Methods for dimensional stability improvement of end measurement tools

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Abstract: As a result of high pressure and temperature and the speed of relative movement, the contact surfaces of tools deteriorate during operation. The low dimensional stability of a tool is one of the reasons for the degradation of processing accuracy. Due the stability of this low-dimensional tool, surface treatment operations with precise dimensions are inefficient and expensive. This work presents methods for the stability improvement of end measurement tools. Three practical examples for engineering applications are presented along with relevant equations. Furthermore, the locating chart of the tool on the machine and work surfaces on the cut surface and edge was designed. A scheme to obtain a hole with a constant diameter in case of tool deterioration is also presented. The results show that differential methods significantly increase the service life of tools beyond their dimensional stability. Moreover, differential methods are simple and cost-effective.

Keywords: cutting tool; location; measuring tool; dimensional wear; inside diameter tooling; machine surface; work surface; cut surface.

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1 Introduction

The purpose of this study is to identify a method that will help increase the dimensional stability of end measuring tools. Several articles whose topics were related to that of the present work were found in Pratap and Patra (2018), Liu and Qu (2020), Sahin (2009), Kang and Tang (2018), Luo et al. (2005), Law et al. (1999), Rahman et al. (2007) and Kumar and Choudhury (2008). In certain studies, the object of study was specific alloys such as Ti-6Al-4V (Pratap and Patra, 2018). In other cases, a family of alloys was studied as in the case of TB6 titanium alloy (Pratap and Patra, 2018) and hardened steel (Liu and Qu, 2020). To prevent wear, coatings are used for machining processes such as ceramic-coated Ni-superalloy (Sahin, 2009). Design studies were also performed on machine tools. For example, the target applications are the manufacturing of miniature and micro-components (Kang and Tang, 2018). The authors developed and tested a process-design approach for error compensation in end milling of pockets (Luo et al., 2005). Nanotechnology has been applied to the nanofinishing of tools and is coupled with micromachining (Law et al., 1999). In machining processes, wear is always an important aspect as it is related to the cost of tool replacement and the quality of machined parts. It was shown that the design of experiments methodology can be used to investigate tool wear and cutting force. Under the wear criterion, linear flank wear is usually understood. Under the criterion, there is permissible value under technological constraints such as a sharp increase of surface roughness, the occurrence of vibrations of the manufacturing system, excessive heat of parts, tool breakage, and loss of a tool's original size (Rahman et al., 2007). Two studies found that addressed methodologies for adjustment/compensation in manufacturing processes of machining (Liu and Qu, 2020; Balla, 2018). Several distinct sorts of tools were created, each with a different sloping construction at the end. The goal was to make the electrochemical jet macro machining technique more efficient (Liu and Qu, 2020). The discovery of titanium alloys has demonstrated that machined surface quality may meet industrial production standards (Pratap and Patra, 2018). A standard linear compensation method (LCM) and tool wear sensing were used to develop an adaptive tool wear compensation technique. To demonstrate its relevance, the proposed control approach was demonstrated in an industrially significant case, namely the shape of a diffuser for a turbine blade (Kumar and Choudhury, 2008). Balla (2018) determined that machining accuracy in the range of the milling layer thickness applied could be achieved without the need of any tool measurements. Profile measurements show that the dimensional error was reduced to less than 200 μm in the revised design. Bellotti et al. (2021) predicted the material removal distribution for a component. The compensation of the component during design was conducted by adding material to the part. The low dimensional stability of the tool complicates and intensifies the processing of accurate surfaces. Thus, in the case of processing deep holes, the dimensional wear of the tool causes the formation of conical holes. In the case of processing of small-length holes with parts made of high-strength materials, the dimensional wear of the tool causes a significant reduction of the hole diameter for each detail. With these considerations in mind, an investigation of a precision drilling method of small deep holes in difficult-to-cut materials was conducted. Bellotti et al. (2021) also studied the influence of the geometry of the tool and the cutting speeds and feed rates on the surface quality of drilled holes. The results show that lower surface roughness values (Ra) in the range of 0.2–1.6 μm can be achieved and the problem of axial deviation of drilled holes was minimised under optimised cutting parameters through a new/improved BTA drill (Bellotti et al., 2021). Altintas and Weck (2004) discusses the fundamental modelling of chatter vibrations in metal cutting and grinding processes. Various stability models are compared to time domain simulation model results that have been experimentally proven. The study discusses a number of research problems that have still to be investigated in order to make the most use of noise prediction and suppression strategies in industry (Altintas and Weck, 2004). The current trend in manufacturing is to produce precise components with greater accuracy. Geometrical, thermal, and process faults all have an impact on component precision. Thermal error accounts for more than half of all machining errors, accounting for more than 50%–60% of total machining error. Reddy et al. (2020) focuses on the development of a real-time thermal error compensation module for precision machine tools, and discusses effective thermal error modelling, the development of a thermal error compensation model using a feed-forward backpropagation neural network, as well as a simplified model using regression analysis techniques, algorithm development for real-time compensation and implementation (Reddy et al., 2020).

In Uekita and Takaya (2016), the authors design a revolutionary on-machine dimension measurement technology to increase the productivity of large-part manufacturing. The goal is to create a traceable and automated system in a traditional production area to ensure product quality. The on-machine system is intended to measure the rotor of a steam turbine that is mounted on a large CNC lathe. The length-measurement device is a laser tracker, and the system also includes a probing unit and a length-calibrating artefact (Uekita and Takaya, 2016). Unwanted self-excited chatter vibrations are a common concern in milling. The research presented in Totis et al. (2017) study presents a new model of tooling system dynamics and the regenerative effect in milling. The revised model offers a considerable adjustment to the projected stability borders when the cutter diameter is significantly larger than the tooling system overhang and curved or inclined cutting edges are used. As a result, the unique approach could be valuable in a wide range of industrial applications (Totis et al., 2017). The fractal dimensionality and the informational entropy are proposed as new parameters for assessing cutting stability in the analysis of a vibroacoustic signal. In Kabaldin et al. (2010), a neural network model is presented for the regulation of the stability of a dynamic cutting system. Wavelet analysis allows for real-time cutting stability diagnostics. Machining processes are comprised of a multitude of process variables, and when combined, these variables determine the quality of the manufactured part. Some problems of machining are the wear of the tool, which represents the cost of tool replacement, and problems with dimensional tolerances. The dimensional stability is a factor that, if taken into consideration in the design and operation processes, can lead to higher quality final parts. Considering that the process of surface coating with hard materials is expensive and usually does not have the required efficiency for target applications, methodologies involving design, such as those analysed in this work, may be an effective and affordable alternative. Although several related studies have already been published, a single paper that reviews all possible solutions and methodologies, including relevant equations, was not found in the literature. The purpose of this work is to create a document that can be used by design engineers to make informed decisions on existing solutions and considering specific aims and the scope of their projects. The research question that this study aims to answer is: is it possible to create a document that allows engineers to identify the best solution for a specific engineering situation? The approach in this study was based on three steps. First, a bibliographic review was performed. Then, several situations were studied and three examples are provided. The last step was an applied solution in practice.

2 Reducing dimensional instability

The degree of dimensional instability observed in a completed metal item is controlled by three factors: material composition and structure (Muir et al., 1955), thermal and mechanical history (Hughel, 1960) and exposure and usage conditions (Kossowsky and Brown, 1964). These variables are outside the designer's control. Material selection, for example, is frequently dependent on physical or mechanical properties other than dimensional control, such as strength, density, magnetic behaviour, corrosion resistance, and so on. The thermal and mechanical histories are further constrained by factors such as the need to fabricate into a specific shape or the need to heat treat to achieve a high strength or hardness. Environmental and use conditions are also essentially aspects that the designer cannot entirely control, however he may be able to restrict some of their impacts; for example, the stress level in a component can be lowered by increasing the section site. The processing methods that define the thermal and mechanical history are the most under the manufacturer's control of the three factors. As a result, selecting appropriate processing processes is critical for achieving sufficient dimensional stability in a completed product. These may have something to do with the mechanism. As a result of the previously mentioned instabilities, stress relief between machining operations is common procedure, as is doing stabilising heat treatments before and after finish machining. The following are the general procedures outlined in the MIT work (Lament and Averbach, 1955):

1. relax
2. rough machine
3. rough machine
4. rough machine
5. machine somewhat large
6. stabilise
7. machine to final dimensions
8. stabilise.

Optional Steps 1, 3 and 8 are indicated.

The effects of thermal and mechanical treatments on dimensional stability can be summarised as follows:

- Because progressive transformation is one cause of instability, phase equilibrium under service conditions should be approached as closely as feasible. It is common practice in quenched and tempered steels to quench to subzero temperatures before tempering to remove as much remaining austenite as possible from the structure. Because definite links between dimensional instability and the progressive transition of retained austenite have been discovered, this is the case. Although repeated subzero exposures are occasionally recommended to lower the quantity of austenite retained, they are not always necessary. The efficiency of such cyclic treatments is called into question in the structure.

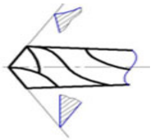
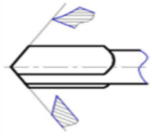
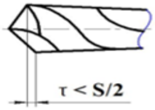
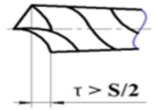
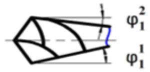
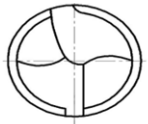
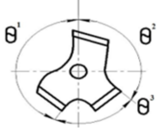
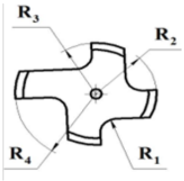
- Stabilisation treatments are used to speed up any aging that would otherwise occur at the service temperature. Lament and Averbach (1955) suggests that a portion of the therapy be done at room temperature stabilisation for 24 hours at 200 F. It is also worth noting that the stabilisation temperature should not surpass the primary heat treatment's final temperature to avoid losing mechanical qualities.
- During processing, severe heating or cool might introduce residual tensions that cause distortion. To avoid high temperature gradients, pat should be heated and cooled slowly wherever possible. This is especially true when dealing with huge and complex geometric forms. It may be desired to limit the severity of quenching as much as feasible when quenching is required as part of a heat-treatment procedure. After solution annealing, certain age hardening aluminium alloys may be quenched in boiling water rather than a cold vat.
- During machining grinding operations, residual tensions and the resulting distortion/warpaged may be introduced. Furthermore, residual tensions in a heat-treated item may cause distortion during machining as a result of uneven metal removal. As a result, it may be more difficult to achieve the appropriate dimensional tolerances, necessitating finish machining in stages, each followed by a specific stress-relieving treatment.
- Achieving an adequate stress relief without losing mechanical pro nags may necessitate making a time and temperature compromise. Newer ways for increasing the rate of stress reduction, including the use of ultrasonic energy, are in the works and could be very valuable. In the long run, residual strains have also been relieved by temperature cycling. This is normally accomplished by cycling between a moderately raised temperature and a significantly lower temperature (Lament and Averbach, 1955). It has been noted that ten cycles or less are usually enough.

3 Methods

3.1 Concepts

If adjustable tools are used for processing holes, they compensate with their dimensional wear. For purposes of wear compensation, one also uses adaptive systems of corrective maintenance (Kum et al., 2020). However, this use has limitations due to high complexity and low reliability. It is even more difficult to compensate for the dimensional wear of non-adjustable dimensional edge tools that are widely applied in ID tooling. To restore the working dimensions of these tools, the most common method is to replace the cutter plate; less frequently, workers perform evaporation or tool material deposition on the working face or use special heat treatment methods that cause severe temperature deformations resulting in the increased dimensions of tools. All of these methods are ineffective and slightly increase the service life of tools. It is known that most measuring edge tools have characteristics of some dissymmetry for the working area due to manufacturing and grinding errors or their design features as in Table 1.

Table 1 Types of working part dissymmetry for axial measurement tools (see online version for colours)

Type of dissymmetry	*The dissymmetry schemes*
Different state of opposite blades	 
Axial displacement of blades	 
Different angles within the plan	 
The cross-section error	
From the rotatory symmetry	 
From the radial symmetry	

The most pronounced dissymmetry of cutting properties refers to single-sided cutting tools such as rifle and cannon drills, reamers, BTA drill heads and others. In the analysis of form-manufacturing processes by two-part tools with geometric dissymmetry of the working part, there is a specific interest regarding models that apply to several types of dissymmetry at once as the most common (Deryabin and Golovachev, 2018). If this approach was practically impossible for three and four-part tools, due to the sharp complexity of the model, it can be implemented with two-part tools. In this case, the most interesting is shaping by the tool with unequal angles in terms of opposite blades, their axial shift and various cutting properties. These types of dissymmetry are typical in cases of processing with a spiral drill, a two-blade vertical drill, or a float-boring block. One can reduce more specific cases of tools geometric dissymmetry to the axial shift of blades and various properties of blades, but the correct analysis of axial vibrations requires clarification of these models.

3.2 Analytical models

Stationary models were developed and studied for the generation of geometry with two-blade tools of two types:

a when diametrically opposite blades are separate in the axial direction at a distance of $\tau < S / 2$, where S is the axial feed

b when this axial distance is $\tau > S / 2$.

By the input of radial forces proportional to the areas of sections Δ_1 and Δ_2 with coefficients k_1 and k_2, one obtains equations (1)–(4):

$$\rho_1(\psi) + \rho_2(\psi) = D \tag{1}$$

$$P_1 \approx P_2 \tag{2}$$

$$P_1 = k_1 \delta_1 h_1 \tag{3}$$

$$P_2 = k_2 \delta_2 h_2 \tag{4}$$

where

δ the width of the section

h the height of the section.

Let one examine the generation of geometry towards a pre-treated hole with a radius r_0 (Figure 1).

In accordance with Figure 1, and as shown in equation (5):

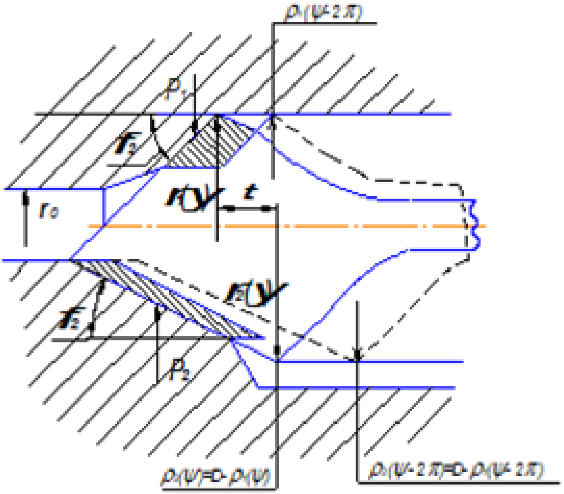
$$\begin{aligned} \delta_1 &= S \cdot tg\varphi_1 + \rho_1(\psi) - \rho_1(\psi - 2\pi) \\ \delta_2 &= S \cdot tg\varphi_2 - \rho_2(\psi) + \rho_2(\psi - 2\pi) \end{aligned} \tag{5}$$

$$\begin{aligned} h_1 &= \rho_1(\psi) - \frac{tg\varphi_1 \cdot tg\varphi_2}{tg\varphi_1 - tg\varphi_2} \cdot \left[\frac{D - \rho_1(\psi - \pi)}{tg\varphi_2} - \frac{\rho_1(\psi - 2\pi)}{tg\varphi_1} - \tau + \frac{S}{2} \right] \\ h_2 &= \frac{tg\varphi_1 \cdot tg\varphi_2}{tg\varphi_1 - tg\varphi_2} \cdot \left[\frac{D - \rho_1(\psi)}{tg\varphi_2} - \frac{\rho_1(\psi - \pi)}{tg\varphi_1} - \tau + \frac{S}{2} \right] - r_0 \left(\psi - \psi_0 \right) \end{aligned} \tag{6}$$

Based on formulas (3), (4), (5) and (6) in equation (1), we obtain:

$$
\begin{aligned}
&k_1\left[\rho_1(\psi)+S\cdot tg\phi_1-\rho_1(\psi-2\pi)\right]\cdot\Big[\rho_1(\psi)\left(tg\phi_1-tg\phi_2\right)-D\cdot tg\phi_1+\rho_1(\psi-\pi)\cdot tg\phi_1\\
&+\rho_1(\psi-2\pi)\cdot tg\phi_2+tg\phi_1\cdot tg\phi_2\cdot\left(\frac{S}{2}-\tau\right)\Big]\\
&=k_2\left[-\rho_1(\psi)+S\cdot tg\phi_2+\rho_1(\psi-2\pi)\right]\cdot\Big[D\cdot tg\phi_1-\rho_1(\psi)\cdot tg\phi_1-\rho_1(\psi-\pi)\cdot tg\phi_2\\
&+tg\phi_1\cdot tg\phi_2\cdot\left(\frac{S}{2}-\tau\right)-r_0\cdot\left(tg\phi_1-tg\phi_2\right)\Big]
\end{aligned}
\tag{7}
$$

Figure 1 The design model for the generation of geometry by a tool with different angles within the plan and a pre-treated hole (see online version for colours)



The values of *A*, *B*, *C* and *E* can be obtained by equations (8), (9), (10) and (11), respectively:

$$A=Stg\varphi_1-\rho_1(\psi-2\pi) \tag{8}$$

$$B=\rho_1(\psi-\pi)\cdot tg\phi_1+\rho_1(\psi-2\pi)\cdot tg\phi_2-D\cdot tg\phi_1+tg\phi_1\cdot tg\phi_2\cdot\left(\frac{S}{2}-\tau\right) \tag{9}$$

$$C=S\cdot tg\phi_2+\rho_1(\psi-2\pi \tag{10}$$

$$E=D\cdot tg\phi_1-\rho_1(\psi-\pi)\cdot tg\phi_2\cdot\left(\frac{S}{2}-\tau\right)-r_0\cdot\left(tg\phi_1-tg\phi_2\right) \tag{11}$$

Based on formulas (8)–(10), equation (11) is:

A quadratic equation in the form of equation (12) was obtained by:

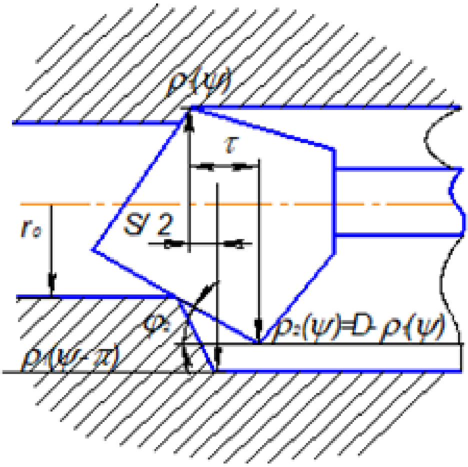
$$P_1=k_1\left(tg\phi_1-tg\phi_2\right)-k_2\cdot tg\phi_2 \tag{12}$$

The solution of this formula refers to the generation of tool model geometry with the above-described dissymmetry:

$$\rho_1(\psi) = -\frac{P_2}{2 \cdot P_1} + \sqrt{\left(\sqrt{\frac{P_2}{2P_1}}\right)^2} - \sqrt{\frac{P_2}{P_1}} \tag{13}$$

When extreme dissymmetry of tools and blade cutting properties with unequal angles within the plan occur, the blade with a smaller main angle does not cut but rests on the edge formed by the intersection of the cut surface with the pre-treated surface (Figure 2); one can obtain a geometric-kinematic model as follows.

Figure 2 Design model for the generation of geometry in the case of a location on the edge (see online version for colours)



According to Figure 2, the following set of equations can be obtained:

$$r_0.ctg\left(\varphi_1\right) = m \tag{14.1}$$

$$r_0.ctg\left(\varphi_2\right) = m + a \tag{14.2}$$

$$r_0 ctg\varphi_2$$

In solving a system of equations comprised of equations (14.1) and (14.2), we obtain equation (15):

$$a = r_0.\left[ctg\left(\varphi_2\right) - tg\left(\varphi_1\right)\right] \tag{15}$$

Then:

$$\rho_2(\psi) \cdot tg\phi_2 = a + \left(\tau - \frac{S}{2}\right) + \rho_1(\psi - \pi) \cdot ctg\phi_1 \tag{16.1}$$

and

$$\rho_1(\psi) = D - r_0 \cdot \left(1 - \frac{tg\phi_2}{tg\phi_1}\right) - \left(\tau - \frac{S}{2}\right) \cdot tg\phi_2 + \rho_1(\psi - \pi) \cdot \frac{tg\phi_2}{tg\phi_1} \tag{16.2}$$

A similar asymptotic transition from the model (Figure 3):

$$A \cdot w(\psi) = w(\psi - n\pi) + C \tag{17}$$

where

$$A = 1 + \frac{S}{2t} \cdot tg\phi + \frac{\tau}{t} \cdot \frac{k_2 - k_1}{k_2 + k_1} + \frac{ky\pi p}{k_2 + k_1} \cdot \frac{tg\phi}{t}$$

$$C = tg\phi\left(\frac{S}{2} \cdot \frac{k_2 - k_1}{k_2 + k_1} + \tau\right)$$

Figure 3 A design scheme for the generation of the geometry for a two-blade tool at $\tau < S/2$ (see online version for colours)

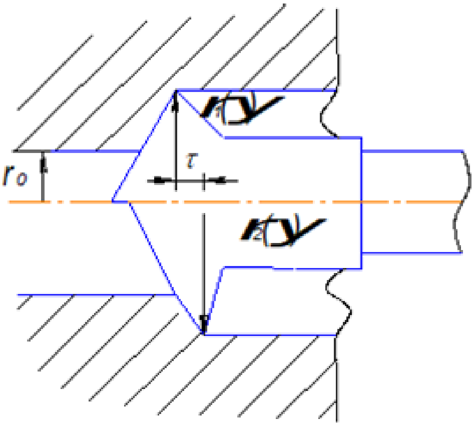
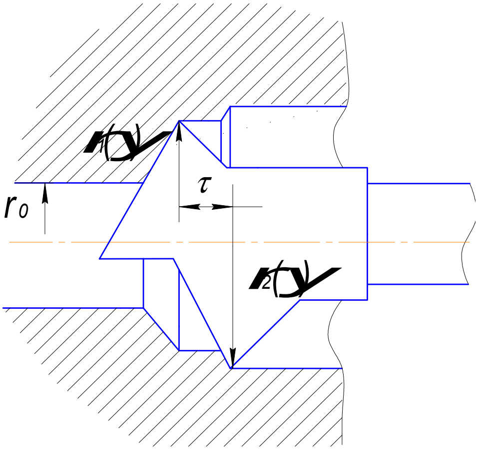


Figure 4 A design model for the generation of the geometry of a two-blade tool at $\tau > S/2$ (see online version for colours)



The model of processing with a single-sided cutting tool located on the machine surface is represented in Figure 4:

$$\rho_1(\psi) = -\rho_1(\psi - \pi \cdot n) \cdot D(1)$$

4 Results and discussion

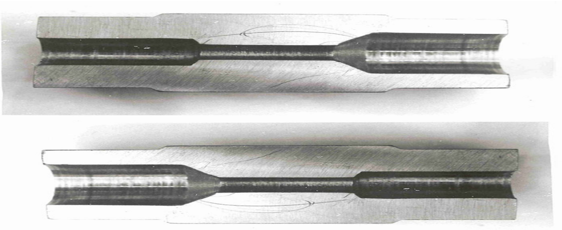
In this section, the theoretical concepts of Section 2.1 and the theoretical knowledge of Section 2.2 are applied in a practical case. The locating chart of the tool on the machine and work surfaces were designed on the cut surface and the edge. Moreover, the scheme was used to obtain a hole with a constant diameter and this is presented in the case of tool deterioration.

Thus, we designed models at the geometric-kinematic level, which can be divided into four varieties:

- models with a location on the machine surface
- models with a location on the cut surface
- models with a location on a preliminary surface
- models with a location on the edge of the intersection between the cut surface and the preliminary surface.

The locating charts for the work surface and the pre-processed surface can be compared. The obtained holes differ by one and a half times as shown in Figure 5.

Figure 5 Holes for various locating charts of the cutting tool



The specific examples of ID tooling processes can be compared with a gun drill with compensation for dimensional wear for tools at different locations.

Example 1: In sharpening a tool, there is a decrease in diameter due to dimensional wear so that the cam locates on the cut surface during the dimensional wear (Figure 6).

Moreover, the distance between the vertices of the cam and blade τ from the ratio, equation (18) can be determined.

$$D_0 = D_{\text{ин}} + \left(\frac{S}{2} - \tau\right) \cdot tg\varphi \qquad (18)$$

When necessary and using the diameter measurement of the tool, the resharpening is produced and provides the calculated value of τ.

Example 2: In the case of multi-faced ID tooling with a large-length (Deryabin, 2016; Deryabin and Golovachev, 2018; O'Toole et al., 2020) (Figure 7), for example, tool 1 shows that the boring tool is worn so and the generated hole is conical

In the next transition, processing is maintained with a tool that locates using its cam on the surface of the conical hole. Due to the conical form of the hole, the 2nd tool will deviate in the radial direction from the value of the current wear size δ_{p1} of the tool 1, and tool 2 itself will have the current dimensional wear δ_{p2}. By equalising the values of dimensional wear for tools 1 and 2, i.e., by the provision of $\delta_{p1} = K \cdot \delta_{p2}$, it is possible to obtain a hole of a constant diameter. In this case, the K coefficient refers to a design feature of tool 1. Thus, for one-sided cutting tools $K = 2$ and two-blade tools have $K = 1$. Furthermore, the maintenance of the dimensional wear specified proportionality by the appropriate cut modes that apply to tool materials and other processing conditions can be obtained.

Figure 6 The diameter maintenance of the hole under processing within tool diameter reduction

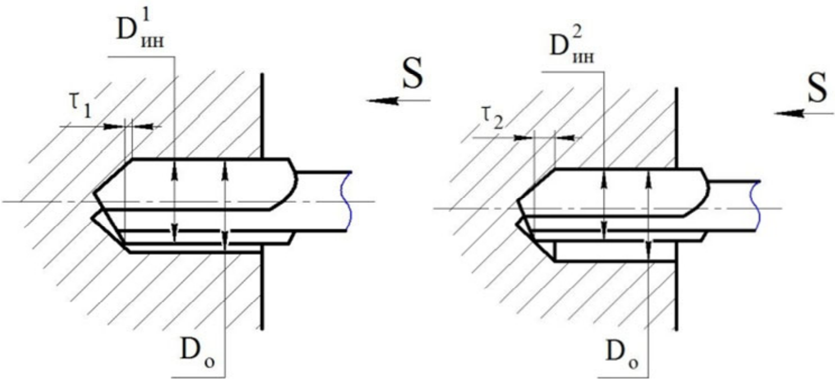
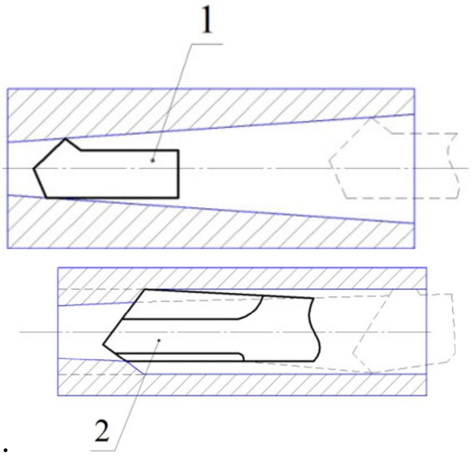
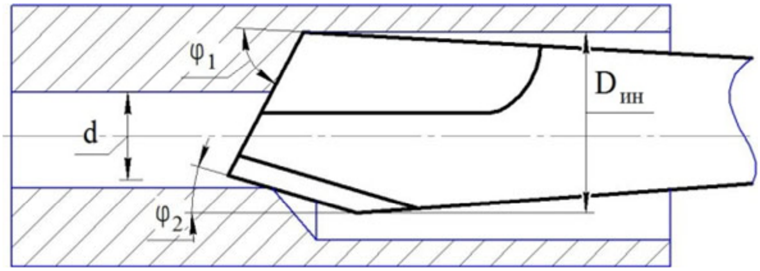


Figure 7 The compensation of dimensional wear for the tool (see online version for colours)



Example 3: Processing of a pre-formed hole occurs with a tool and the cam rests on the transition edge (Figure 8) (Deryabin and Golovachev, 2018). In this case, compensation for dimensional wear can be provided in several ways. First, it is similar to the method under description and in Example 1, i.e., by the change in the value of *τ*. Second, by a proportionality provision of dimensional wear that automatically compensates for tool wear on the first and second transitions.

Figure 8 A hole design of the same diameter with an increase in tool wear (see online version for colours)



Consist with the most recent overview (O'Toole et al., 2020), in Example 1, the measurement and monitoring of tool body diameter permits the prediction of maintenance/replacement of the tool and allows a maintained quality of machined parts. Example 2 represents a method to correct the trajectory of the tool that might be affected by excessive wear. The method is based on the changing geometry of the tool. In Example 3, a useful and effective method for minimising wear during machine operation is presented. Automatic compensation of tool wear is of the utmost importance for practical application. In this section, it is possible to see that the methodologies already developed can be applied to practical cases. The existing approaches can be applied to any machining application comprising end measurement tools, as to improve its stability. The developments of this work can be successfully used for improving the stability of end measuring tools, resulting in machined parts of better geometric tolerance and potentially in more even surface roughness.

5 Conclusions

The differential methods stated above were shown to significantly increase the service life of tools beyond their dimensional stability in terms of dimensional wear. The applied differential methods are simple and cost-effective. These methods can be successfully used to increase the service life of all end measurement tools. This is because qualitatively, all regularities toward the generation of geometry with one-sided cutting tools are inherent in blade tools whose blades have different cutting properties. Moreover, all examples stated in Section 3 can be applied in suitable situations in engineering practice. Therefore, they can be used as a guide for mechanical design and industrial engineers working in the field of machine design and operation. From a practical point of view, the feasibility and usefulness of this work can be successfully demonstrated. In the future, the methodology can be further tested in different practical cases, which can be different machining processes. It can also be tested in different processing conditions, for different machined geometries and different cutting tools. New experimental results may allow to further adjust the methodology to get more accurate results for specific situations.

References

Altintas, Y. and Weck, M. (2004) 'Chatter stability of metal cutting and grinding', *CIRP Annals*, Vol. 53, No. 2, pp.619–642, ISSN: 0007-8506 [online] https://doi.org/10.1016/S0007-8506(07)60032-8.

Balla, O.M. (2018) *Processing of Details on CNC Machines, Equipment, Rigging, Technology: Tutorial*, 3d ed., Lan Publishing House, Saint Petersburg, Russia.

Bellotti, M., Caballero, J.R.D.E., Qian, J. et al. (2021) 'Effects of partial tool engagement in micro-EDM milling and adaptive tool wear compensation strategy for efficient milling of inclined surfaces', *Journal of Materials Processing Technology*, Vol. 288, p.116852, DOI: 10.1016/j.jmatprotec.2020.116852.

Deryabin, I.P. (2016) *Investigation of the Durability of Multifaceted Non-resurfaced Plates During Turning of Titanium Alloys*, pp.66–72, Deryabin, Trekhgorny.

Deryabin, I.P.P. and Golovachev, S.Y. (2018) *Investigation of the Influence of Axial Vibrations When Drilling Deep Holes*, pp.87–88, Deryabin I Publishing House, Dechko EM.

Hughel, T.J. (1960) 'An investigation of the precision mechanical properties of several types of beryllium', in Holden, F.C. (Ed.): *A Review of Dimensional Instability in Metals*, General Motors Research Staff Report MR-120, 3 April 1960, Defense Metals Information Center, Battelle Memorial Institute, Columbus 1, Ohio.

Kabaldin, Y.G., Seryi, S.V., Prosolovich, A.V. and Burdasov, E.N. (2010) 'Improving the stability of cutting on the basis of fractal, dimensional, and wavelet analysis', *Russian Engineering Research*, Vol. 30, No. 6, pp.587–595, Allerton Press, Inc., original Russian text was published in Vestnik Mashinostroeniya,

Kang, X. and Tang, W. (2018) 'Micro-drilling in ceramic-coated Ni-superalloy by electrochemical discharge machining', *Journal of Materials Processing Technology*, Vol. 255, pp.656–664, DOI: 10. 1016/j.jmatprotec.2018.01.014.

Kossowsky, R. and Brown, N. (1964) 'Microyield study of dispersion St re asthenia' in spheroidized steel at room temperature', in Holden, F.C. (Ed.): *A Review of Dimensional Instability in Metals*, Technical Report on Contract No. 551001 to Office of Naval Research, 7 February, Defense Metals Information Center, Battelle Memorial Institute, Columbus 1, Ohio.

Kum, C.W., Wu, C.H., Wan, S. et al. (2020) 'Prediction and compensation of material removal for abrasive flow machining of additively manufactured metal components', *Journal of Materials Processing Technology*, Vol. 282, pp.116704–116704, DOI: 10. 1016/j.jmatprotec.2020. 116704.

Kumar, K.V.B.S. and Choudhury, S.K. (2008) 'Investigation of tool wear and cutting force in cryogenic machining using design of experiments', *Journal of Materials Processing Technology*, Vol. 203, pp.95–101.

Lament, B.S. and Averbach, B.L. (1955) 'Measurement and control of the dimensional behavior of metals', in Holden, F.C. (Ed.): *A Review of Dimensional Instability in Metals*, Report R-95, December, Massachusetts Institute of Technology, Defense Metals Information Center, Battelle Memorial Institute, Columbus 1, Ohio.

Law, K.M., Geddam, A. and Ostafiev, V.A. (1999) 'A process-design approach to error compensation in the end milling of pockets', *Journal of Materials Processing Technology*, Vols. 89–90, pp.238–244, DOI: 10.1016/s0924-0136(99)00031-x.

Liu, Y. and Qu, N. (2020) 'Obtaining high surface quality in electrolyte jet machining TB6 titanium alloy via enhanced product transport', *Journal of Materials Processing Technology*, Vol. 276, pp.116381–116381, DOI: 10.1016/j.jmatprotec.2019.116381.

Luo, X., Cheng, K., Webb, D. et al. (2005) 'Design of ultra-precision machine tools with applications to manufacture of miniature and micro components', *Journal of Materials Processing Technology*, Vol. 167, Nos. 2–3, pp.515–528, DOI: 10.1016/j.jmatprotec.2005.05.050.

Muir, H., Averbach, B.L. and Cohen, M. (1955) 'The elastic limit and yield behavior of hardened steels'. in Holden, F.C. (Ed.): *A Review of Dimensional Instability in Metals*, Trans. AS/4, Vol. 47, p.380, Defense Metals Information Center, Battelle Memorial Institute, Columbus 1, Ohio.

O'Toole, L., Kang, C.W. and Fang, F.Z. (2020) 'Precision micro-milling process: state of the art', *Adv. Manuf.*, DOI: 10.1007/s40436-020-00323-0.

Pratap, T. and Patra, K. (2018) 'Fabrication of micro-textured surfaces using ball-end micromilling for wettability enhancement of Ti- 6Al-4V', *Journal of Materials Processing Technology*, Vol. 262, pp.168–181, DOI: 10.1016/j.jmatprotec.2018.06.035.

Rahman, M., Lim, H.S., Neo, K.S. et al. (2007) 'Tool-based nanofinishing and micromachining', *Journal of Materials Processing Technology*, Vol. 185, Nos. 1–3, pp.2–16, DOI: 10.1016/j.jmatprotec.2006.03.121.

Reddy, T.N., Shanmugaraj, V., Vinod, P. and Krishna, S.G. (2020) 'Real-time thermal error compensation strategy for precision machine tools', *ICMMM 2019, Materials Today: Proceedings*, Vol. 22, pp.2386–2396.

Sahin, Y. (2009) 'Comparison of tool life between ceramic and cubic boron nitride (CBN) cutting tools when machining hardened steels', *Journal of Materials Processing Technology*, Vol. 209, No. 7, pp.3478–3489, DOI: 10.1016/j.jmatprotec.2008.08.016.

Świć, A., Gola, A., Sobaszek, Ł. and Šmidová, N. (2021) 'A thermo-mechanical machining method for improving the accuracy and stability of the geometric shape of long low-rigidity shafts', *Journal of Intelligent Manufacturing*, Vol. 32, pp.1939–1951 [online] https://doi.org/10.1007/s10845-020-01733-4.

Totis, G., Albertelli, P., Torta, M., Sortino, M. and Monno, M. (2017) 'Upgraded stability analysis of milling operations by means of advanced modeling of tooling system bending', *International Journal of Machine Tools and Manufacture*, Vol. 113, pp.19–34.

Uekita, M. and Takaya, Y. (2016) 'On-machine dimensional measurement of large parts by compensating for TRIC errors of machine tools', *Precision Engineering*, Vol. 43, pp.200–210.