ARCH. MECH. TECH. MATER. VOL. 37 (2017) 85-90

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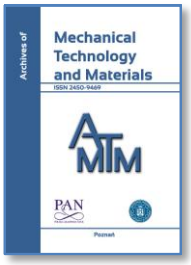

Accuracy and repeatability positioning of high-performance lathe for non-circular turning

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ARTICLE INFO

Received 01 June 2017
Received in revised form 23 October 2017
Accepted 09 November 2017

KEY WORDS

machine tool
laser interferometer
cyclic pitch error
accuracy and repeatability

ABSTRACT

This paper presents research on the accuracy and repeatability of CNC axis positioning in an innovative lathe with an additional X_s axis. This axis is used to perform movements synchronized with the angular position of the main drive, i.e. the spindle, and with the axial feed along the Z axis. This enables the one-pass turning of non-circular surfaces, rope and trapezoidal threads, as well as the surfaces of rotary tools such as a gear cutting hob, etc. The paper presents and discusses the interpretation of results and the calibration effects of positioning errors in the lathe's numerical control system. Finally, it shows the geometric characteristics of the rope thread turned at various spindle speeds, including before and after-correction of the positioning error of the X_s axis.

1. INTRODUCTION

The method of testing the accuracy and repeatability of axis positioning in the machine tool proposed in ISO 230-2 [1] includes the measurement of a setpoint displacement in static conditions, i.e. when stationary in a setpoint position (quasi-static measurements). However, this technique does not take into account the real conditions of the motion of the bearing system elements. In addition, it is time-consuming, especially when we need to obtain measurement data at a low increment in the setpoint position Z. This situation occurs, for example, when identifying cyclic pitch errors in the lead screw in axis drives with encoders mounted directly on the shaft of the drive motor [2]. ISO 230-2: 2014 [1] requires a minimum of 5 points per meter for axes up to 2 m in length. Due to this requirement, machine tool owners want to maximize the availability of the machine tool in the production process. It is therefore possible that many machine tool owners will customize their machines to meet minimum standards. Such conditions favor the incorrect identification of the volumetric error of CNC axes.

The measurements of the accuracy and repeatability of positioning of CNC axes via the synchronization of a laser interferometer with a machine encoder were presented by Castro H.F.F., Burdekin M. [3]. Those authors also developed methods of coupling the angular positioning of rotary and translational axes of the grinder and lathe with interferometer indications [4]. They also determined the uncertainty of such measurements [5,6]. Miller J.E., Longstaff A.P., Parkinson S., Fletcher S. [7] note that tests according to ISO 230-2 can be performed at several measuring points and supplemented with the positioning error obtained with continuous data capture. The combination of these two methods has made it possible to significantly shorten the duration of tests and increase the resolution of results, due to the terms of the step of the setpoint position measurement target. The conclusions of the aforementioned papers are included in the research presented in this article. Particular

DOI: 10.1515/amtm-2017-0014

attention was paid to the step of setpoint position in testing the positioning error.

One of the most demanding and distinctive types of machining on a lathe that requires a combination of several technological moves is the machining of non-circular surfaces. Threading has been evolving over the years. At first, threading was conducted on copying lathes. Dedicated master patterns, however, had to be made beforehand. Owing to the low efficiency of the method and the progress made in numeric control, CNC machines began to be used for threading purposes. CNC threading has gained popularity as it does not require specialist equipment to produce a specific element, e.g. rolls used in thread rolling [8, 9]. Standard threading is conducted on CNC machines at a constant position of the cutting edge towards the X axis. It is possible owing to synchronisation of the spindle rotational speed with tool feed rate in the Z axis to ensure that each spindle rotation would be equal to the thread pitch. The drawback of the process is that it involves several machine operations in which the tool path can be set, which makes the process less efficient. Recently, to minimise the unnecessary motion of the CNC machine, while at the same maintaining its versatility, rope threading started to be considered and applied. The rope threading method is particularly common in machining rope threads, as defined in ISO 10208:1991(E).

Since the method does not require much setting of motion operations, it is very efficient. The challenge of the method is the high dynamics of the tool in the X axis which is perpendicular to the axis of spindle rotation. Acceleration increases as threading time decreases. The structure of a machine tool, as well as the limitations of its electric motors and control, pose the main constraints limiting speed of operation [10, 11]. The substantial receptance of the feed drive in the X axis is the weakest link of the system. A typical feed drive in a standard CNC machine can hardly follow the pre-set trajectory which changes with high frequency. The main function of a typical feed drive is to provide a wide range of setting movements allowing the machine to operate with workpieces of distinctly different diameters. A wide range of feed movement can be obtained thanks to elements of adequate length.

The case study presented here concerns the accuracy and repeatability of the CNC axis positioning in a lathe with an additional Xs axis. This axis is characterized by a small travel range, i.e. 35 mm. It is used to perform fast-moving movements in the radial direction, synchronized in the CNC system with the angular position of the main drive, i.e. the spindle, and with the axial feed along the Z axis. Such synchronization enables the turning of non-circular surfaces, e.g. pistoning, polygon turning, one-pass threading (including trapezoidal or rope threads), turning the contact surfaces in rotary tools (e.g. gear and hobbing cutters). Examples of one-pass thread turning are shown in Figures 1 and 2.

The problem of maintaining the accuracy of non-circular turning is mainly related to the dynamics of the setpoint technological movements and the variable loads associated with the changes in the depth of cut for each spindle rotation (typically about 2 mm) [12]. For example, a speed of at least 8-10 rpm is necessary to achieve a satisfactory machining rate for a rope thread. The greatest requirements are for the X axis, which during each spindle rotation must recreate a path consisting of 6 phases lasting approximately 17÷20 ms [13].

Figure 1. Example of a trapezoidal thread in one-pass threading

Figure 2. Example of a rope thread in one-pass threading

If the tool path error of the machined thread exceeds the permissible levels, then it is difficult to determine which of the errors are the most significant. It is important to determine:

- the servo mismatch,
- the reversal spikes of the X axis,
- the cyclic pitch error of the Z axis,
- the spindle rotation uniformity error,
- the errors of radial displacement of the rotating object (axis synchronous error and the eccentricity of the holder, which can reach up to 50 μm [14]), and
- the tool positioning error.

Threading errors caused by the above-mentioned errors in technological movements can reach 50÷150 μm [13].

Synchronizing the current position of technological movements is performed using specialist procedures offered by CNC manufacturers. These procedures provide, among other factors, minimization of the servo mismatch of rectilinear motion of translational axes due to the current angular position of the main drive. In the case study presented we used Path Table Operations by Fanuc.

The results of the study presented in subsequent sections of this paper show a course of action that has improved the accuracy of rope threading. The influence of spindle rotational speed on accuracy was also investigated.

2. Examination of accuracy and repeatability of X_s axis positioning of a high-performance lathe for turning non-circular surfaces

The subject of the study was the static properties of the X_s axis positioning of a prototype of a lathe for turning non-circular surfaces (DEFUM S.A in Andrychów, Poland). The view of the machine when performing measurements using a laser interferometer is shown in Figure 3. In mobile joints, rolling guides with a ball bearing cage are used (undefined manufacturer). Feed rate is achieved by means of a ball screw. Synchronous motors with permanent magnets drive the individual ball screws of individual axes via spring clutches. The measurement of the displacement of the machine tool's actuators is indirectly based on the indications of multi-turn encoders placed directly on shafts of electric motors.

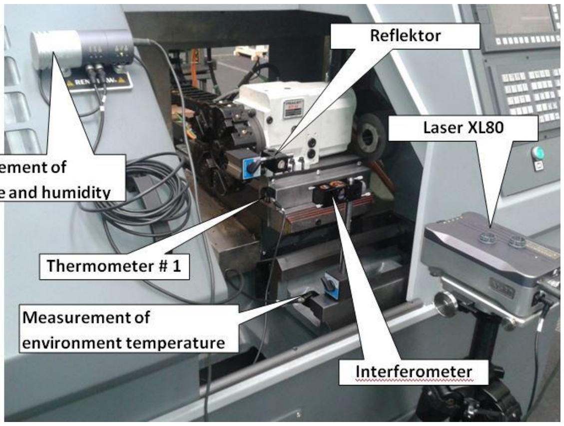

Figure 3. View of a lathe for turning non-circular surfaces during accuracy and repeatability testing with a laser interferometer

The CNC system is manufactured by Fanuc. Based on the G-code machining program, the setpoint position is generated, which is sent to the servo-drive network via real-time computing. The task of the servo drive is to achieve successive interpolator positions synchronized with the spindle angular position, with user-specified motion parameters in the machining cycles available under the Path Table Operations option.

The measurements concerned X_s axis positioning, i.e. the radial displacement of the tool relative to the headstock. They were based on the use of a laser interferometer, used by machine tool manufacturers to perform measurements as specified in ISO 230. The basic operating principle of an interferometer is described in [15]. According to the manufacturer of the interferometer used in this study, the accuracy of the measurements of displacement is ±0.5 ppm (excluding the corrections due to the thermal expansion of the material of the test object). During measurements, laser wavelength compensation was used for temperature, pressure and humidity. The relative location of the interferometer and reflector is shown in Figure 3. In view of the range of the axis examined (only 35 mm), particular attention was paid in this study to minimize the cosine error, i.e. to make the axis travel parallel to the laser beam. Adjustments were carried out until the maximal measurement distance was reached.

The first measurements were made after the initial lapping, according to the manufacturer's recommendations. The results are presented in Figure 4.

Comparing the results shown in Figure 4 with similar machine tools, with the axis travel of c. 30 mm, it should be noted that the machine tested displays a very large positioning error and a very high axial feedback value. Although these results were obtained without axis error correction in a CNC system, they are still very large. In addition, a very unusual course of positioning errors was revealed. The positive direction characteristics showed a clearly disturbed monotonic trend compared to the negative direction. However, the most important thing is that the repeatability of positioning was 1.5 μm, regardless of the direction of the test. Such a small value is rare in these machines, and testifies to their high suitability for precision machining.

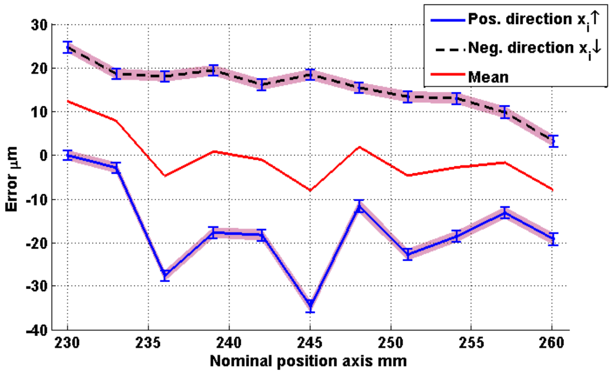

Figure 4. X_s axis positioning accuracy characteristics for non-circular turning prior to the correction of the setpoint position in a CNC system

In order to perform precision machining on this machine, first a one-way correction table (unidirectional) was established for a setpoint position in CNC, and a parameter was entered to compensate for the backlash value. The results obtained after the CNC correction are shown in Figure 5.

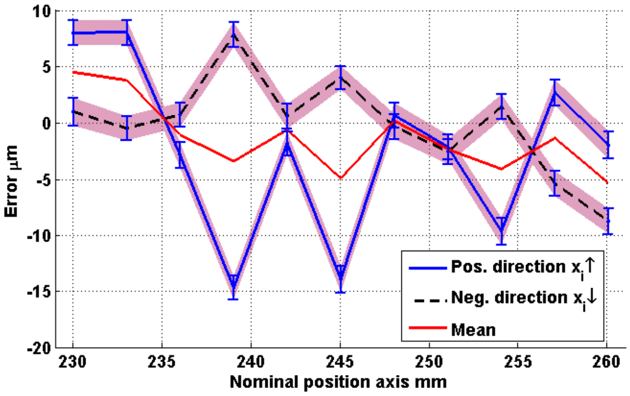

Figure 5. Characteristics of X_s axis positioning accuracy after the unidirectional correction of a setpoint position in CNC

Correcting the setpoint position of the axis in unidirectional mode did not produce the expected improvement in positioning accuracy. As shown in Figure 5, the axis feedback was the dominant axial error. However, because there was too much difference in the axial position accuracy characteristics obtained for the positive and negative directions, correction of the setpoint position in CNC must take the direction of movement into account. The entire study cycle was repeated for more steps of the setpoint position, and position-correction tables for positive and negative direction were developed and implemented in the control system. The results obtained after this correction are shown in Figure 6.

The repeatability of unidirectional positioning of the axis at the level of 1.5 μm and bidirectional positioning accuracy at 3.5 μm, as seen in Figure 6, show that the examined axis of the lathe for non-circular turning is capable of performing precision machining.

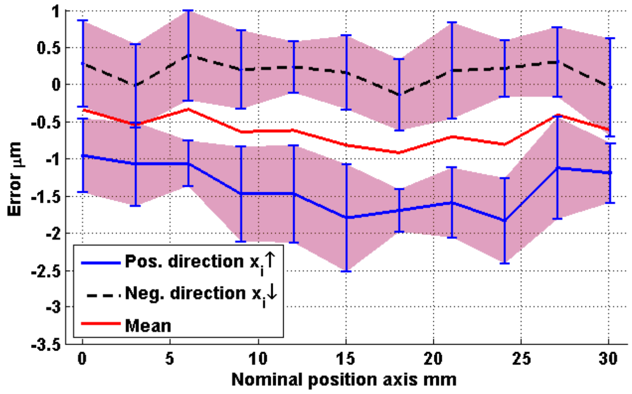

Figure 6. X_s axis positioning accuracy characteristics two-way position correction in CNC control

3. Work trials and identification of geometric specification parameters of rope thread

In order to verify the rationality of setpoint position correction in terms of the accuracy of rope threading, in the next part of this study the geometrical characteristics of the rope thread were presented, first including the correction (Figure 6) and without it (Figure 4). In addition, a series of rope thread samples were planned for different spindle speeds. The aim was to investigate the effect of the axis tracking error on the accuracy of rope threading. The results obtained were compared to ISO 10208 for rope threads (Figure 7).

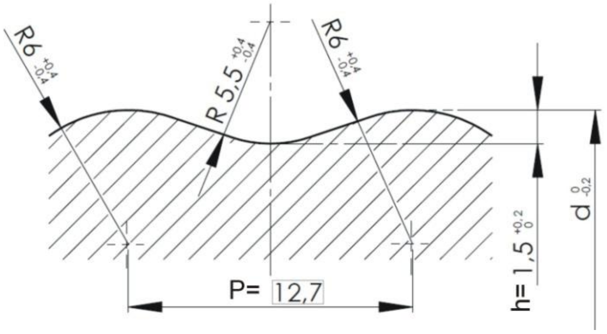

Figure 7. Geometrical specifications of rope threads according to ISO 10208

Threading was performed with at Z-axis feed rate at 0.1 mm/rev. All rollers were threaded in one pass. The machining program took into account the displacement of the nominal profile into the center of the thread depth tolerance area (h) according to ISO 10208. In the first threading operation, the surface of the initial roller base area (roller axis) was cleaned. The circular radius of the carbide sintered plate was 0.8 mm. The details after turning were checked using a CMM ECLIPSE 700 measuring machine manufactured by Zeiss, available at the Faculty of Mechanical Engineering and Mechatronics at the West Pomeranian University of Technology in Szczecin. The CMM ECLIPSE 700 has an ST-3 electrode head (see Figure 8). The maximum permissible error in MPE length measurement is ±(2.9+L/250) μm. The CMM software limitation error declared by the manufacturer was less than 0.1 μm. The measurement concerned the co-ordinates of the rope thread in a plane parallel to and passing through the axis of the roll on which the thread was machined. The geometrical elements were matched with the coordinates with the use of the least squares method. The measurement programming was performed in the Zaiss CALIPSO environment. Curve measurement is also used to determine contour tolerance.

Figure 8. View of a rope thread sample during geometry measurements performed with CMM

Prior to the measurements, the thread surface was cleaned. Sharp edges were blunted by hand grinding with fine grained sandpaper (grade 1000). In order to define the axis of the thread, a roller on the cleaned surface of the shaft was measured as the main base, 2 revolutions with a helix curve, at 11 mm of the roller's height. The nominal length and radii of the measuring tips were Z=-60 and R=4 for the cylinder and X=-40 and R=1.5 mm for the curve of the rope thread. The measurements were made on the fragments of two arcs with a nominal radius r1=r3=6.0 and two arcs with radius r2=r4=5.5 mm, one stroke (P) from one another. The radii of these arcs were determined using the radius measurement function for arc fragment available in the CALIPSO software. Additionally (outside the scope of the ISO 10208 requirements), the deviation of the outline of the rope thread was determined. Its assessment involved an *a priori* assumption of limit deviations being symmetrically distributed against the nominal value. The outline measured was subjected to filtration and the best fit to the nominal outline.

Exemplary end effects in the form of the metrological characteristics of a rope thread turned on a lathe in one pass are shown in Figure 9 and Table 1.

Deviations of the outline shape of the rope thread are shown on top of the tolerance field in Figure 9. Tolerance values have no practical relevance and are shown for comparative and visualization purposes. The following figures present deviations of the outline shape: Figure 9a - obtained before CNC error compensation, Figure 9b - obtained after CNC error compensation, Figure 9c - obtained during machining with maximum feed rate after CNC error compensation.

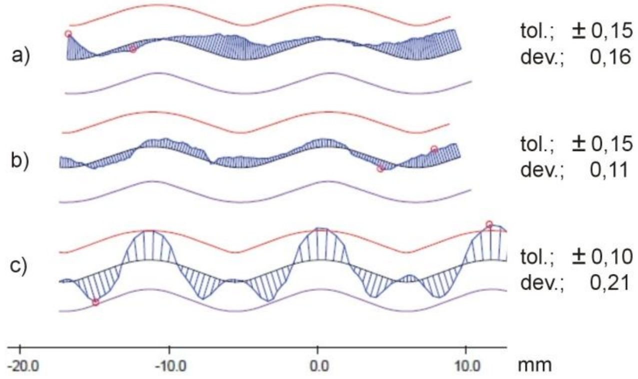

Figure 9. Deviation of the outline shape (dev.) of the rope thread against the tolerance area (tol.); a) machining before backlash compensation and X_s axis positioning errors in CNC, b) machining after backlash compensation and X_s axis positioning error in CNC, c) machining for maximum lathe performance (spindle speed at 650 rpm)

Table 1. Results of co-ordinate measurements of rolled corrugated threads for different spindle speeds

spindle speed rpm	50	100	400	600
radius r_i; 6.0±0.4 and 5.5±0.4 mm according to ISO 10208				
r_1=6.0	6.07	6.05	6.08	5.88
r_2=5.5	5.59	5.57	5.62	5.67
r_3=6.0	6.05	6.06	6.09	5.89
r_4=5.5	5.56	5.57	5.55	5.66
radius deviation in mm				
r_1	0.07	0.05	0.08	-0.12
r_2	0.09	0.07	0.12	0.17
r_3	0.05	0.06	0.09	-0.11
r_4	0.06	0.07	0.05	0.16
thread height; 1.5 < h < 1.7 mm according to ISO 10208				
h	1.55	1.51	1.58	1.52
deviation of shape outline in mm				
	0.12	0.15	0.21	0.18

4. Conclusions

The results of the measurements presented in this article allow us to draw some general conclusions based on the trends obtained.

In comparison with the requirements of the ISO 10208 norm, the tested rope thread samples were characterized by a tendency to increase the radius r=5.5 and reduce the radius r=6.0 when increasing the machining efficiency (i.e. increasing the cutting speed). This demonstrates the correlation between the tracking error of the numerically controlled axis and the errors of the turning objects. It should be noted, however, that deviations in the outline of the rope thread, even for high-speed machining (more than 600 rpm spindle rotation), were only about 0.2 mm. In relation to the accuracy requirements for rope threads, this result should be regarded as highly satisfactory. Lowering the machining efficiency slightly improved the accuracy of threading. The same applies to the requirements of the ISO 10208 geometric specification, because all the requirements were met for maximum machining efficiency, defined as the acceleration of translational motions of numerically controlled axes to the values close to the slope value set in the CNC (i.e. the limiting values for the servo drive). In the lathe presented here, the slope value for the synchronization of technological movements is achieved at a spindle speed of 666 rpm. At higher speeds, the CNC disconnected the axis drives, which was solely due to the limitation of the slope parameter set for the servo drive. Attempts to increase machining efficiency were made, but were abandoned due to the danger of catastrophic tool wear.

By comparing the profile of the outline deviation (Figures 9a and 9b), it is concluded that the compensation of the positioning error tool and the backlash in the CNC machine allows the geometric accuracy of the rolled non-circular outline to be improved. The outline obtained prior to the compensation of these error sources was clearly ‘flattened’ in comparison to the one after axial error compensation. This can be explained by the failure to reach a setpoint position due to the occurrence of a significant backlash. In summary, the compensation of axis errors determined by a laser interferometer is fully justified and meaningful, even for such a small axis range (only 32 mm).

The range of activities presented here, i.e. compensation of backlash and the axis positioning error, combined with the electronic synchronization of the technological movements of the numerically controlled axes, ensure the formation of non-circular outlines of the rope threads in accordance with ISO 10208.

Further research in this area should concern the mastering of non-circular threading with tolerances of less than 0.01 mm. Such research should take into account the impact of technological parameters, the type of turned material, and spindle axis motion errors on the parameters of the surface geometry.

The presented results refer to the recently launched Hanka lathe, manufactured by the DEFUM Andrychów Machine Factory S.A. According to the authors, only this manufacturer (and the Japanese maker of Okuma machine tools) offer commercial lathes for turning non-circular sections. Only the listed manufacturers will openly publicize the technological parameters and the effects of object-shaping using the technology presented in this article.

ACKNOWLEDGEMENTS

We would like to thank Krzysztof Filipowicz and Janusz Paluch for their help in the implementation of the experimental research and the configuration of the corrections table in CNC. This work was carried out as part of the INNOTECH/K3/IN3/18/226861/NCBR/14 project funded by NCBiR.

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