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Determination of cutting forces based on DMG MORI CTX300 ecoline CNC lathe drive power data

A P Starostin[1, 2, 3] and D M Elkind[1]

[1] Ural Federal University named after the First President of Russia B N Yeltsin, 19, Mira str., Yekaterinburg, 620000, Russia
[2] Ural Federal University named after the First President of Russia B N Yeltsin, Nizhniy Tagil Technological Institute, 59, Krasnogvardeyskaya str., Nizhniy Tagil, 622000, Russia

E-mail: [3] andrey.starostin@urfu.ru

Abstract. Modern machine building needs demand for machines and control systems which provide higher accuracy of machining. For this purpose, setup methods are being researched and accuracy of machines and devices is being improved. The main topic of this paper is a tool path predistortion system which is necessary for improvement of shaft turning accuracy when a steady rest cannot be used on a CNC machines. Calculation of such tool path requires one to know the cutting force during turning on a CNC lathe. The research in question allowed to determine the dependence of cutting force during turning on the power consumed by the feed drive, cutting depth, cutting velocity, and feed value. An equation for further calculation applicable to a specific lathe in the turning process was derived. This equation serves as basis for adaptive turning of shafts and other parts with the aid of a mathematical model, which must account for the cutting force. Application of this formula in a CNC controlled lathe's parametric program will provide for higher accuracy of turning without special devices.

1. Introduction

Machining accuracy improvement is one of research trends in modern machine and instrument building. Depending on work piece fixation practice various deviations of form develop in the process of machining of long nonrigid parts, such as shafts. For such scenarios path predistortion [1] is one of the ways of accuracy improvement for CNC lathes. Other accuracy improvement methods are available for nonrigid shaft machining [2–7].

In actual production the problem of form in the chuck-center setup is addressed only in case of tapering. Development of tapering during shaft machining is related to varying compliance of headstock and tailstock. To solve this problem the machining program and tool path are adjusted after preliminary machining to compensate for the deviation by means of linear interpolation equal to the deviation value. Thus, additional time is needed to perform intermediate inspection and qualified CNC machinists to adjust the machining program.

In order to calculate the tool path along the shaft it is necessary to determine the cutting force basing on work piece machining modes. The actual cutting force during cutting will differ from theoretical value calculated by various methods [8]. Hence, the values need to be determined directly during cutting to increase calculation accuracy. Special equipment is required to measure the cutting

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force and installation of such equipment in an attempt of implementing adaptive machining with obtainment of cutting force reading in real production would be problematic for everyday operations.

2. Research methodology

The task set in the course of this research was to determine the cutting force on the basis of cutting modes and CNC lathe parameters collected during task execution by the CNC unit.

Four resistive strain gauges were installed on a straight-turning tool (Figure 1) and connected in a half-bridge circuit to decrease the impact of noises and obtain readings for the X and Z axes. Furthermore, to increase signal accuracy and eliminate noise of other grid sources the resistive strain gauges were connected to an ATMEL controller via a 24-bit analog-digital converter with subsequent calibration of the whole system on the lathe by means of an electronic dynamometer. A 50 mm starting diameter shaft made of ‘grade 45’ steel was turned on the lathe in order to determine the dependency of cutting modes on the lathe's feed drive power. The length of the shaft was divided into three sections which were then turned at different feeds. Thus, by turning one diameter it was possible to obtain the data of feed dependence on the feed drive power. The dependence of cutting velocity on drive power was determined on different diameters under identical shaft rotational speed.

Figure 1. General view of the instrument with gain plate and strain gauges.

Readings of the strain gauges were taken continuously with a time step of 0.13s, which is comparable to the lathe's CNC system drive power data recording time step. After acquisition, a comparison of the data the starting point of the tool incision and strain gauges data based on abrupt drive power increase, as well as many-fold increasing load on the tool was performed. This resulted in a set of 2400 points at different cutting modes.

3. Experimental Studies

In the course of the experiment set up to determine the dependency of cutting force on power consumed by the feed drive several data sets have been produced, i.e. cutting velocity of 100–200 m/min, 0.15–0.25 mm/rev feed, and 0.1 to 1.5 mm depth of cut.

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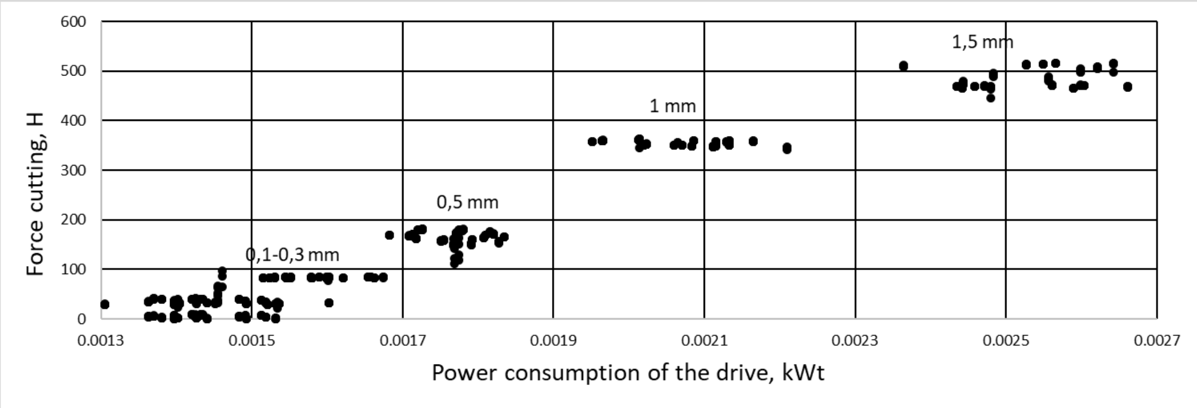

Figure 2. The graph of cutting the distribution of cutting force depending on the drive power consumption with at depth of cutting 0.1–1.5 mm.

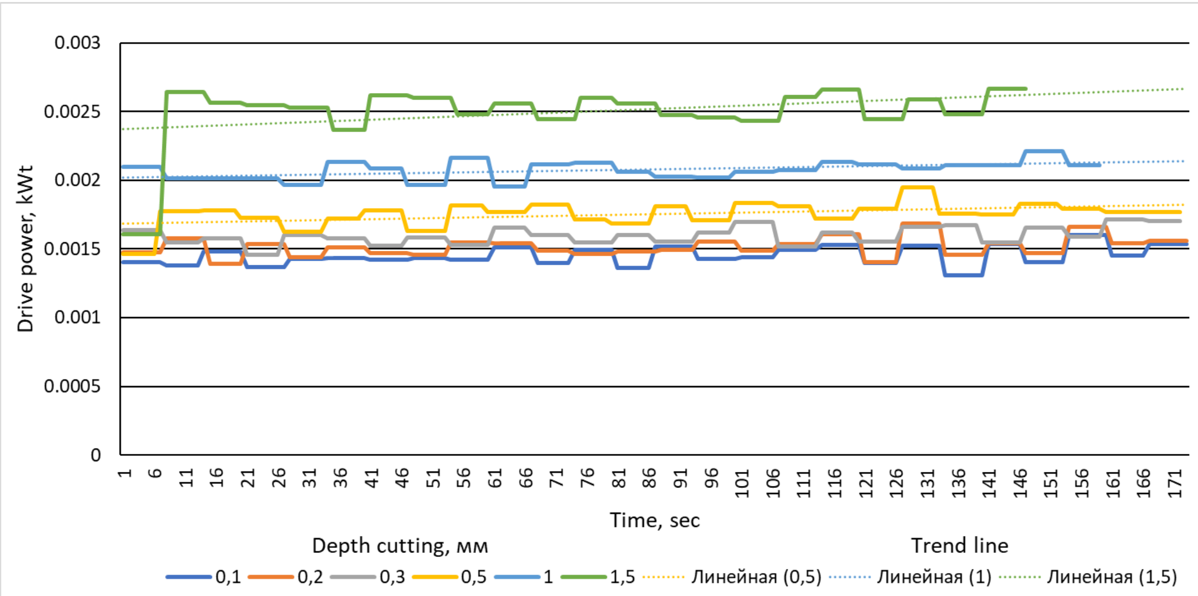

Figure 3. The graph of cutting the distribution of cutting force depending on the drive power consumption with at depth of cutting 0.1–1.5 mm.

Figure 2 shows several large concentrations of points which correspond to various cutting depths at a feed rate of 0.15 mm/rev. Similar graphs of cutting force dependence on drive consumed power can be made for feed rates of 0.1; 0.5; 0.75; 1; 1.5 mm. Changes on consumed power during turning are illustrated in Figure 3. This graph shows inconsistency of the load on the drive, which may be caused by variation in cutting, forces during tool movement. Besides cutting modes, this variation is prone to other factors, such as material hardness, material inhomogeneity, etc. Abrupt consumed power spiking is associated with sensitivity of the feed drive load sensor. Trend lines of 0.5 and 1.5 mm depth of cutting have been plotted in this chart for clarity. These trends illustrate the increase in consumed power during tool movements to the chuck due to decreasing shaft compliance and stock curvature and increasing depth of cut.

To derive the dependencies, 22 data sets were made under various cutting modes.

A regression analysis of variance [9] was performed basing on the obtained data.

As a result of this analysis, the following dependency between cutting force and power was obtained for the DMG MORI CTX300 ecoline lathe:

R-square coefficient of determination: 0.815

The equation of the cutting force along the X axis of the DMG MORI CTX310 ecoline lathe:

$$P = -68{,}6082 + 270{,}354 * S + 204{,}815 * t + 59312{,}668 * N - 0{,}462 * v,$$

where S – feed rate; t – depth of cut; N – power consumption of the drive; v – cutting velocity.

The coefficient of determination shows that the created model proves variance and dependence of variables, i.e. depth of cut, feed, drive consumed power, and cutting velocity.

4. Conclusion

Based on this model a practical calculation of the lathe operational cutting force can be made and used to calculate the tool path predistortion during work piece turning.

The derived equation specific to the DMG MORI CTX300 ecoline lathe lacks referencing to referential power ratios of a generally accepted equation for cutting force calculation, such as depth of cut, feed, and cutting velocity. Therefore, such ratios are replaced by drive power consumed at a specific moment of time. The calculated cutting force was verified during subsequent shaft turning operations basing on comparison of feed drive power consumption figures of the CNC unit and actual cutting force measured by the strain gauges. Difference between calculated and measured cutting force comprised below 5%.

Basing on this research it is possible to increase the qualitative characteristics of CNC lathe turning by accounting for the cutting force during turning on the lathe. This also provides an opportunity for parametric lathe programming on the basis of data acquired by the lathe in the process of turning, i.e. depth of cut, feed, and drive power at a given moment.

Further experimentation is necessary to increase calculation accuracy which would require changing of the main angle in plane to derive a comprehensive equation for determination of in-process tool cutting force. Also, to improve the accuracy and comparison of measured power consumption and cutting force on the tool, a single controller is required combining the measurement of drive current consumption with the simultaneous reading of strain gauge signals.

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