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Precision turning with instrumented vibration-damped boring bars

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Abstract

The paper presents the theoretical background and experimental results with a new approach for achieving high accuracy in finish turning with slender tools. The approach is developed especially for high-accuracy turning with vibration-damped boring bars with a length-to-diameter ratio up to 14, and equipment with strain sensors for in-process measurement of tool deflection. The approach is developed from an established three-pass method commonly used for precision turning with conventional slender tools without integrated sensors. It is shown that strain sensors can be utilized to achieve high accuracy in internal turning operations.

Keywords: Precision machining, Turning, Strain gage

1. Introduction

Finishing operations are carried out to achieve the desired surface finish and dimensional accuracy of a machined component. As these machining operations are the last operations in the process chain, the value of the workpiece is high. The cost of scrapping the workpiece in the finishing stage includes both the price of the stock material and the cost of the machining hours that have been spent.

To achieve high surface finish and high dimensional accuracy a rigid setup of the machine tool system is recommended. The stiffness of the machine tool and the tool holders should be high to avoid static and dynamic deflections. However, in internal turning operations – and especially in finishing – the machining conditions are difficult. The workpiece is sometimes thin-walled and flexible, and the internal turning is often performed by using long boring bars with relatively low stiffness.

The paper presents a method that is developed by the authors especially to achieve high dimensional accuracy in internal turning operations. Although high accuracy in turning operations with slender tools is a very common problem, it is difficult to find publications that address the problem and suggest a solution that could be easily implemented. The method is based on a scheme that specifies three finishing passes. The method can be used without prior knowledge of the cutting force relations or the stiffness parameters in the machining operation.

One of the most common tools for internal finish turning is the boring bar, which is a cantilever beam with a cutting insert at the free end. The bar should be clamped in a high-stiffness tool post in the lathe. The main problem with ordinary steel boring bars is vibrations that tend to arise if the ratio of boring bar overhang to boring bar diameter, L/D, is higher than 4. When using special boring bars made of tungsten carbide, a higher threshold can be achieved of about 6 or 7, thanks to their higher stiffness and damping. When even higher L/D ratios are necessary, special boring bars having internal dampers are typically recommended [1,2,3].

Passively damped tool holders which utilizes a tuned mass damper can be used to increase the dynamic stiffness the boring bars [4, 5]. The damper is attached inside the boring bar close to the free end. The damper mass is usually made of a material with high density to increase the mass ratio between the damper

Fig. 1 Vibration-damped boring bar (Sandvik Coromant)

and the effective mass of the boring bar body. Boring bars with passive vibration dampers are commonly used for L/D ratios up to 14.

Passively damped tool holders are popular because of their reliability and ease of use. In more advanced applications, actively damped tool holders or workpiece clamping systems with sensor systems and actuators can be found. Also, semi-active damping systems that can be adjusted during the machining operations has been demonstrated, for example by the use of magnetorheological fluid [4].

An example of a vibration-damped boring bar using a tuned-mass damper is shown in Fig. 1. The vibration damper gives the boring bar a high dynamic stiffness, and vibrations that would cause poor surface finish are eliminated. However, such boring bars have a low static stiffness because of the reduced cross section area and the large overhang. Boring bars with a high L/D ratio will inevitably get a static deflection because of the cutting forces. The deflection should be compensated for in finishing operations to achieve high dimensional accuracy.

Deflections caused by cutting forces are generally the main source of dimensional error in machining [6]. This is especially the situation when long and flexible tools are used. A large number of empirical and analytical models are developed to predict cutting forces in machining. Measurements of cutting forces and predictive force models in turning have been presented by Armarego [7,8], Kronenberg [9], Altintas [10], and several others. A reliable cutting force model is however difficult to develop because of the many influencing parameters, e.g. edge rounding, tool wear, friction, and tool rake angle. Therefore, cutting force models can not be used to predict tool deflection in high-accuracy turning operations. Instead, in-process dimensional measurements and a suitable cutting strategy is necessary to achieve high accuracy with slender tools.

2. The three-pass method for high-accuracy internal turning

An efficient three-pass method for high-accuracy internal turning with boring bars has been described by Sørby and Sundseth [11]. The method uses three finishing passes with constant cutting speed and feed, and the depth-of-cuts of the passes are adjusted based on in-process measurements. The cutting data should be selected for optimal chip control and surface finish. It is important to leave enough material after the rough turning operation for machining allowance before the finishing passes – it is generally recommended that the depth of cut should be equal to or slightly above the nose radius.

The workpiece diameter is measured before the first pass to find the start diameter and to calculate the machining allowance. The measurements after the first and second pass are used to calculate the tool deflection. A measurement can be taken after the last pass to verify the final dimensional accuracy.

The programmed radial position of the cutting tool in the three-pass method is as follows:

First pass: Start radius + one third of the machining allowance

Second pass: Start radius + two third of the machining allowance + half the radial deflection in the first pass

Third pass: The target radius + the radial deflection in the second pass

The corresponding formulas are

First pass: $$r_{p,1} = r_{a,0} + \frac{1}{3}\left(r_t - r_{a,0}\right) \quad (1)$$

Second pass: $$r_{p,2} = r_{a,0} + \frac{2}{3}\left(r_t - r_{a,0}\right) + \frac{1}{2}\left(r_{p,1} - r_{a,1}\right) \quad (2)$$

Third pass: $$r_{p,3} = r_t + \left(r_{p,2} - r_{a,2}\right) \quad (3)$$

where $r_{p,i}$ is the programmed part radius, $r_{a,i}$ is the actual (measured) part radius, and r_t is the target part radius. By combining Eq. (1) and Eq. (2) we obtain the following simplified expression for the second pass:

Second pass: $$r_{p,2} = r_{p,1} + \frac{1}{2}\left(r_t - r_{a,1}\right) \quad (4)$$

In practical machining tests with boring bars in the range ∅25–∅60 and a L/D ratio of 10, the three-pass method gives a machined diameter that deviates less than 15 µm from the target diameter, even if the deflection of the boring bar is up to 0.2 mm. The method is designed with the tool deflection in mind, but it will also correct for deflections in the machine tool structure and in the workpiece, and minor errors in the tool offset value.

The three-pass approach is very useful in a situation where there is limited a priori knowledge about the relation between the programmed and the actual depths-of-cut. Therefore, the three-pass approach is a secure method when a new machining operation is carried out, for example in machining of prototypes.

2.1. Generalized multi-pass method for high-accuracy turning

The expression for the programmed tool position shown in Eq. (4) is similar to

Second pass: $$r_{p,2} = \left(r_{a,1} + \frac{r_t - r_{a,1}}{2}\right) + \left(r_{p,1} - r_{a,1}\right) \quad (5)$$

which can be interpreted as "the radial position that represents half the remaining machining allowance after the first pass + the deflection in first pass". This leads us to suggest the following generalized formula for a multi-pass finishing operation:

$$r_{p,1} = r_{p,(i-1)} + \frac{r_t - r_{a,(i-1)}}{m-i+1}, \qquad (i=1 \rightarrow r_{p,0} = r_{a,0}) \tag{6}$$

where i is the pass number and m is the total number of passes. Eq. (6) is a generalization of Eqs. (1)–(3), that can be used for a higher number of finishing passes. However, a large number of passes is usually not desired from an economical point of view, and three passes are normally sufficient to obtain the necessary accuracy.

2.2. Tool deflection vs. depth-of-cut

Different alternative approaches to the three-pass method has been tested by the authors and analyzed in practical tests and simulations [6]. It has been shown that an accurate compensation of the final pass is conditional on a situation where the tool deflection in the two last passes are of equal size. If the two passes have different deflection, the compensation of the final pass is difficult decide accurately. In order to have similar tool deflection, we should have similar radial cutting force.

Figure 2 shows measurement of radial cutting force for different depth-of cuts for a triangular insert with a nose radius of 0.4 mm and a major cutting edge angle of 91°. The force measurements were carried out with a shank tool holder mounted on a Kistel 9257B dynamometer. The cutting force is increasing up to a depth-of-cut slightly above the tool nose radius. At larger depth-of-cut the radial force is approximately constant. The tool deflection is not very sensitive to the depth-of cut when the depth-of-cut is larger than the tool radius. For a tool similar to the one used for the force measurements in Figure 2, the depth-of-cut in the final passes in the three-pass method should be in the range 0.5–0.7 mm.

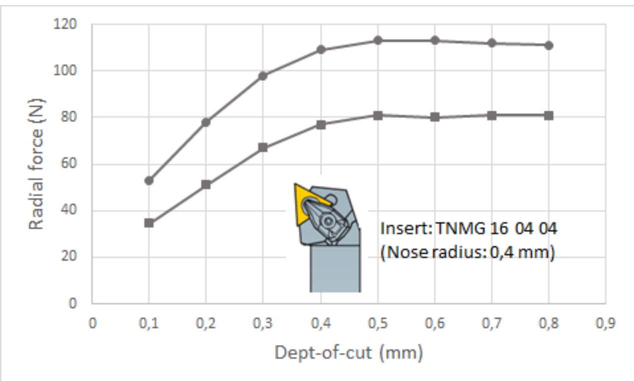

Fig. 2. Radial cutting force vs. depth-of-cut. Insert TNMG 16 04 04, major cutting edge angle: 91°

Fig. 3. Vibration-damped boring bar with strain gages in the test lathe.

3. Deflection measurement with strain gages

3.1. Strain gage measurements

In the three-pass method, there is a need for in-process diameter measurements of the workpiece. Such in-process measurements are usually carried out with a touch trigger probe that is automatically picked up from the tool magazine. In large machine tools with long boring bars, the tool-changing time is relatively long, and it would be more convenient to monitor the process and carry out dimensional measurements by use of devises that are integrated in the boring bar itself.

Figure 4 shows a boring bar equipped with four strain gages that is used for indirect measurement of cutting forces and tool tip deflection. The strain gages measure the strain caused by forces in both horizontal and vertical direction. The dimensional error in the turning operation is mainly related to the horizontal force (the thrust force) in the turning process. However, it is also observed that the vertical force (the cutting force) will slightly affect the horizontal deflection, probably due to the large torque at the tool post combined with some compliance in guideways and tool post.

In order to use the strain gages for diameter measurement in the three-pass method, the system was calibrated by applying a series of deflections of the tool tip. The deflection was applied by running machining tests with different combinations of feed and depth-of-cut, and the size of the deflection was found from diameter measurements on the workpiece. A linear model that used both the signal from the horizontal and the vertical strain gages was used to calculate a reliable calibration of the system.

When the three-pass method is used together with independent measurements, for example a manually operated internal micrometer, minor errors in tool offset values will not affect the final part diameter. When the diameter, however, are measured by sensors in the boring bar, any tool offset error will result in a similar offset in the part diameter. Therefore, care must be taken to set the tool offset with high accuracy.

3.2. Practical machining test

After careful calibration and tool presetting, a test was carried out to demonstrate the capability of achieving high

Table 2. Example of practical internal machining test with three-pass method and dimensional measurement based on strain gage. Workpiece start radius: 39.955, Target radius: 41.500

	Programmed radial tool position	Actual part radius after cutting, strain gage measurement (micrometer measurement)	Programmed depth-of-cut	Actual depth-of-cut
First pass	40.47	40.379 (40.380)	0.515	0.424
Second pass	41.031	40.945 (40.950)	0.652	0.566
Third pass	41.586	41.498 (41.502)	0.642	0.554

accuracy with the instrumented boring bar in internal turning. The cutting parameters used in the tests are shown in Table 1.

Table 1. Cutting data used in the tests.

Parameter	Value
Cutting speed, v_c	200 m/min
Feed, f_n	0.13 mm/r
Machining allowance (radial thickness)	3.09 mm
Tool holder	Boring bar, Ø60 Length 600 mm

The result of the three-pass method is shown in Table 2. The table shows that there is a good agreement between the strain gage measurement and the manual three-point internal micrometer.

The programmed radial tool positions are based on Eqs. (1)–(3). Because of the tool deflection, the actual part radius is always smaller than the programmed radial position (and the actual depth-of-cut is smaller than the programmed depth-of-cut). As always when the three-pass method used, the second and third pass have approximately the same depth-of-cut, which is an indicator of the success of the method.

4. Conclusion

The three-pass method is useful for achieving high accuracy in internal boring operations with long and slender boring bars. The method will compensate for deflections in the boring bar, and it will eliminate the effect of minor errors in the tool offset.

Calibration of the strain gages must be carried out for each clamping configuration and boring bar overhang length. When machining workpieces with high rigidity, the same calibration data can be used for all workpieces. Less rigid workpieces require that the calibration includes the effect of workpiece deflection, i.e. the calibration must be carried out in machining tests on the specific workpiece.

The results show that strain gages can be used for indirect measurement of the tool tip position. The three-pass method can be used together with strain-gage measurements in automated and high-accuracy finish turning operations.

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