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Non-rigid shaft processing with pre-emphasis of tool trajectory on CNC machines

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Non-rigid shaft processing with pre-emphasis of tool trajectory on CNC machines

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Abstract. This article presents shaft accuracy increase method using a mathematical modelling. This modelling considers deformation of process system at required process modes. Herewith, given are experimental findings for several approaches, which confirm the effectiveness of the method use. Thus, decrease of an error by at least 42% turned out well when using the given mathematical modelling.

1. Introduction

Any machine-building production facility tries to increase accuracy and improve quality of its products. Non-rigid workpieces as shafts, torsion bars, beams, etc., where length to diameter ratio is more than 10, are those of many typical workpieces processed at cutting machines. When processing this type of workpieces, a major problem is a shape error as barrel, bow or waviness. This error is related to pliability variableness of the "machine-workpiece" system along the tool coordinate.

Accuracy of non-rigid workpiece processing may be increased by change of cutting modes or use of pre-emphasis of trajectory at processing [1-5], and preparatory actions for control program for a CNC machine in the CAD/CAM systems.

2. Theoretical dependencies of rigid deformations

Process system deformation is determined by well-known dependence [6]

$$y = P_y \omega_{\text{тс}} \tag{1}$$

where P_y is cutting force component, ω_{PC} – process system pliability.

When positioning a workpiece in the centres, formula (1) is as follows [7]:

$$y = P_y\left[\mu\frac{x^2(1-x)^2}{3EJl} + \left(1-\frac{x}{l}\right)^2\omega_{\text{пб}} + \left(\frac{x}{l}\right)\omega_{\text{зб}} + \omega_c\right], \tag{2}$$

where x is workpiece length force coordinate from front headstock; l is workpiece length; J is moment of workpiece inertia (for round solid cross-section of a shaft of diameter d: $J = 0.048d^4$); E is elasticity modulus of a workpiece material; ω_{FH}, ω_{RH}, ω_C are pliabilities of front headstock, rear headstock and a carriage respectively; μ is a coefficient of dynamics.

Determine cutting force P_y by well-known formula [8]:

$$P_y = 10C_p v^u S^x t^z K_p, \quad (3)$$

where C_p is a constant coefficient; v is cutting speed; S is feed; t is cutting depth; u, x, z are exponents of power, K_p is a coefficient of process condition reduction.

When processing on CNC machines a control program is set. This program regulates a trajectory of a tool displacement along the workpiece. For example, when processing a smooth cylindrical workpiece, tool (cutter) top is given a trajectory, which represents a straight line at a distance of given processing radius from the workpiece axis of rotation. Hence, due to cutting force process system [9] deforms, the workpiece "disengages" from the tool and its actual processed diameter increases. Rigidity of the process system along the workpiece length is variable, which results in non-uniform deformation and obtained profile of the workpiece (figure 1.*a*).

To increase processing accuracy of low-rigid workpieces, use may be made of compensating loads [10-13] or process modelling grounded on cutting modes and material parameters followed by corrections introduced into the control program (CP) of a CNC machine on the mathematical modelling, i.e. pre-emphasis of tool movement trajectory.

Pre-emphasis trajectory is calculated considering cutting force, which affects the shaft when processed at the change of cutting depth. The tool shifts relatively to axis of the workpiece towards the direction reverse to that of process system deformation subject to cutting force.

Figure 1.*b* gives modelling of a suggested method.

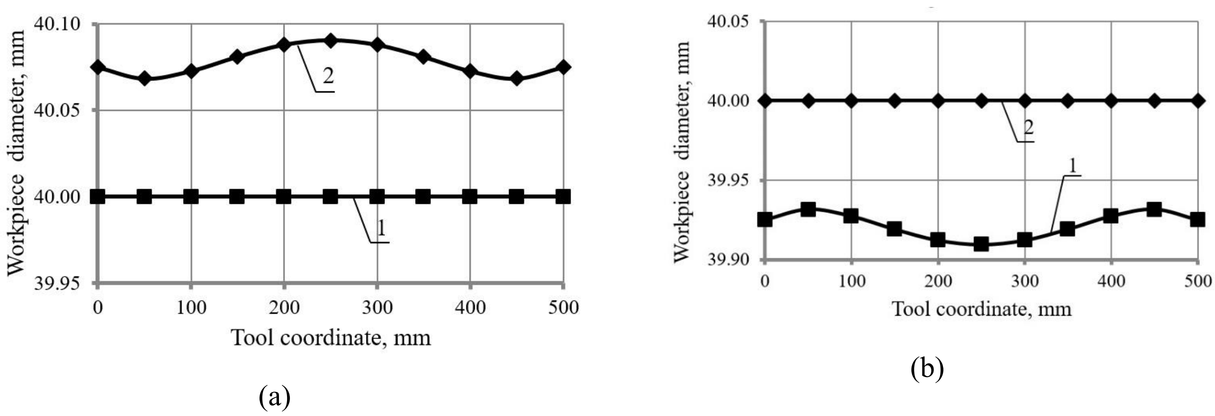

Figure 1. Shaft profile at shaft lathing in centers: (*a*) at traditional processing, (b) with pre-emphasis of toll movement trajectory; *1* is a given trajectory of a tool, *2* is an obtained workpiece profile.

3. Experimental studies

Effectiveness of a suggested method to increase accuracy of non-rigid workpiece processing has been researched on a CNC machine.

The 320-mm long shafts (steel grade 45, HRC 36…39) have been processed when positioned in centres with cutters with cutting plates (by *Mitsubishi WNMG080404-MA)* with top rounded radius 0.4 mm and plan approach angle 95° on *DMG MORI CTX 310 Ecoline* machine (static measurements of the machine rigidity have been taken beforehand).

Figure 2 gives comparison of processing errors with and without the use of pre-emphasis of trajectory of non-rigid workpiece process on CNC machines.

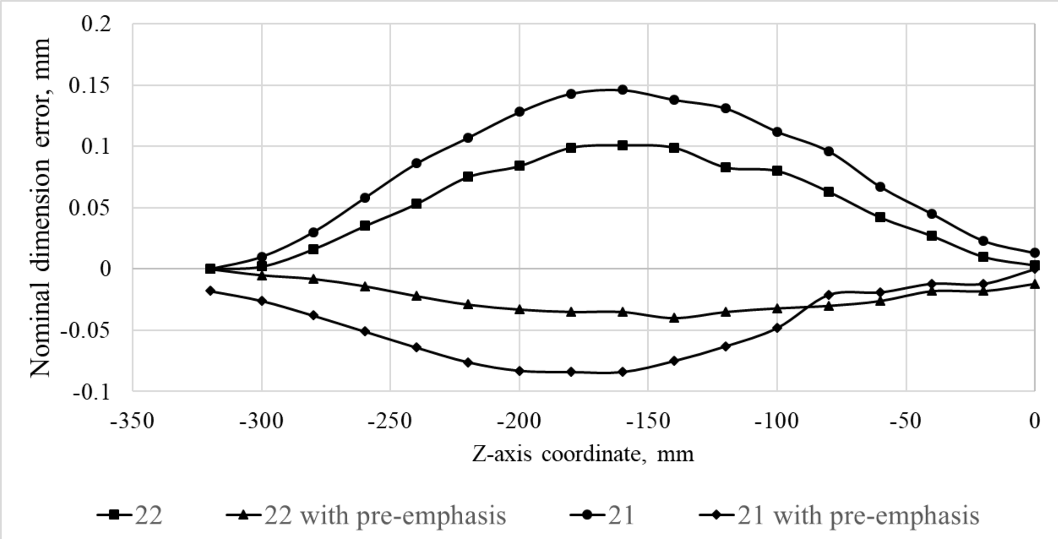

Figure 2. Comparison of errors of processed diameters with cutting plate by Mitsubishi WNMG080404-MA.

Some results of experiments are given in table 1.

By the table a shaft barrel generation can be traced when processed traditionally. With the pre-emphasis of trajectory, the error of a shape considerably decreases. But some bow is available, the one which results from the error of determination of cutting force against reference books.

Table 1. Shaft Nominal Size Deviation Table.

Cutting modes: *S*=0.15 mm/rev, *v*=100 m/min, *l*=320 mm, *t*=0.5 mm																			
Workpiece diameter, mm	L/D	Coordinate, μm																	Δmax
		-320	-300	-280	-260	-240	-220	-200	-180	-160	-140	-120	-100	-80	-60	-40	-20	0	
22	14,55	0	2	16	35	53	75	84	99	101	99	83	8	63	42	27	1	3	101
22[a]		0	-5	-8	-14	-22	-29	-33	-35	-35	-40	-35	-32	-3	-26	-18	-18	-12	40 (-60%)
21	15,24	0	1	3	58	86	107	128	143	146	138	131	112	96	67	45	23	13	146
21[a]		0	1	-7	-19	-35	-46	-55	-62	-63	-65	-6	-46	-34	-23	-3	6	8	63 (-57%)

[a] workpiece processed diameter with pre-emphasis

4. Conclusion

Decrease in error when processing a lot of shafts with pre-emphasis has amounted to 42% min. at similar modes and diameters of processing compared to classic straight-line processing. This method may be used without additional sensors on a CNC lathe. With complete digitalization of preproduction, automatic calculation of pre-emphasis of trajectory may be introduced at a development stage in CAD/CAM programs with the use of their bases of material physical characteristics. In case of possible introduction of adaptive processing with the use of pre-emphasis of trajectory, use may be made of means and sensors of the CNC machine proper to increase processing accuracy and obtain minimum error at processing long non-rigid workpieces.

To increase accuracy and determine cutting force, cutting force should be obtained during operation grounding on data measured by a self-diagnosable machine.

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