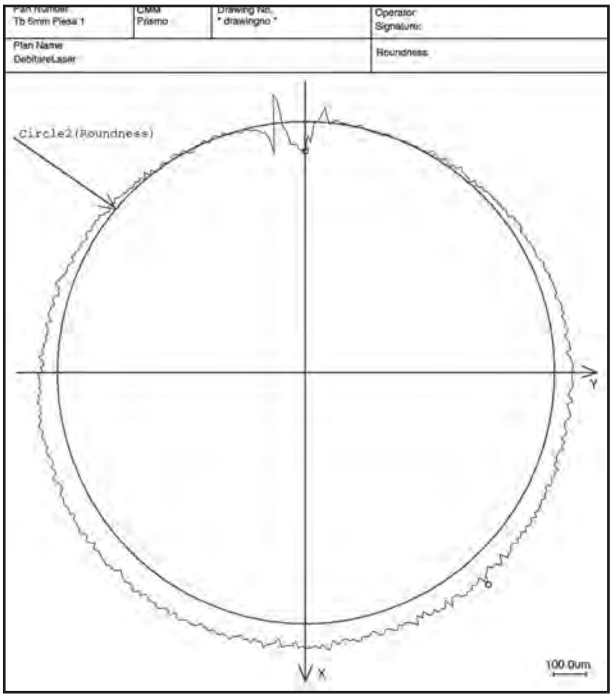

Figure 8. Errors for speed of 1500 mm/min and K_{PD}=19.69

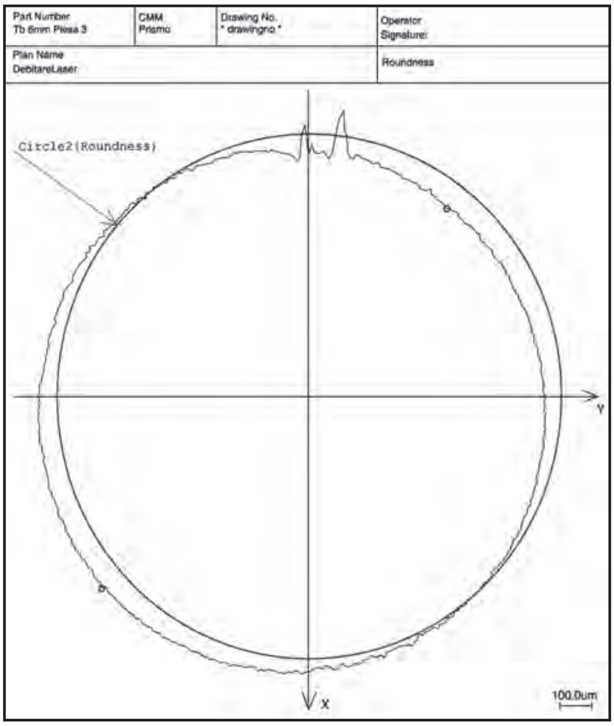

Figure 9. Errors for different KPD on each axis

As a general conclusion one can say that the precision of the machined parts is significantly influenced by the variation of the control system parameters of the numerical axis, as outlined above.

Thus, the use of optimal feed rates, even if it leads to a corresponding roughness of work piece cannot compensate for errors due to the dynamically unadjusted control system. Finding the optimal control parameters for each processing system based on mathematical models and simulation diagrams provide reduced errors generated by circular interpolation, reflected in increasing precision of the machined parts.

4. Experimental study of the generation of a circular profile on a CNC punching machine

To test the behavior of numerical axes under contouring (nibbling), processing was made on a quarter circle trajectories, in different conditions.

As highlighted during the theoretical research and simulations, tuning of the numerical controller's axes for the positioning system also meets the requirements of contouring system. The main factor influencing the precision of the machined part by nibbling is the trajectory speed. To assess the performance of numerical control punching machine under contouring, nibbling of a 90° circle arc was performed with a speed trajectory speed of 10 m/min, with the default settings of the machine. The rhythm in which the punch is hitting the part is set to 300 rates/min.

The values of position and speed controllers parameters (identical X and Y) are: K_{pp} = 1.32; K_{ip} = 0.5; K_{dp} = 0; K_{pv} = 5; K_{iv} = 0; K_{dv} = 0.

The measurement result of the part is presented in Figure 10, using the conditions mentioned above.

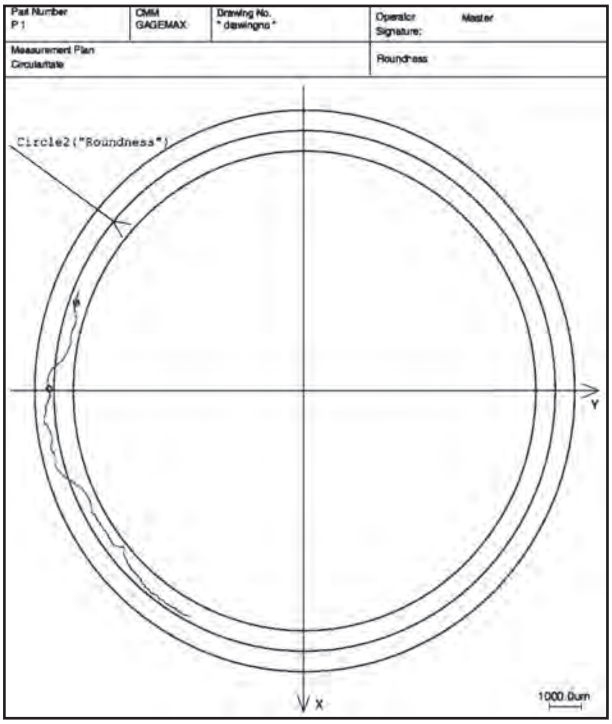

Figure 10. Error measurement of a nibbled part

It may be noted that although the trajectory speed is reduced, errors are relatively high; the maximum circularity deviation is 0.4988 mm.

In the subsequent phase, compensation of the numeric axes system was made by changing the position and speed controller's parameters of the numerical axes, according to the results of theoretical research and simulations, validated by experimental research related to the positioning system.

New values of the control constants are listed below: K_{pp} = 0.3535; K_{ip} = 0; K_{dp} = 0.01; K_{pv} = 5; K_{iv} = 0; K_{dv} = 0.01.

Part processing was done also with a trajectory speed of 10 m/min, ram blows cadence of 300 cd/min and the radius was maintained at 1200 mm.

The measurement result of the part is presented in Figure 11, processed with the new settings.

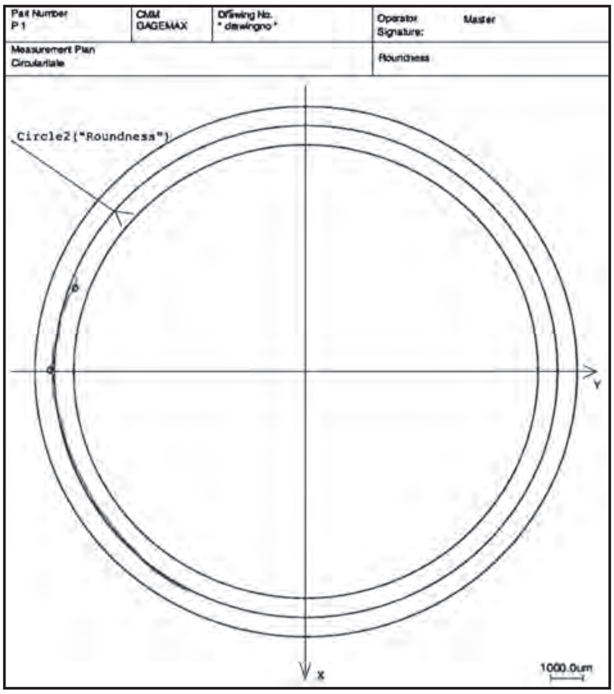

Figure 11. Error measurement of a nibbled part with tuned system parameters

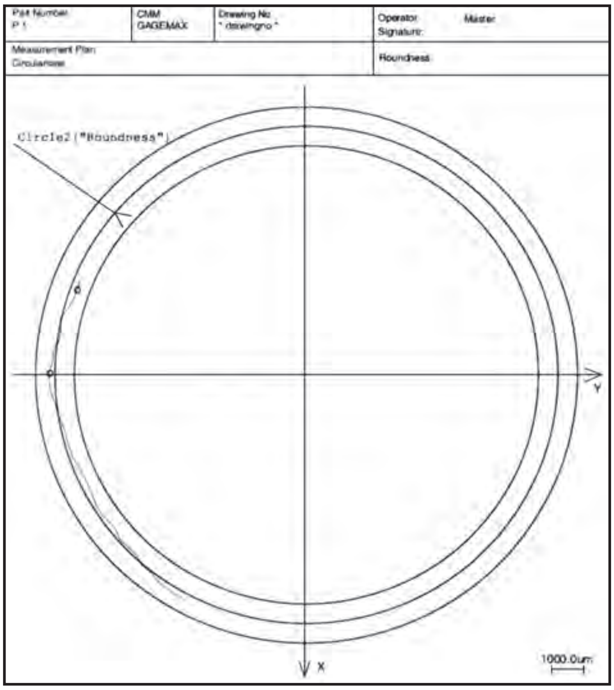

Figure 12. Error measurement of a nibbled part with tuned system parameters and speed of 30 m/min

From the figure one can see that the error values were much lower, the maximum deviation from circularity is in this case is 0.1921 mm.

One can also conclude that this value is very close to the values obtained through simulation. The maximum deviations obtained were: 0.11 mm on X- axis and 0.12 mm on axis Y.

The following two aspects must be taken into consideration:

- For simulation, a resistant torque was considered with a value equal to the nominal torque developed by the electric motor. In reality a lower estimated value is used.

- The reduced trajectory speed of 10 m/min causes that the errors regarding the wear does not affect clearances and contouring accuracy as much as for positioning, where positioning speed was set at the maximum allowed by machine (60 m/min).

Basically, the two aspects mentioned above contribute to the fact that the simulated errors are much closer to reality than those concerning positioning. In that case compared with the influence of errors due to wear of the mechanical parts and the machine the resistance torque was practically negligible.

The measurement results of parts processed in similar conditions is presented in Figure 12, but with trajectory speed of 30 m/min. It is noted that increasing the speed of travel on circular path adversely affect the value of deviation from circularity.

In this case, this deviation has a maximum value of 0.3978 mm.

5. Conclusions

This result confirms that increasing movement speed influences proportionally the size of the deviation from circularity, even if the position and speed regulators are given the appropriate number of axes.

As a general conclusion about the experimental testing measurements of numerical axes CNC punching machines behavior under contouring, one can say that in this case largely confirms these theoretical research results. Thus, it was demonstrated experimentally that for circular interpolation, in addition to numerical constants regulators axis, contouring accuracy is significantly influenced by the speed of on trajectory.

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