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Error Compensation of Complex Three-Dimensional Surfaces Machined on Computer-Numeric-Control Grinding Machine Tools

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Abstract: This study discusses the development of a method for compensating profile errors, resulting from the deviation of the actual grinding wheel radius from the calculated one. The study also elaborates on a control strategy that may be followed to minimise the profile error and allow the use of a four-axis grinding machine instead of five-axis one to perform the same machining task. This approach can be completely justified when the reduction in the machining cost is achieved as a result of grinding the gauge profile on a four-axis CNC machine tool instead of the five-axis one. When a number of five segments are chosen, the first control program is established for the first mean radius (170 mm) of the first segment. When the grinding wheel radius reaches 150 mm as a result of wheel dressing, a new control program that will consider a new nominal radius of 160 mm will be activated.

Key words: Profile error compensation, form grinding, CNC grinding machine tools

INTRODUCTION

In the metal cutting industry, form grinding process is still intensively used for finishing and super finishing operations of three-dimensional profiles surfaces to impart them the desired shape and dimensional accuracy and the required surface roughness. However, the CNC machine tools used for this process need to be stopped from time to time to dress the grinding wheel to expose new and free cutting abrasive grains and to eliminate the deviation in the grinding wheel profile resulting from the effect of the wheel non-uniform wear. Usually, the dressing step is achieved by a diamond tip that is moved according to a secondary CNC programme. As a result of that, the diameter of the grinding wheel changes and new calculation of the tool path is required to compensate for the deviation of the actual wheel size from the initial one.

The accuracy of the form grinding process and different methods of machining error compensation have been investigated by a number of researchers in earlier literature. Tso and Yang (1998) developed a mathematical model of the thermal deformation and cutting forces by utilising the thermal bending moment and specified grinding energy. They found that the thermal factor and grinding forces contributed to negative compensation, whilst wheel wear and deformation contributed to positive compensation. Choi and Lee (2002) proposed a method for machining error compensation in the process of cylindrical grinding. The method was based on mechanical modelling of the work piece supporting system including the work piece itself. Tian *et al*. (2008) presented a study dealing with the analysis of dimensional error variation in CNC grinding. The study also discussed a new intelligent error pre-compensation technique that was based on employing a touch probe for part dimension measurement. Saleh *et al*. (2007) developed an ultra-precision intelligent ELID five-axis grinding machine that incorporated error compensation capability. Huang *et al*. (2007) followed a compensation method that used the ground profile measured from a Talysurf profilometer to modify the NC tool path for the next grinding cycle by offsetting the residual profile error along the normal at the grinding point. There are also other works that reported various error compensation

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techniques and methodologies for improvement of machined surfaces form accuracy using on-line approaches for different machining operations which also can be applied successfully for grinding operations. Park *et al*. (1999) analysed the shape-generation process of a long slender shaft supported by correction steadies. They obtained a simulation model of form accuracy of the traverse grinding process from experimental data. Yang *et al*. (1996) investigated the accuracy of a horizontal machining centre using a strategy that was based on real-time error compensation. Quafi *et al*. (2000) presented an approach that was established on software compensation of the geometric, thermal and dynamic errors. This approach made use of a multi-sensor monitoring system. Yuan and Ni (1998) applied a real-time error compensation technique for 10 different machine tools. They managed to improve the accuracy in ranges between 3-10 times as they compensated for geometric and thermal errors. Tian *et al*. (2002) was focused on the development of an error-compensation system that used the approach of self learning. Dirts and Gutman (1986) developed a system for active error compensation during machining. The system provided a support table on which the work piece could be mounted and controlled in its position through a friction-free spring type hinge. In addition, the authors have also published a number of works dealing with grinding efficiency and control (Adamczyk *et al*., 2002; Müller and Wehmeyer, 1990; Wang, 1999). In contrast with other works, this study elaborates on a methodology, which is based on mathematical modelling, that can be used to minimise the profile error resulting from changing the wheel diameter after dressing. It also highlights the possibility of achieving highly accurate machining tasks that previously have been performed on five-axis machine tools on four-axis grinding machine tools, which will result in cost effective production of those time-consuming finishing operations. This research project was conducted from Sep. 2006 to 2008.

MATERIALS AND METHODS

Case study and concept of error compensation: In order to compensate for the effect of the deviation of the actual wheel size from the initial wheel size on the accuracy of the ground profile, a special grinding procedure that is based on providing positioning of the grinding wheel along a normal to any specific point of the ground surface. For example, in a local industry, the practice followed to perform grinding of the gauge (calibre XПT-90) is shown in Fig. 1a, which is used for pilger tube inspection, a five-axis CNC grinding machine tool (GG 52) is employed (Fig. 1b). The profile of this gauge is formed by ellipses that are located on a cylindrical surface. The law according to which the principle axes of the ellipses are varied is formed based on the optimal reduction approach followed during the process of plastic deformation of the tube ingot.

For forming complex profiles, the CNC grinding machine is equipped with a special profile-forming kinematical system, which provides the necessary generating motions required for both, the grinding wheel and work piece. As shown in Fig. 1, the work piece (1) rotates about axis C, while the grinding wheel (2) moves along axes X and Z and also has the ability turn around axis A. This turning of the wheel about axis A provides the opportunity to position its axis of rotation along any perpendicular to any point of the machined profile.

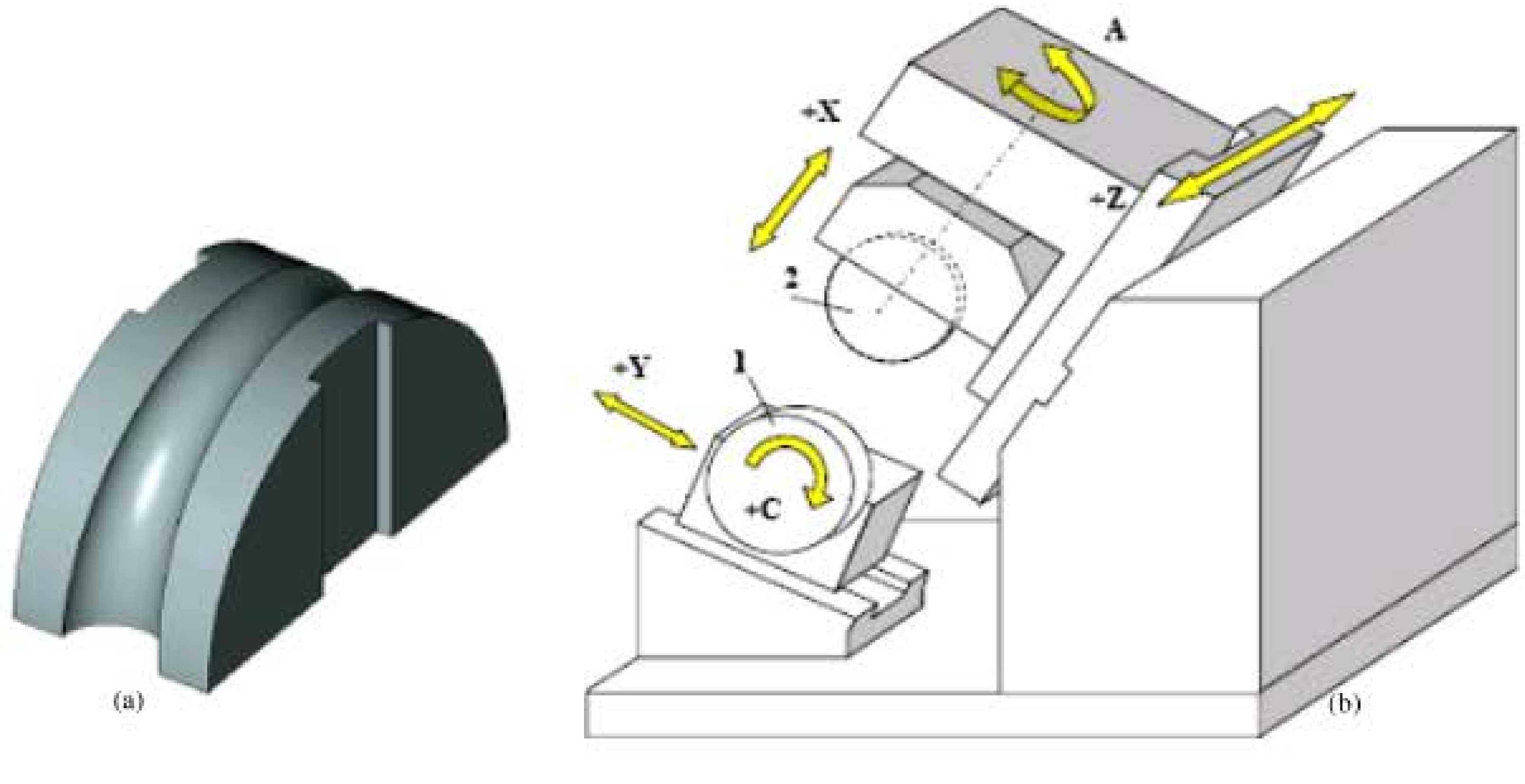


Fig. 1: Scheme of form grinding of (a) gauge profile XПT-90 on (b) GG 52 five-axis CNC machine tool

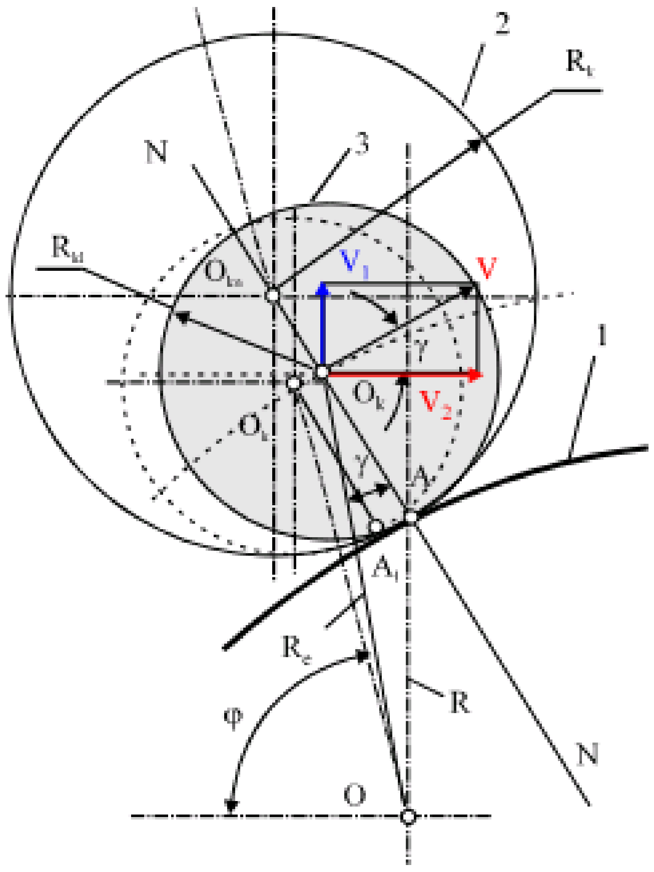


Fig. 2: Scheme of tool path for form generation

Therefore, the mentioned above four axes (X, Z, A and C) are adequate to form the desired profile of the tube gauge. However, the machine tool possesses another fifth controlled axis (Y) that is used to mount the grinding wheel perpendicular to the machined profile.

The function of the controlled Y coordinate can be explained using the scheme of profile generation shown in Fig. 2. The scheme shows a cross sectional view of the work piece (1) in an instantaneous contact with the grinding wheel (2). The wheel, having an initial radius R_k, is positioned in such a way that its center is located at a point O_{kn} of an equidistant and at the same time it touches the machined profile at point A. If during form generation the axis Y is not used, the wheel centre will be shifted to a new position located at point O_{k1}, as a result of wheel dressing. This shift will takes place along axis X_1 , which coincides with the centers line O_{kn}-O. Therefore, for the same work piece diameter, the grinding wheel can be in contact with the machined surface at a different point À$_1$. Obviously, this will result in an error in the work piece profile. The controlled Y coordinate may allow correction and compensation for the error resulting from the change in the wheel diameter. The correction can be accomplished along the NN (axis X) normal to the machined profile at the point A. Hence, the dressed wheel (with the smaller diameter) and the work piece will have the same contact point fixed before dressing.

This approach will eliminate the error received in the machined profile and allow us to determine the positioning coordinates of the wheel centre and at the same time produce a universal file for the cutter location data (CLDATA) regardless of the actual value of the grinding wheel radius. However, it is an obvious fact that the wheel radius needs to be always taken into consideration when programming the tool paths required for profile generation.

When creating a simulation program for form generation, there is an opportunity to eliminate the effect of varying the grinding wheel radius I the control files. Therefore, the given gauge profile (Fig. 1) can be ground on a four-axis machine tool with the help of a special model that correlate the change in the wheel radius with machined profile error.

Mathematical model development for error compensation: In order to establish a strategy for machining error compensation, we need to determine the effect of the change in the grinding wheel radius on the profile accuracy. Based on that, we will develop a program that will be able to implement this error compensation strategy.

The machined profile error δ(φ), that specifies the deviation of the actual wheel radius from the initially programmed one, is expressed as a function of the polar angle φ and is found by using Eq. 1:

$$\delta(\varphi)=(R_{kn}-R_k)\left[1-\cos\gamma(\varphi)\right]-\left[\rho(\varphi)-R_k\right]\left[1-\cos\varepsilon(\varphi)\right] \tag{1}$$

where, R_{kn} is nominal (design) radius of the grinding wheel, R_k is actual wheel radius, ρ(φ) is profile curvature radius and γ(φ) is angle of transmission of motion of the kinematic couple: grinding wheel and work piece. The angle ϵ(φ) can be determined by Eq. 2:

$$\sin\varepsilon(\varphi)=\frac{(R_{kn}-R_k)\sin\gamma(\varphi)}{\rho(\varphi)+R_k} \tag{2}$$

Because the gauge dimension is a standard size (found from tables) and is given as discrete geometrical values, the calculations of the parameters in Eq. 1 and 2 should be accomplished using numerical methods relying on classical relations. In addition, the calculations should be carried out for the most inconvenient (in terms of machining feasibility) cross sections of the gauge profile, i.e., along the profile depths where changes in the two equations parameters can take on big ranges. Therefore, the profile radius along different depths can be determined numerically by the following Equation:

$$\rho(\varphi)=\lim_{\Delta\varphi\to 0}\frac{\Delta s}{\Delta\varphi} \tag{3}$$

The radius vector $R_e(\varphi)$ of the equidistant of the wheel centre can be determined from the following formula:

$$R_e(\varphi)=\sqrt{R_k^2+R_{ka}^2+2R(\varphi)R_k\cos\gamma_0(\varphi)} \tag{4}$$

where, $\gamma_0(\varphi)$ is angle of motion transmission of the profile. Angles $\gamma_0(\varphi)$ and $\gamma(\varphi)$ can be determined using the geometrical relations from Fig. 2. From the velocity vector relations:

$$V_1=\frac{dR_e(\varphi)}{d\varphi}\omega,\ \ V_2=R_e(\varphi)\omega \tag{5}$$

where, ω is the angular velocity of the work piece, now we have:

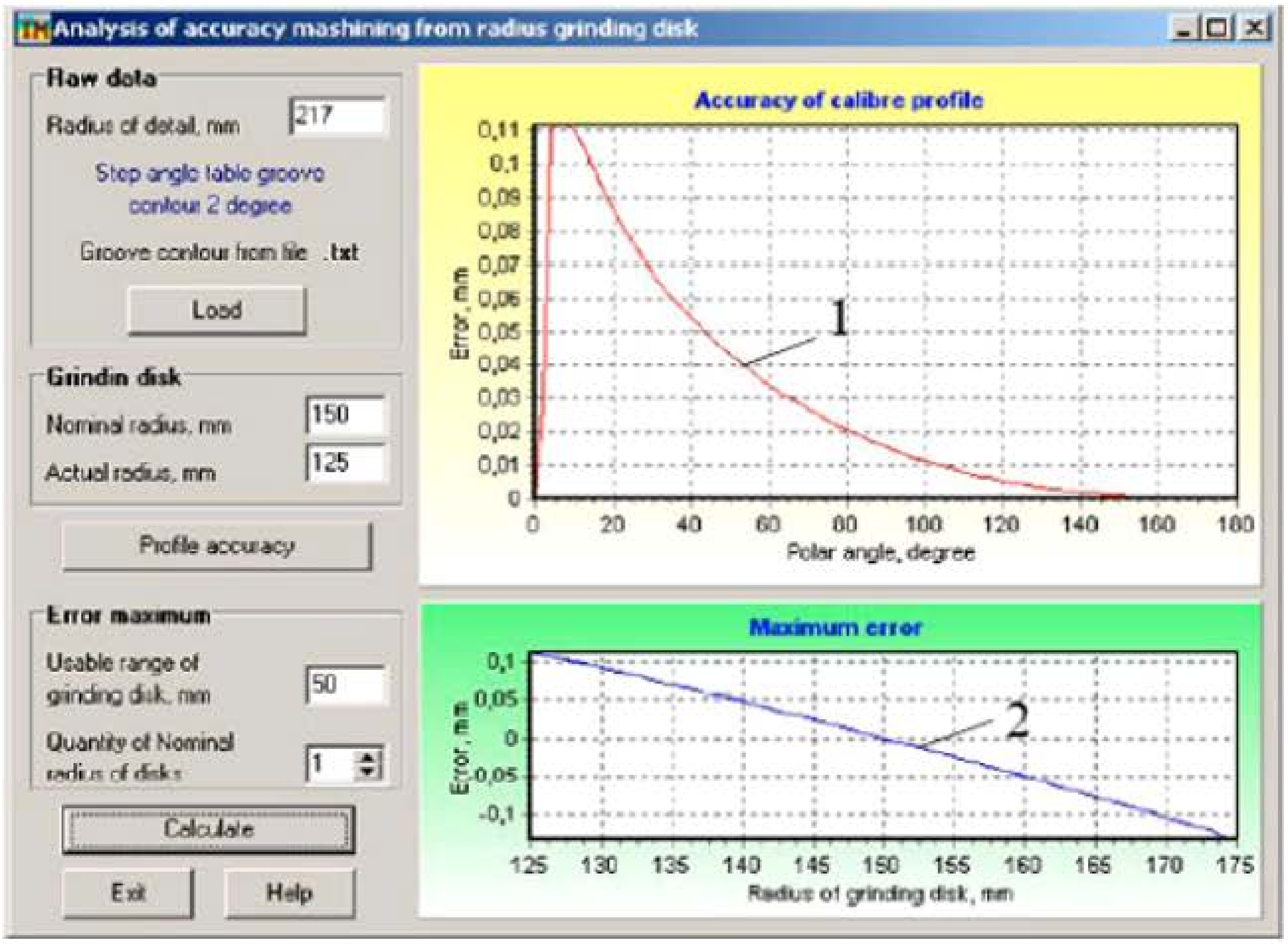
$$\gamma(\varphi)=\mathrm{Arc}\tan\frac{dR_e(\varphi)/d\varphi}{R_e(\varphi)} \tag{6}$$

In order to determine the angle $\gamma_0(\varphi)$, the function $R_e(\varphi)$ will be replaced by $R(\varphi)$.

RESULTS AND DISCUSSION

Analysis and discussion: The mathematical model developed by the Eq. 1-6 was used in an application program to analyse the profile error resulting from the change in the grinding wheel size after dressing. Figure 3 shows a screen print of the program. With the help of the icon Load, the geometrical data of the machined profile can be imported. The data can be stored in the form of a simple text file. In addition, the input data of the grinding wheel are also inserted in another window below that of the profile one. Activating the icon Profile accuracy, calculation of the profile error can be achieved as a function of the profile polar angle (curve 1 in Fig. 3). The input characteristics shown herein in Fig. 3 correspond to the specifications of the machined gauge XПТ-90 and a grinding wheel of nominal radius and usable range of 150 and 50 mm, respectively. The simulation results show that the maximum error, when an actual wheel radius of 125 mm is used (after dressing), is positive (+0.11 mm). The maximum error occurs for small values of the profile polar angle (less than 20°).

To minimise the profile error while maintaining a maximum usable range of the grinding wheel (from R_{min} to R_{max}), it is suggested implementing a new control approach for the grinding process. The suggested approach considers dividing the grinding wheel usable range (R_{max}-R_{min}) into several segments. For each segment, its mean radius is taken into consideration as the nominal



Radius of detail, mm 217

Step angle table groove contour 2 degree

Groove contour from file .txt

Nominal radius, mm 150

Actual radius, mm 125

Usable range of grinding disk, mm 50

Quantity of Nominal radius of disks 1

Fig. 3: Interface of application program for profile error calculation

radius of the grinding wheel. For this radius value of each segment, a separate NC tool path program (using the coordinates X, Z, A and C) is established.

Efficiency of the compensation strategy: The second part of the of the maximum error calculation program is designed to estimate the efficiency of the suggested compensation strategy. The program efficiency can be illustrated through the following example. If, for example, we employ a grinding wheel of 175 mm radius a usable grinding range of 50 mm with five segments (with nominal radii equal to 130, 140, 150, 160 and 170 mm), the maximum error can be reduced from ±0.11 to ± 0.027 mm (Fig. 4a). If we further increase the number of segments to 10, for example, the machined profile error will further decrease to ±0.013 mm (Fig. 4b).

As it might be earlier noticed from the above discussion, the main drawback of the suggested control approach and compensation strategy is the increased number of the required tool path programs (one tool path program for each segment) depending on the desired profile accuracy. However, as it has been mentioned earlier, a four-axis grinding machine can be successfully employed instead of the five-axis one as only four programmed axes (X, Z, A and C) are sufficient with the proposed compensation strategy.

To arrange the proposed error compensation technique, a four-axis CNC grinding machine, equipped with an online control system operated via a PC, with a special simulation program should be employed (Fig. 5). The simulation program automatically calculates the required controlled coordinates and transforms them into G-codes used to control the machine tool drives. For examples, when a number of five segments are chosen, the first control program is established for the first mean radius (170 mm) of the first segment. When the grinding wheel radius reaches 150 mm as a result of wheel dressing, a new control program that will consider a new nominal radius of 160 mm will be activated. It is worth mentioning that the simulation time is completely within the machining time and has no influence on the total performance of the form grinding process.

The developed error compensation strategy and control program can be also successfully used to overcome different concerns related machining accuracy of similar profiles on CNC grinding machine tools.

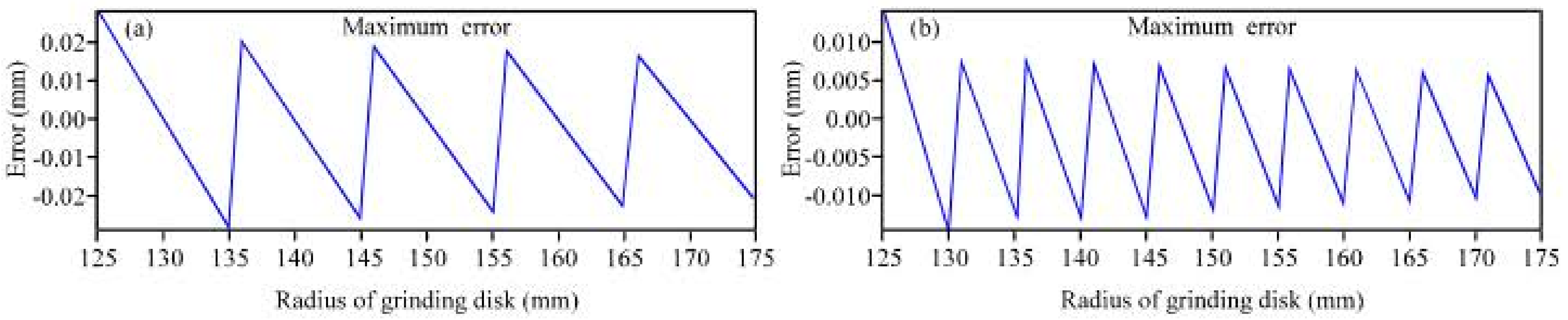


Fig. 4: Simulation results of profile error calculation using grinding wheel of 175 mm radius and 50 mm usable range for the case of: (a) five segments and (b) ten segments

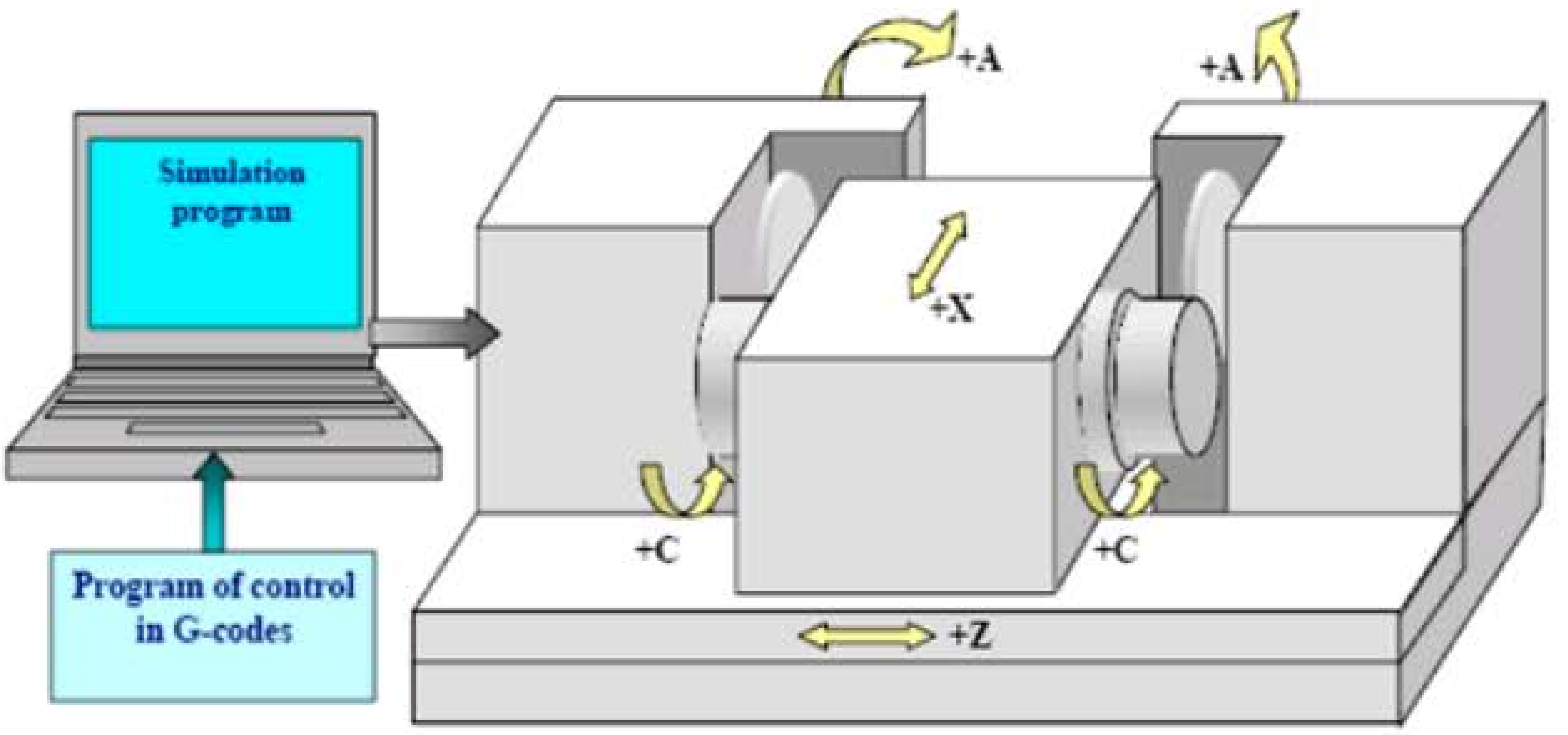


Fig. 5: Scheme of four-axis CNC grinding machine

CONCLUSION

The current study has demonstrated an approach for machining error compensation that was applied for an industrial case where the profile of a gauge is currently machined by form grinding on a five-axis CNC grinding machine tool. The approach which is based on a mathematical model considers minimising the machined profile error resulting from dressing the grinding wheel and changing its diameter. The simulation results of the gauge profile accuracy show that the machining error can be dramatically decreased by dividing the usable range of the grinding wheel into several segments. For each segment having its own (mean) nominal radius, a separate NC tool path program needs to be generated. Therefore, the major drawback of this strategy is the increased number of the secondary tool paths required for those nominal radii of the wheel usable range segments. However, this approach can be completely justified when we consider the reduction in the machining cost achieved as a result of grinding the gauge profile on a four-axis CNC machine tool instead of the five-axis one. The developed error compensation strategy and control program can be also successfully used to overcome different concerns related machining accuracy of similar profiles on CNC grinding machine tools.

NOMENCLATURE

R_k = Initial radius of grinding wheel
R_{k1} = Minimal radius of grinding wheel
$\delta(\varphi)$ = Machined profile error
R_{kn} = Nominal radius of grinding wheel
$\rho(\varphi)$ = Profile curvature radius
$\gamma(\varphi)$ = Angle of transmission of motion of the kinematic couple
$\gamma_o(\varphi)$ = Angle of motion transmission of profile

REFERENCES

Adamczyk, Z., D. Jon Czyk and K. Kocioek, 2003. A new approach to a CAD/CAM system as a part of distributed environment: Intranet database. J. Mater. Process. Technol., 133: 7-12.

Choi, H.S. and S.K. Lee, 2002. Machining error compensation of external cylindrical grinding using a thermally actuated rest. Mechatronics, 12: 643-656.

Dirts, V. and Y. Gutman, 1986. System for active error compensation during machining. http://www.google.com/patents?hl=enandlr=andvid =USPAT 4602459andid=Ghc9AAAAEBAJandoi =fndanddq =System+for+active+error+compensation+during+machining.

Huang, H., W.K. Chen and T. Kuriyagawa, 2007. Profile error compensation approaches for parallel nanogrinding of aspherical mould inserts. Int. J. Mach. Tools Manuf., 47: 2237-2245.

Müller, P. and K. Wehmeyer, 1990. CNC-grinding controls with error compensation. http://de.scientificcommons. org/20288499.

Park, C.W., D.E. Kim and S.J. Lee, 1999. Shape prediction during the cylindrical traverse grinding of a slender workpiece. J. Mater. Proc. Technol., 88: 23-32.

Quafi, A.E., M. Guillot and A. Bedrouni, 2000. Accuracy enhancement of multi-axis CNC machines through on-line neurocompensation. J. Intell. Manuf., 11: 535-545.

Saleh, T., M. Sazedr Rahman, H.S. Lim and M. Rahman, 2007. Development and performance evaluation of an ultra precision ELID grinding machine. J. Mater. Proc. Technol., 192-193: 287-291.

Tian, X.C., B. Peng and Q. Xu, 2002. Self-learning error compensation in CNC grinding. Proceedings of the International Conference on Machine Learning and Cybernetics, Nov. 4-5, IEE Xplore, pp: 1044-1047.

Tian, X., J.P. Huissoon, Q. Xu and B. Peng, 2008. Dimensional error analysis and intelligent pre-compensation in CNC grinding. Int. J. Adv. Manuf. Technol., 36: 28-33.

Tso, P.L. and S.Y. Yang, 1998. The compensation of geometrical errors on forming grinding. J. Mater. Proc. Technol., 73: 82-88.

Wang, Y.U., 1999. CNC machining of B-spline, bezier and nurbs surface. http://de.scientificcommons.org/36092771.

Yang, S., J. Yuan and J. Ni., 1996. Accuracy enhancement of a horizontal machining centre by real-time error compensation. J. Manuf. Syst., 15: 113-124.

Yuan, J. and J. Ni, 1998. The real-time error compensation technique for CNC machining systems. Mechatronics, 8: 359-380.