Journal of Machine Engineering, Vol. 9, No. 1, 2009

cutting process, correction of feed rate,
radius errors, workpiece,
CNC machine

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THE ANALYSIS OF FEEDRATE CORRECTION INFLUENCE ON CORNER RADIUS ERRORS OF WORKPIECES DURING MILLING

Geometrical accuracy of workpieces manufactured in CNC technology is dependent on many different factors, such as the parameters of a cutting process. The most significant are: cutting velocity v_c and feed rate v_f but also proper cooling and appropriate rigidity of a machine tool. Values of these parameters are dependant on the kind of a workpiece and on the applied tools. Considering shape complexity of a workpiece, dimensional and shape errors can appear, for example deviations of flatness, rectilinearity and radius roundness, etc. To avoid errors connected with geometrical profile, the parameters of machining should be selected in such way to obtain maximal value of quality rating of a product considering its shape and dimension. The aim of this paper is to evaluate the correction of feed rate (v_f) influence on radius errors of a workpiece's corners and to define the relation between technological conditions of cutting process and the actual shape of radius after machining. In theoretical part, the influence of different factors on the accuracy of cutting on CNC machine was included; the main focus was on the accuracy of cuttings the corners with different radii. The practical part consists of corner's radius errors measurements with the usage of coordinate measuring machine and complex analysis of research findings. The findings were presented in the form of diagrams and charts. Because of the fact that the feed rate influences the global time of workpieces' machining, the findings presented in this paper enable the production engineers to choose the optimal value of feed rate during the cutting of corners on CNC machines. It is very important during machining of matrices which construction consists of many corners with given radii that are placed between perpendicular and slant walls.

1. INTRODUCTION

Geometrical accuracy of a workpiece machined on CNC machine tool is the most important factor influencing technological quality of a product. Also the properties of a new-designed surface layer are very important. Reaching high geometrical accuracy is the priority of manufacturing systems but in real conditions it is determined by a number of internal and external factors present during the process of machining [2,11]. Implementation of CNC machines in metal cutting enables to construct new accurate layers which can be compared with those made during the process of grinding but it is impossible to avoid errors which appear during the process of cutting. These errors concern not only the

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condition of manufacturing surface [4,5],[7],[9],[12],[16] but also its shape and dimensions – particularly when we discuss thin-walled elements [17-18]. The estimation of errors is made not only with the usage of mathematical knowledge [3] thanks to which we can consider the conditions of cutting and geometry of cutting elements; we can also use the artificial intelligence [6],[8],[14]. Many scientist, in their works [1],[5,6],[10],[13],[15], base on interactive models to reach a compromise between the efficiency and quality of a workpiece manufactured on CNC machines. However, the results of experimental verification are often far from the results obtained on the basis of a model. It is the effect of complexity of the physicochemical process of cutting and the interaction between factors influencing the accuracy of shape and dimensions.

The condition of the surface after machining and dimensional accuracy is not very difficult when we consider a simple outline. However, with more complex outline like curvilinear contours, the maintenance of desirable accuracy of shape can be problematic [8],[15],[17,18]. These problems arise from the accuracy of the machines (for example the perpendicularity of numerically-controlled axis decides how accurate are the representations of circle, arch, etc.), the rigidity of a machine and a tool, the condition a tool itself as well as the technological conditions of a cutting process [8-7],[10]. Shape errors of workpieces, for example deviations of flatness, rectilinearity and radius roundness, etc. are dependent on the degree of geometrical shape complexity. To avoid errors connected with geometrical profile, the parameters of machining should be selected in such way to obtain maximal value of quality rating of a product considering its shape and dimension [2],[8,9],[17].

2. METHODOLOGY OF RESEARCH

The paper presented here has the experimental character. The aim is to evaluate the correction of feed rate (v_f) influence on radius errors of a workpiece's corners (during the transition between two perpendicular planes) and to define the relation between technological conditions of cutting process and the actual shape of radius after machining.

The practical part consists of corner's radius errors measurements with the usage of coordinate measuring machine and complex analysis of research findings. The methodology of experimental research covers the elaboration of research sample model, the technology of cutting process (choice of machining datum surface, strategy of machining, machining operation, cut, tools, technological conditions of cutting, NC codes on CNC machine tool). Because of the fact that the feed rate – as the estimator of measured quantity (of radius and radii deviation) – is the most important parameter determining the duration of cutting process, the condition of manufactured surface and mechanical load of a tool, the parameter v_f was accepted. The results given here are only a part of researchers' findings in the field of the influence of feed rate on radius errors during shaping of arcs on CNC machines. This influence is very important during the cutting of matrices which construction consist of many corners with given radii that are the transition between perpendicular and slant walls.

2. 1. GEOMETRICAL MODEL OF RESEARCH SAMPLE

Experimental research are preceded by the project of the research sample. The body model was made in Catia V5R17 programme. A shape of research sample was modelled as a rectangular prism with overall dimensions 120x120x60mm and recess as „pocket" type (Fig.1). The transitions of perpendicular walls were made with different values of corner radius R_i (10, 15, 25, 30 mm). This model has three square pockets and their total depth is h_{max}=45mm.

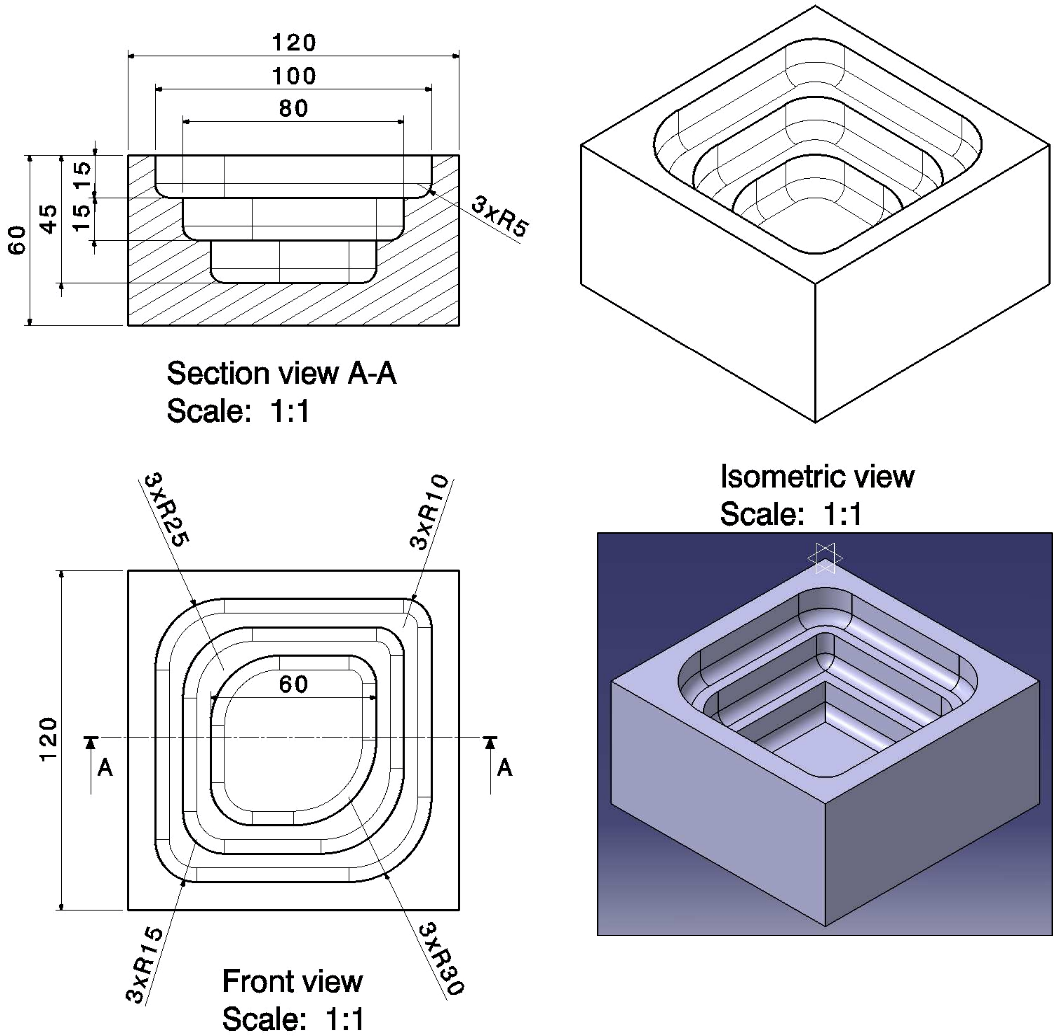

Fig. 1. Model and dimensions of the workpiece

File format with geometry of a product was generated as *.IGES that is used by SprutCam program. In this program, the technology of CNC machining of the research samples prepared before was elaborated for FV 580A vertical machining center. The samples were made of aluminium PA4.

2.2. TOOLS AND PARAMETERS

The process of cutting was run in two stages. In the first stage, rough machining of research samples was implied; the second stage included finish machining. In relation to different kinds of machining, different tools and technological conditions of cutting process were implied (Table 1). Shank cutter MTC 215850 with 25mm diameter produced by Garant Company was used during the rough machining. This tool is equipped with three exchangeable cutting plates made of sintered carbides covered with titanium compounds.

Table 1. Machining conditions

l.p.		CUTTING PROCESS	
		ROUGH	**FINISH**
1.	**TOOL**	shank cutter	ball cutter
	Symbol Diameter [mm] Quantity of blades /plates [pieces] Blade material	MTC 215850 25 3 covered sintered carbides	monolithic 8 2 sintered carbides
2.	**WORKPIECE**		
	Material/Symbol Geometrical dimensions [mm] Quantity of samples [pieces]	aluminium alloy / PA4 120x120x60 12	
3.	**CUTTING PARAMETERS**		
	Cutting sped v_c [m/min] Rotational speed n [rpm] Feed per tooth f_z [mm/edge] Feed rate v_f [mm/min]	200 2546 0,05 382	(420) (13376) **7000** (0,05) (1338) **700**

a)  b) 

Fig. 2. Cutting tools used for machining of a research sample pocket:
a) Garant's shank cutter (25mm diameter), b) Fenes' ball cutter (10mm diameter)

Basic parameters of rough machining were fixed according to the producer's recommendation and were as follows: v_c=200m/min and f_z=0,05mm/edge.

The rotational speed n was determined as $n = \frac{1000 v_c}{\pi d}$ where n=2546 rpm. The feed rate was estimated as v_f=382 mm/min.

The finish machining was performed with the usage of full-carbide double-feather ball mill by Fenes (Fig.2b). According to the producer's recommendation, technological parameters of cutting: v_c=420m/min and f_z=0,05mm/blade were applied. Rotational speed of the spindle was n=13376rpm and the feed rate was v_f=1338mm/min. Because of the fact that on FV580A machine tool the force of the spindle was limited, the rotational speed of the spindle was limited to n=7000rpm and the feed rate to v_f=700 mm/min. In this paper, basic value of feed rate v_f=700 mm/min was accepted. The correction x of feed rate basic value was applied; its task was to lower the feed rate appropriately by: 0%, 20%, 35%, 50%, 65% and 85%.

2.3. TESTING STATION AND THE COURSE OF CUTTING PROCESS

Experimental tasks were performed on CNC FV-580A – a four-axial vertical machining centre, equipped with numerically-controlled steering system FANUC 0i-MB (Fig.3).

a) b)

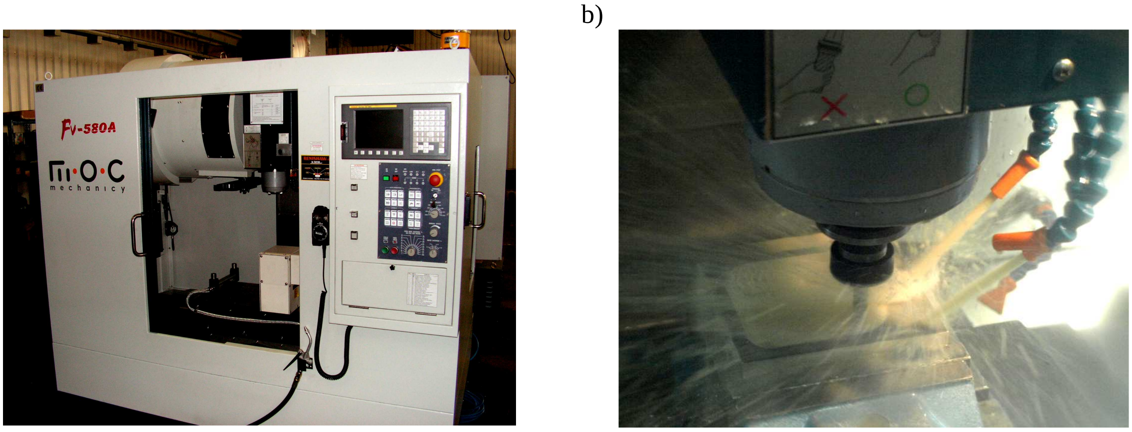

Fig. 3. CNC FV-580A machining centre; a) overall view, b) cutting zone, n=50÷8000rpm

The FV-580A machining centre is equipped with barrel tool store consisting of 20 elements, tool exchanger, three numerically-controlled linear axes (X, Y, Z) and one rotational axis. It allows for performing many different technological tasks, such as: milling, drilling, reaming, boring, counterboring, threading, peripheral milling, cutting with special - purpose tools. Length and diameter measurement of a tool is performed directly on the machine tool which is equipped with non contact interaction measurement system NC4 and OMP60 workpiece sonde by Renishaw.

a) b)

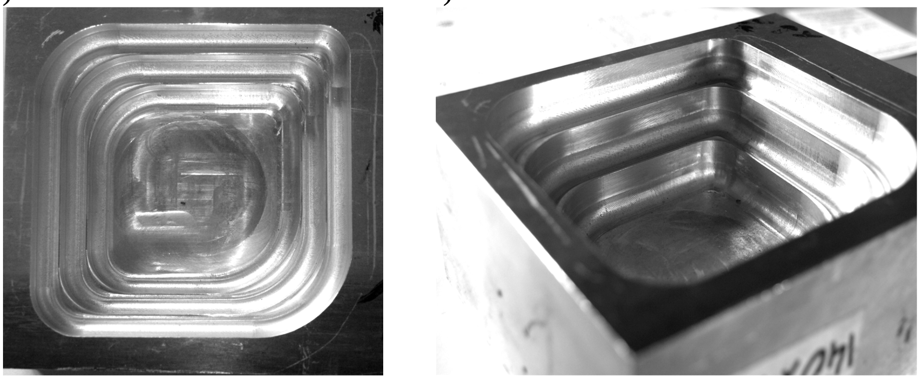

Fig. 4. The research sample after machining; a) top view, b) isometric view

The effects of cutting were products with given geometrical dimensions (Fig. 4). The process was performed for 12 different samples, all of them contain 3 values of every given radius R_i (10, 15, 25, 30 mm).

The evaluation of influence of feed rate correction on geometrical accuracy was made on the basis of measurement results gained with the usage of Global Performace coordinate measuring machine constructed by Brown & Sharpe (Fig. 5).

a) b)

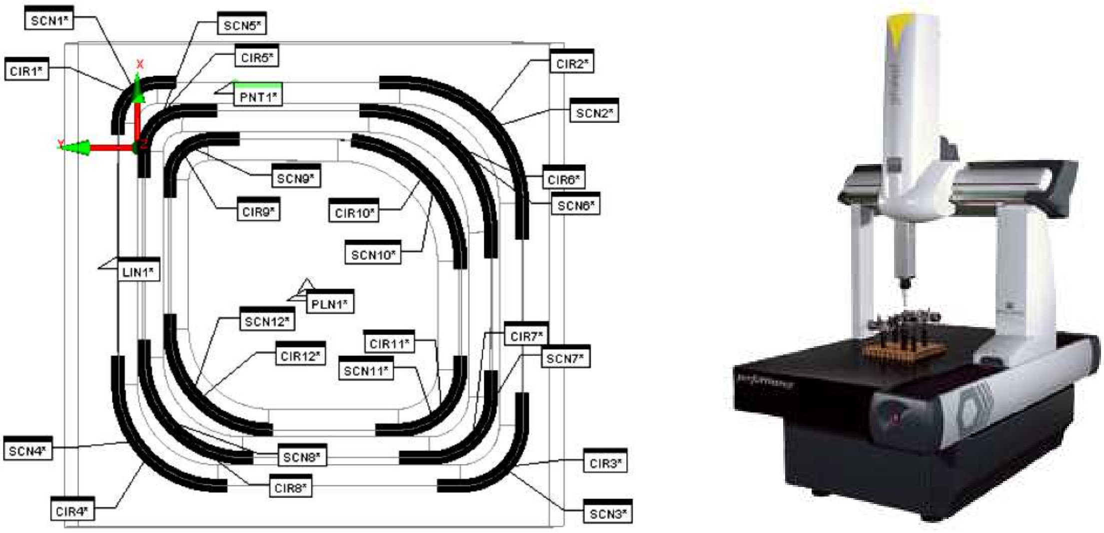

Fig. 5. Sample model and radii measurement (a) CMM Global Performace (b)

The measurement results of corner radius R_i errors ΔR_i which are the transition between perpendicular walls of research samples are presented in the form of diagrams and charts.

3. MEASUREMENT RESULTS AND THEIR ANALYSIS

The characteristics showing the relation between radius errors ΔR_i and the value of feed rate correction *x [%]* were obtained on the basis of experimental studies and measurements with the usage of CMM coordinate measuring machine. The results presented in the next part of this work were obtained for determined and exactly specified set of technological conditions of cutting process.

In Table 2, the average values of radii R_i and average of maximal radius errors $\Delta R_{i\ max}$ for different values of feed rate correction *x* were presented. The discrete values of errors given here apply to all radii of perpendicular internal walls R_i accepted on the designing stage. It can be observed that the values of radius errors for different nominal values of tested radii are on the level from 0,009mm to 0,084mm.

Table 2. The results of observed radii values R_i and maximal radii errors $\Delta R_{i\ max}$ obtained for different percentage values of feed rate correction *x[%]*

R_{in} [mm]	***R_i $\Delta R_{i\ max}$***	**Feed rate correction values *x***					
i=1,2,3,4	[mm] *i*=1,2,3,4	**85%** 105mm/min	**65%** 245mm/min	**50%** 350mm/min	**35%** 455mm/min	**20%** 560mm/min	**0%** 700mm/min
R_{1n} =10	**R_1**	9,952	9,927	10,061	9,946	9,948	10,047
	ΔR_{1max}	0,044	0,050	0,033	0,009	0,010	0,022
R_{2n} =15	**R_2**	15,006	14,995	14,981	14,982	14,986	14,975
	ΔR_{2max}	0,050	0,047	0,048	0,084	0,074	0,063
$R_{3\ n}$ =25	**R_3**	24,991	25,007	25,009	24,975	24,979	24,990
	ΔR_{3max}	0,015	0,017	0,021	0,030	0,037	0,036
$R_{4\ n}$ =30	**R_4**	29,995	30,016	30,013	29,968	29,970	29,984
	ΔR_{4max}	0,075	0,063	0,057	0,052	0,042	0,033

Fig. 6 shows an exemplary result of radius R_4=30mm errors ΔR_{4max} measurement for *x*=85% (v_f=105mm/min). They were obtained with the usage of CMM Global Performance. It can be noticed that the contour of obtained radius is displaced in respect of nominal outline. The undercut of nominal outline is characteristic and it leads to substantial errors of shaping curves. Considering the quantification, the average value of maximal radius errors were presented on Fig. 7-10.

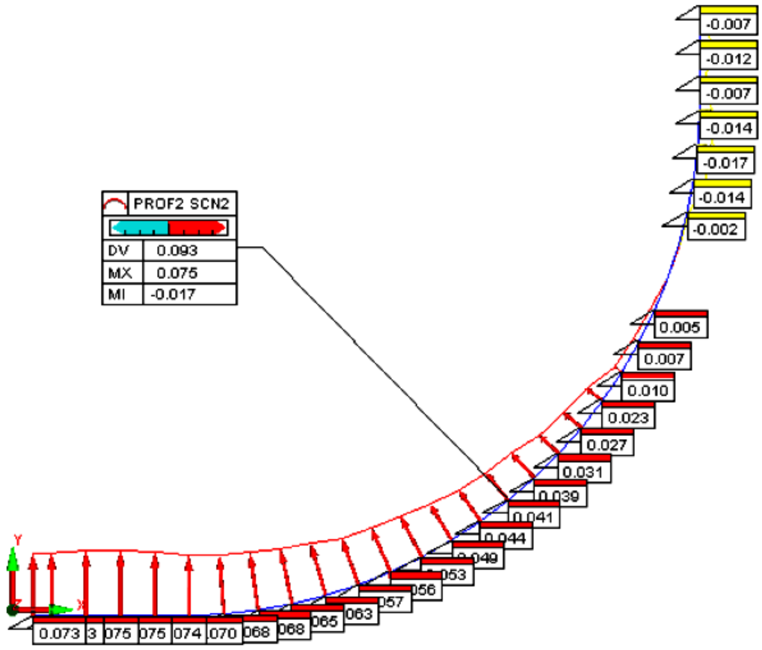

Fig. 6. The results of radius R_4=30mm errors ΔR_{4max} measurement for x=85% (v_f =105mm/min)

4. EVALUATION OF INFLUENCE OF FEED RATE ON RADIUS ERRORS VALUES

On the basis of the measurements, the characteristics describing the relation between radius errors value ΔR_{imax} and feed rate v_f correction x were constructed. Fig. 7 shows averaging values of maximal errors ΔR_{1max} from the test in the function of percentage value of feed rate v_f correction x for $R_1=10mm$.

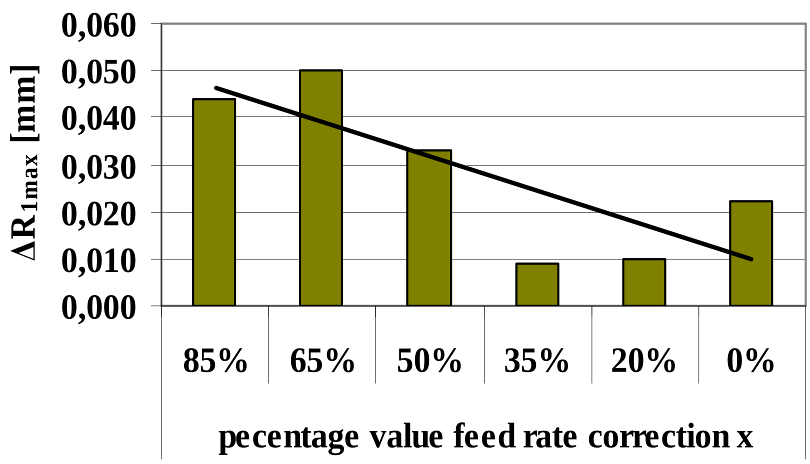

Fig. 7. Averaging values of maximal errors ΔR_{1max} from the test in the function of percentage value of feed rate correction x for $R_1=10mm$

The relation represented on Fig. 7 proves that the highest values of errors ΔR_{1max} of the radius $R_1=10mm$ were obtained during maximal values of feed rate correction x=85% and x=65% and the lowest for x=35% and x=20%. From these results, we can draw the conclusion that during machining of $R_1=10mm$ radius the lowering of correction x value leads to the improvement of precision when we discuss the manufacturing of radius that is the transition between perpendicular walls of matrix pocket. In consequence, it can be stated that the escalation of feed rate v_f increases the exactness of manufactured radius. The values of maximal radius errors ΔR_{2max} were observed during machining of $R_2=15mm$ radius (Fig. 8) and the results were different than with R_1.

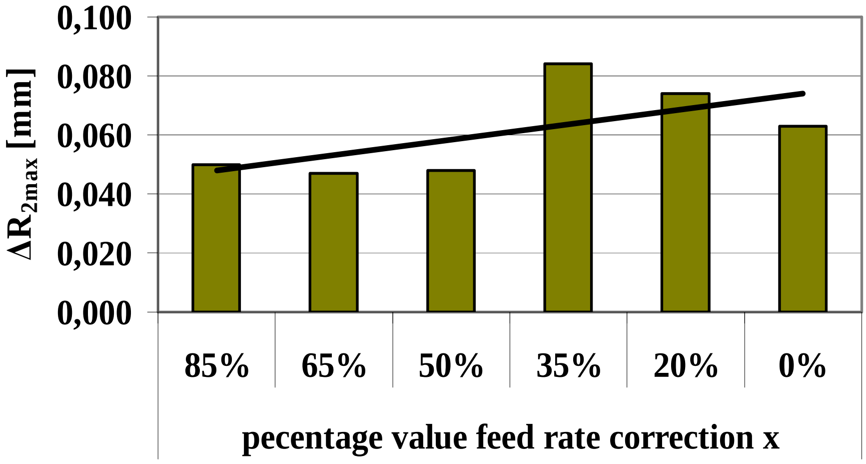

Fig. 8. Averaging values of maximal errors ΔR_{2max} from the test in the function of percentage value of feed rate correction x for $R_2=15mm$.

On the Fig. 8 we can observe that the values of radius errors ΔR_{2max} assume significantly highest values (0,063÷0,084 mm) than during machining of radius $R_1=10mm$, (ΔR_{1max}=0,009÷0,050 mm). Maximal values of radius $R_2=15mm$ errors were observed during correction x=35% (ΔR_{2max}=0,084mm). The results shown on Fig. 8 prove that the values of radius error increase together with the decreasing of feed rate v_f. correction x value. Similar changes of radius ΔR_{3max} errors values were observed during machining of radius $R_3=25mm$ (Fig. 9). The averaging values of maximal errors ΔR_{3max} from the test in the function of feed rate v_f correction x for $R_3=25mm$ show that the values of radius errors grow together with the lowering of correction x value. These observations lead to the statement that the growth of feed rate causes the lowering of exactness of radius $R_3=25mm$ representation. Maximal values of radius $R_2=25mm$ errors were observed during x=20% correction (ΔR_{3max}=0,037mm). The lowest averaging value of maximal error was obtained with application of x=85% correction.

On the Fig. 10, the averaging values of maximal error ΔR_{4max} from the test were shown in the function of feed rate v_f correction x for the radius $R_4=30mm$.

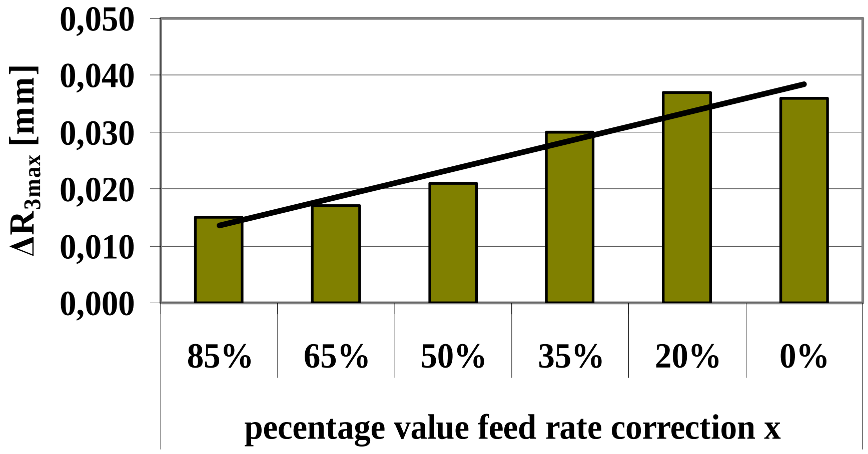

Fig. 9. Averaging values of maximal errors ΔR_{3max} from the test
in the function of percentage value of feed rate correction *x* for $R_3=25mm$

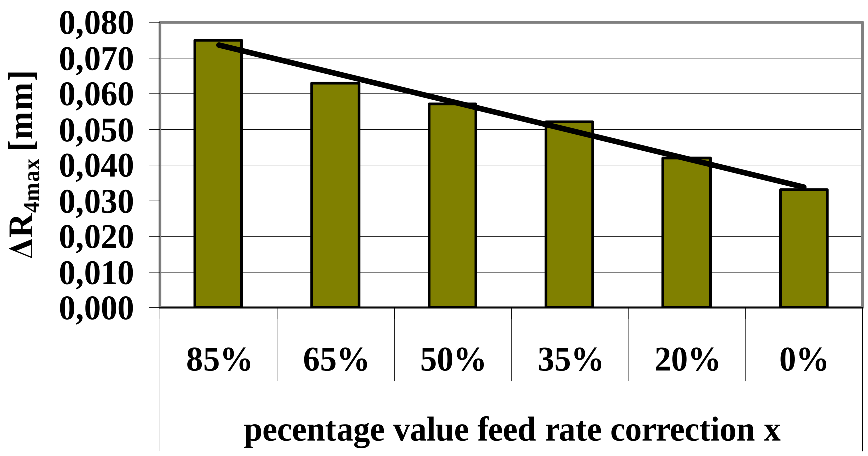

Fig. 10. Averaging values of maximal errors ΔR_{4max} from the test
in the function of percentage value of feed rate correction *x* for $R_4=30mm$

The characteristics of the course of maximal errors ΔR_{4max} changes of radius $R_4=30mm$ (Fig. 10) demonstrated the tendency of changes similar to that observed in the case of radius $R_1=10mm$ forming (Fig. 7). From the measurements presented on that figure, we can observe that maximal values of radius $R_4=30mm$ errors ΔR_{4max} apply to the correction $x=85\%$ and the lowest to $x=0\%$. It can be easily noticed that the lowering of correction *x* value and, what goes with it, the growth of feed rate v_f value contribute to the lowering of errors ΔR_{4max} values and the observed tendency can be described by a linear function.

5. TERMINATION AND CONCLUSION

On the basis of the study and the analysis of results presented in this article it can be stated that the course of changes of radius ΔR_i errors values in the function of feed rate v_f

correction x for the majority of cases is non-linear. For radii with very high and very low values of radius R_i (R_1=10mm, R_4=30mm) and with slight correction x (0÷35%) values the lowering of errors ΔR_i values appears. It indicates the improvement of representation exactness of radius forming for higher feed rate values. This fact can be caused by favourable conditions of processing of the surface into a chip (decohesion) and by the stabilisation of cutting process (lower vibrations for higher feed rate v_f). From the study presented here we can observe that with high feed rate correction v_f (x=85-50%) the exactness of radius representation has lowered and the values of observed errors reach 0,050mm÷0,075mm. With lower feed rate (high correction x) the conditions of a workpiece material's decohesion deteriorate' the tool is pulled into a workpiece by the force of cutting and the elastic strain of a tool influence errors of manufacturing radius.

For the three examined radii tested with the maximal feed rate, the lowering of the radius value appears. For shorter radii (R_i=10mm) and with lower speed of cutting v_f=105 ÷ 245 mm/min, the increase of radius value appears. The effect of this state is the elimination of high quantity of the material and the growth of radius errors values in the middle part of the radius. With higher speeds v_f, and short radii R_i (10 ÷ 15mm) the undercuts of material were observed in zones where the tool direction was changed. The transition from the rectilinear movement into the circular movement causes the increase of removed machining allowance which can be caused by unfavourable conditions of cutting during the transition between the two planes. The geometrical accuracy of a cutting tool may also be the cause of high values of errors. The feedback of machining centre shows that circularity errors presented with the usage of the Ballbar system are on the level of 0,0125mm (data from 2005). The deeper analysis of geometrical imperfection of a cutting machine and its influence on radius errors will be conducted in the future. The experiments will take into consideration a vast range of interactions on the values of examined errors during cutting for different technological parameters of machining and the correction of feed rate value. The optimalisation of feed rate correction can be a base for finding the compromising solution between inaccuracy of radius cutting and its capacity. It is significant because of the utilitarian values of cutting. The maximalisation of feed rate v_f brings visible economical advantages.

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