Pergamon

International Journal of Machine Tools & Manufacture 41 (2001) 89–101

INTERNATIONAL JOURNAL OF
MACHINE TOOLS & MANUFACTURE
DESIGN, RESEARCH AND APPLICATION

A new tooling mechanism for CNC lathes

X. Daniel Fang *, N.J. Lee

Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, USA

Received 2 February 1998; received in revised form 16 June 2000; accepted 10 July 2000

Abstract

The paper describes details of the development of a new CNC lathe tooling mechanism with on-line adjustable cutting edge inclination angle, which is one of the major tool geometry parameters in machining operations. The mechanism is based on the combination of (i) three linkages which adjust the tool inclination angle automatically and continuously, (ii) three curved slots which work simultaneously to compensate the tooltip deviations accurately, and (iii) an input link driven by a linear stepping motor that converts the linear stroke into tool angle rotation. The prototype developed provides a new tooling mechanism for the prospective open architecture-based CNC machines. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Tool inclination angle; Tool geometry; CNC machining

1. Introduction

Tool geometry parameters play an important role in determining the overall machining performance, including cutting forces, tool wear, surface finish, chip formation and chip breaking [1,2]. The importance of optimizing tool geometry has been highlighted recently to be of enormous economic significance in maximizing tool life in machining [3]. Over the past few decades, many investigations have been made to study the important effects of tool geometry, including tool inclination angle, on machining performance. It is well known that the tool inclination angle is a major factor in determining the chip flow direction in machining [4] and has been used in various mathematical models of chip flow [5,6]. In finish turning process, a well-controlled tool inclination angle can effectively guide the chip to flow in a desired direction to reduce the risk of chip entanglement [7,8] and protect the machined surface, thus achieving effective chip control

* Corresponding author. Currently with Stellram, 1 Teledyne Place, LaVergne, TN 37086, USA. Tel.: +1-615-641-4110; fax: +1-615-641-4441.

E-mail address: dfang@stellram.com (X.D. Fang).

PII: S0890-6955(00)00059-6

in automated machining systems. Tool inclination angle has also been included in some researchers' machinability models [9,10] due to its significant effect on cutting forces.

CNC machines are the core of CIM. With the recent worldwide R&D efforts in developing new-generation CNC machines equipped with open-architecture control systems which allow modular integration of sensors, process monitoring and control units with CNC machines, not only the cutting tool path but the machining process performance could be programmed and controlled in real-time CNC machining operations [11–13]. However, no successful work has been reported on development of the tooling mechanism with on-line controllable tool geometry that can be used in CNC machines. There are only two relevant reports based on a recent literature survey in the field.

The first one, published by Kolder and Ber in 1990 [14], is a mechanical universal toolholder which allows the user to set up the optimal tool geometry parameters through continuous change of the tool angles. However, the prototype they developed is not applicable to real-time control requirements or CNC machining operations due to the following two major limitations,

1. The mechanism for setting the tool angles is based on the off-line manual operation.
2. The resulting tooltip deviations have to be adjusted manually by the try-and-see method.

The second one, published in 1996 by Fang and Najmossadat [15], has the ability of automatic control of the tool inclination angle, however, their prototype also has limited applications, mainly due to the following two reasons:

1. The tool angle changing mechanism is based on three linear slopes to approximately compensate tooltip deviations, thus results in limited changing range of the tool inclination angle (only ±5°) and limited compensation accuracy of tooltip deviations.
2. The clamping mechanism is only limited to the manual type of lathes. Obviously, there is not much sense for a manual machine to have the function of on-line adjustable tool geometry.

A need is therefore identified to improve the previous work [15] by introducing a new mechanism with better tooltip compensating accuracy, a wider range of angle adjustment and a mechanical structure suitable for CNC machines. A three linkages and three curved slots combined mechanism has been developed in this work to overcome the two limitations as above-mentioned. The three curved slots, which are nonlinear in nature, have proven to be accurate in automatically compensating tooltip deviations for a wide adjusting range of tool inclination angles.

2. Description of the new CNC tooling mechanism

It has long been known that tool inclination angle plays an important role in determining the machining performance, thus it would be desirable if the inclination angle can be on-line controlled in CNC machine-based automatic machining systems.

2.1. Basic structure of the new CNC tooling mechanism

For the new CNC tooling mechanism, the tooltip always keeps at a desired point in space, i.e. its working point, without any deviation while the tool inclination angle is being changed simultaneously during the machining process.

The new tooling mechanism is structured by

1. three linkages which adjust the tool inclination angle automatically and continuously;
2. three curved slots that work simultaneously to compensate tooltip deviations;
3. a standard toolholder for standard indexable tool inserts;
4. a stepping motor with linear output; and
5. a standard tool shank or adapter that can be attached to the tool turret on CNC lathes.

The entire tooling system including the stepping motor fits into the standard tool shank on the turret inside CNC lathes. The mechanism of the three linkages/three curved slots is schematically shown in Fig. 1.

2.2. Formulation of the tooltip deviations resulted from a change in inclination angle

For a tool holder to be able to change the inclination angle in 3-D (oblique) machining processes, it is necessary to rotate the toolholder about one point, which functions as a fulcrum, on the toolholder. The tooltip cannot be chosen as that point because it is the contact point between tool and workpiece. Assuming that the toolholder rotates about point A, the tooltip will have two types of deviations from the contact point with the workpiece, the height deviation h and the

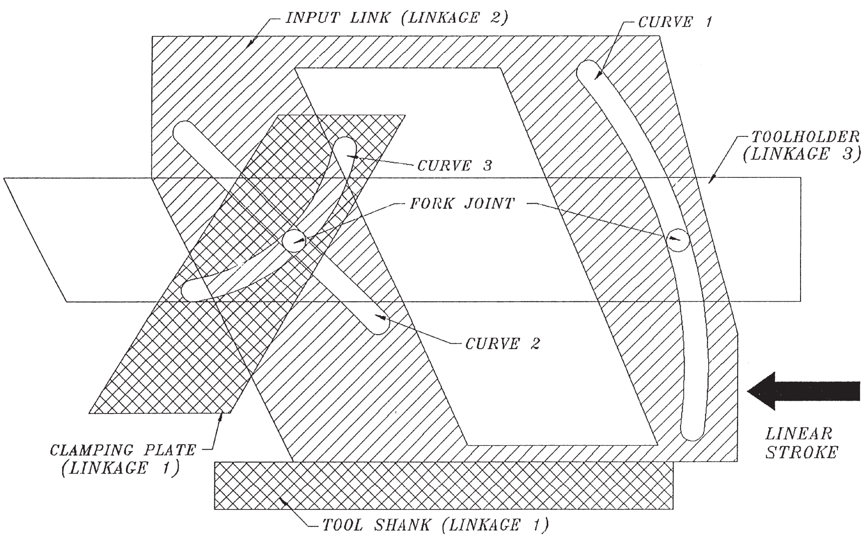

Fig. 1. Schematic diagram of the new CNC tooling mechanism.

radial deviation r as shown in Fig. 2. The equations of the deviations can be referred to the previous work [15], that is,

$$\text{Height Deviation: } h=\sqrt{\left(\frac{w}{2}\right)^2+L_1^{2*}}\sin(\alpha+\theta)-\frac{w}{2} \tag{1}$$

$$\text{Radial Deviation: } r=L_1-\sqrt{\left(\frac{w}{2}\right)^2+L_1^{2*}}\cos(\alpha+\theta) \tag{2}$$

where w is the height of the toolholder, L_1 is the distance between the tooltip and the fulcrum on the toolholder, α is a function of w and L_1, and θ is the angle being rotated which is equal in magnitude to the required inclination angle.

It should be noted that the tooltip deviations are not symmetric about the workpiece axis. It means, for example, that the radial deviation when the angle is $+\theta$ will be different from when it is $-\theta$. Therefore, h^+ and r^+ are used to refer to the tooltip deviations when the angle θ is positive, and h^- and r^- for a negative angle.

According to Fig. 2, the deviation equations can be further simplified for the convenience in formulation and calculation.Height deviation:

$$h=\sqrt{\left(\frac{w}{2}\right)+L_1^{2*}}\sin(\alpha+\theta)-\frac{w}{2}=\frac{\frac{w}{2}}{\sin\alpha}(\sin\alpha\cos\theta+\cos\alpha\sin\theta)-\frac{w}{2}=\frac{w}{2}\left(\cos\theta+\frac{\sin\theta}{\tan\alpha}\right)-\frac{w}{2}$$

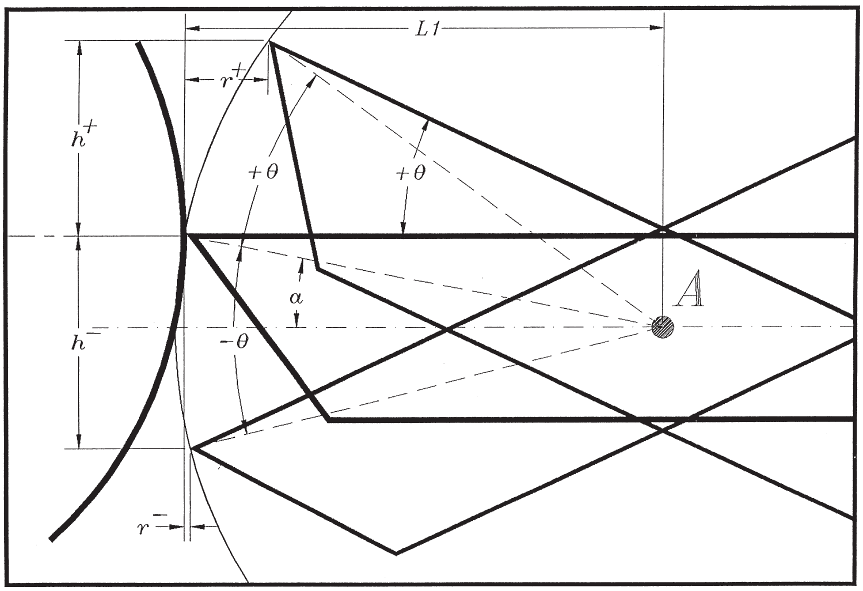

Fig. 2. Tooltip deviations due to the change of the tool inclination angle (assuming A is the fulcrum).

$$=\frac{w}{2}\left(\cos\theta+\frac{2L_1}{w}\sin\theta\right)-\frac{w}{2}$$

thus,

$$h=L_1\sin\theta+\frac{w}{2}(\cos\theta-1) \tag{3}$$

Radial deviation:

$$r=L_1-\sqrt{\left(\frac{w}{2}\right)^2+l_1^{2}}*\cos(\alpha+\theta)=L_1-\frac{\frac{w}{2}}{\sin\alpha}(\cos\alpha\cos\theta+\sin\alpha\sin\theta)=L_1+\frac{w}{2}\left(\frac{\cos\theta}{\tan\alpha}-\sin\theta\right)=L_1$$

$$+\frac{w}{2}\left(\frac{2l_1}{w}\cos\theta-\sin\theta\right)$$

thus,

$$r=\frac{w}{2}\sin\theta+L_1(1-\cos\theta) \tag{4}$$

2.3. Mechanism and design of three curved slopes

The mechanism of three curved slots that work simultaneously can be illustrated in Fig. 3. To compensate the tooltip deviations when the toolholder is rotating, point A has to move simul-

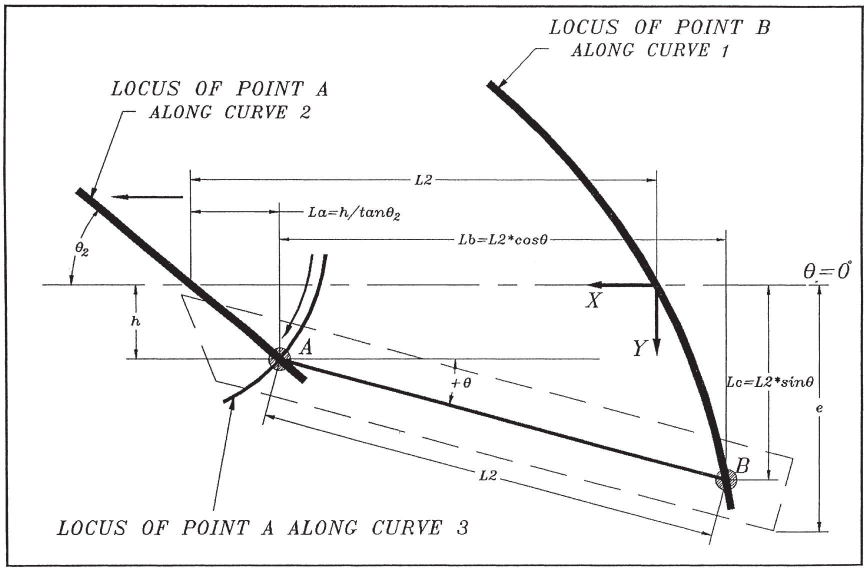

Fig. 3. Principle diagram showing three curved slots that work simultaneously to automatically compensate tooltip deviations.

taneously. This can be achieved by setting point A to move along a fixed and curved slot (Curve 3). A hole is made at point A, and a shaft is inserted through the hole and the curved slot (Curve 3). Thus, if the shaft moves along Curve 3, point A on the toolholder will move at the same distance along Curve 3 accordingly. Curved Slot 2 (Curve 2) is added between the toolholder and Curve 3 in order to move the shaft, and hence, point A along Curve 3. When Curve 2 travels linearly to the right relative to Curve 3, the shaft will be pushed up along Curve 3. To be able to change the tool inclination angle, point B on the toolholder must move along a curved slot (i.e. Curve 1) relative to point A. Both Curves 1 and 2 are set on a moving input link. It should be noted that Curves 1 and 2 have an inherent relationship because the location of point B on Curve 1 depends on the location of point A on Curve 2 for any required tool inclination angle.

Curve 3 should be designed in such a way that it will make point A move to the opposite direction but at the same distance with respect to the tooltip deviations. As a result when the tool inclination angle is rotated by an angle θ, the distance that point A should move in X direction must be equal to the tooltip radial deviation at the same angle θ. Similarly, the distance that point A should move in Y direction must be equal to the tooltip height deviation at the same angle θ. Therefore, according to the coordinate system shown in Fig. 3, the equation of Curve 3 can be expressed as,

$$x(\theta)=r=\frac{w}{2}\sin\theta+L_1(1-\cos\theta) \tag{5}$$

$$y(\theta)=h=L_1\sin\theta+\frac{w}{2}(\cos\theta-1)$$

The function of Curve 2 is to move point A along Curved Slot 3, as shown in Fig. 3. The vertical height of Curve 2 must be larger than the total height deviation of the tooltip. The minimum length of Curve 2 can be found as

$$\min L_2=\frac{h^+}{\tan\theta_2}+\frac{h^-}{\tan\theta_2} \tag{6}$$

where:

θ_2 the slope angle of Curve 2;
h^+ the positive maximum tooltip height deviation;
h^- the negative maximum tooltip height deviation;

L_2 is also the distance between Curve 1 and Curve 3 when both are at the center line of the toolholder corresponding to the tool inclination angle=0.

The angle of Curve 2 (θ_2) and the stroke (Ls) are inversely proportional. Either of them should be chosen, considering the availability of working space. The stroke Ls is the distance the input link travels.

The function of Curve 1 is to move point B relative to point A until the desired tool inclination angle is reached. Curve 1 is obtained by determining the position of point B relative to the position of point A on Curve 2. According to the coordinate system shown in Fig. 3, the equation for Curve 1 can be derived as,

$$x(\theta)=L_2-(L_a+L_b)=L_2-\frac{h}{\tan\theta_2}-L_2\cos\theta=L_2(1-\cos\theta)-\frac{L_1\sin\theta+\frac{w}{2}(\cos\theta-1)}{\tan\theta_2} \quad (7)$$

$$y(\theta)=L_c=h+L_2\sin\theta=(L_1+L_2)\sin\theta+\frac{w}{2}(\cos\theta-1)$$

2.4. Determination of the stroke of the input link

It is important to establish the relationship between the stroke of the input link, which is the linear output from the motor control, and the tool inclination angle so that the magnitude of the stroke can be determined for a required tool inclination angle. According to Fig. 4, the equation for the stroke can be expressed as follows:

$$Ls=x_1+x_2=r+\frac{h}{\tan\theta_2}=\frac{w}{2}\sin\theta+L_1(1-\cos\theta)+\left(\frac{1}{\tan\theta_2}\right)\left(L_1\sin\theta\frac{w}{2}(\cos\theta-1)\right)=\left(\frac{L_1}{\tan\theta_2}-\frac{w}{2}\right)\sin\theta+\left(\frac{w}{2\tan\theta_2}-L_1\right)\cos\theta+\left(L_1-\frac{w}{2\tan\theta_2}\right) \quad (8)$$

If we let $a=\frac{L_1}{\tan\theta_2}-\frac{w}{2}$ and $b=\frac{w}{2\tan\theta_2}-L_1$, Eq. (8) can be further simplified as,

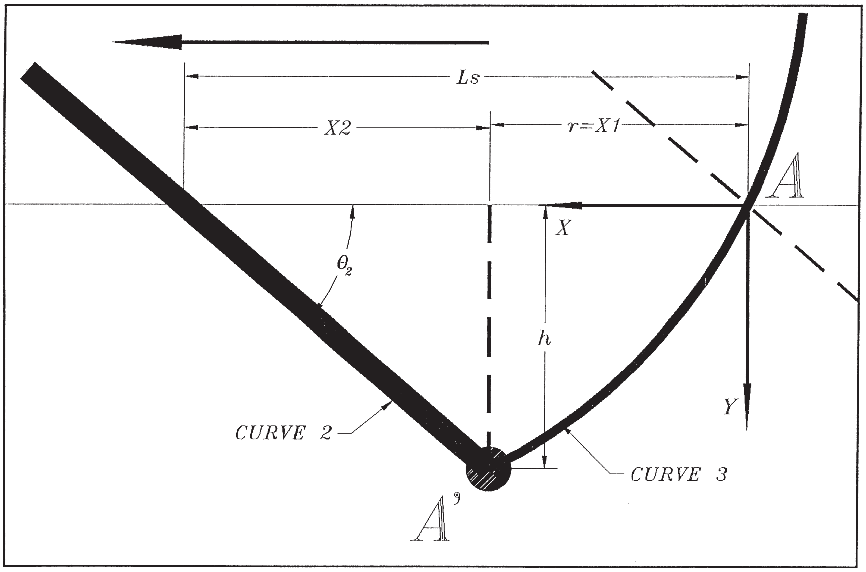

Fig. 4. Formulation of the stroke *Ls* from the motor output in terms of the inclination angle.

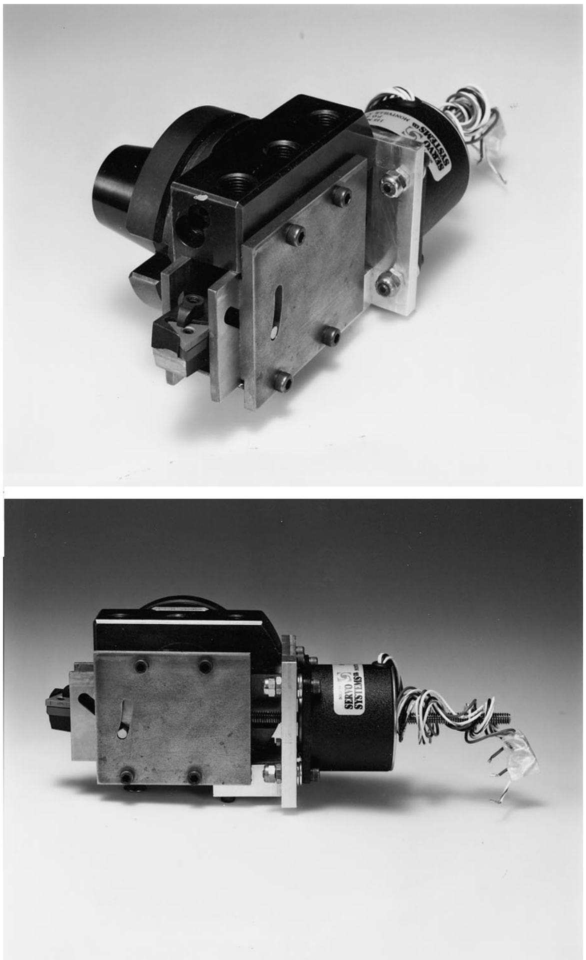

Fig. 5. Photo of the actual prototype of the new CNC tooling mechanism.

$$Ls=\sqrt{a^2+b^2}\sin\left(\theta+\tan^{-1}\frac{b}{a}\right)-b \tag{9}$$

where $\theta=\sin^{-1}\left(\frac{Ls+b}{\sqrt{a^2+b^2}}\right)-\tan^{-1}\frac{b}{a}$.

3. Performance of the new CNC tooling prototype developed

Fig. 5 shows the photo of the actual prototype of the new tooling mechanism for CNC lathes. There are seven major mechanical units that construct the prototype, described as follows.

1. Input link:
   It consists of Curved Slots 1 and 2 and is also used to clamp the toolholder in place.
2. Cover plate:
   It contains Curved Slot 3 and is also used to clamp the input link in place.
3. Motor mounting plate:
   It is used to mount the linear stepper motor that is used to drive the input link.
4. Two shafts:
   They are used to support the holes at points A and B and hold the three slots in place.
5. A standard tool holder with a standard tool insert:
   The toolholder will rotate within the space limit inside the tool shank.
6. A standard tool shank:
   The tool shank is a standard attachment of CNC machines and designed to hold the toolholder on the CNC turret. In this work, the tool shank is also used to hold the whole new CNC tooling mechanism.
7. A stepping motor with linear output:
   The linear output will drive the input link to produce the required stroke corresponding to a tool inclination angle. The three movements, i.e. linkages 1–3 as shown in Fig. 1, will move simultaneously according to the linear stroke which is controlled by the stepping motor.

Fig. 6 shows the computer simulated positions of the new tooling mechanism at three different tool inclination angles. Fig. 7 gives another computer simulation showing that the tooltip stays at the same point, that is, its working point, when the tool inclination angle changes.

The new CNC tooling mechanism can be used to study patterns of cutting forces with continu-

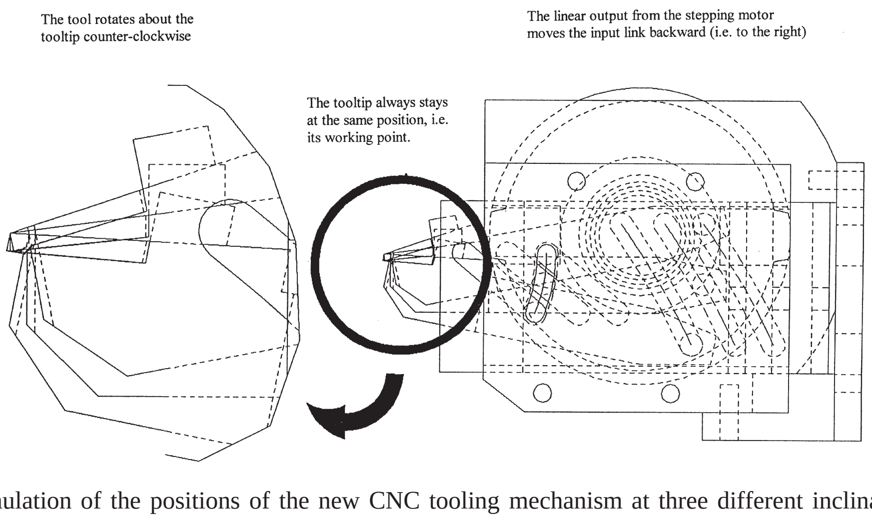

Fig. 6. Simulation of the positions of the new CNC tooling mechanism at three different inclination angles.

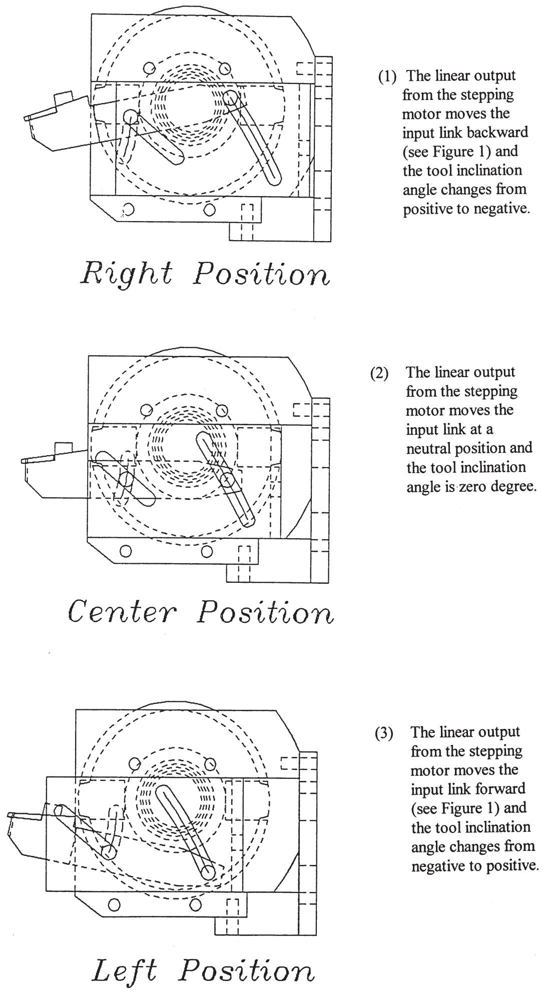

Fig. 7. Simulation of the tooltip locations at three different inclination angles.

ous change of the tool inclination angle, as shown in Fig. 8 for a typical set of results from experimentation where the cutting forces decrease as the tool inclination angle increases. Two case studies using six different tool chip-breakers at the different cutting conditions also confirmed that increasing tool inclination angle decreases the cutting forces, as shown in Fig. 9. The experimental outcomes with different tool chip-breakers also indicate that a controllable tool inclination angle, combined with varying chip-breaker designations, may contribute to on-line optimization of tool geometry in achieving best chip control with reduced cutting forces. Thus, it can be seen clearly that the tool inclination angle has a significant effect on cutting forces, thus an on-line controllable tool inclination angle may play an important role in real-time optimization of machining performance in automated machining systems or in CNC machines equipped with open architecture controllers.

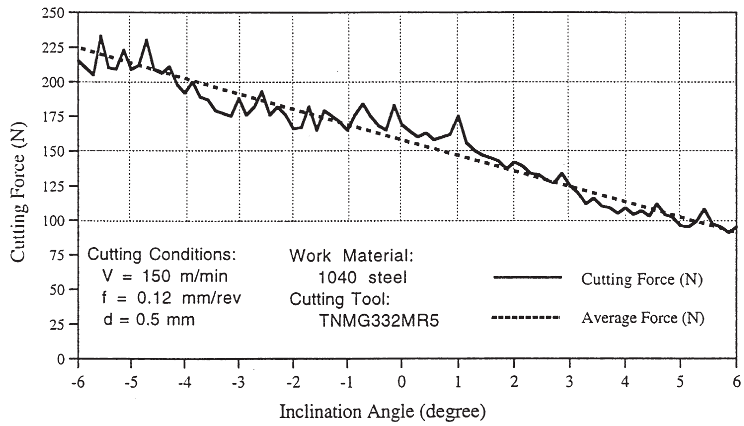

Fig. 8. A typical measurement result of the cutting force pattern with continuing change of the tool inclination angle.

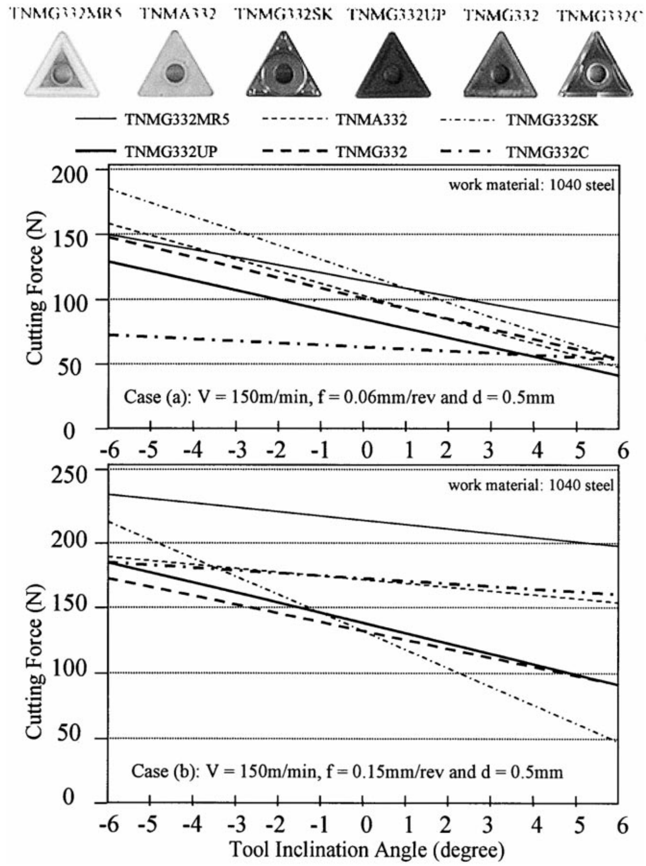

Fig. 9. Cutting force patterns with inclination angles for different tool inserts.

4. Conclusions

With the prospective open-architecture controllers, active control of the on-line machining process performance will become a very important feature of advanced CNC machine functions, allowing both the tool path and the process performance to be programmed and controlled in real-time CNC machining operations. Therefore, the object of this work is to develop a new tooling mechanism with on-line adjustable tool angles to take full advantage of new-generation CNC machines which will be equipped with open-architecture control systems. In effect, an on-line controllable tooling mechanism will be the 'real sense' application of open-architecture CNC control systems.

Tool inclination angle is a major tool geometry parameter in machining and has a significant effect on a number of process performance parameters, such as cutting forces, surface quality, chip flow and formation, process dynamic stability, tool wear/tool life, etc. Thus it is important that the tool inclination angle could be adjusted and controlled in real-time to achieve the optimal machining performance in unattended CNC machining processes.

A motor-controlled toolholder that can be used in CNC machines has been developed with the function of automatic setting of the tool inclination angle and automatic compensation of the resulting tooltip deviations. The new CNC tooling mechanism is a novel design using three curved slots that work simultaneously to compensate continuously and accurately the tooltip deviations resulted from the setting of the tool inclination angle. Since the tooltip always stays at one point in space, i.e. its working point, during the whole adjustment process of the required tool inclination angle, the new tooling mechanism could be used in real-time CNC machining operations to achieve the on-line control of optimal process performance.

References

[1] W. Kluft, W.C. Konig, A. van Luttervelt, K. Nakayama, A.J. Pekelharing, Present knowledge of chip control, Annals of the CIRP 28 (2) (1979) 441–454.

[2] M.C. Shaw, Metal Cutting Principles, Oxford University Press, New York, 1984.

[3] S. Kaldor, P.K. Venuvinod, Macro-level optimization of cutting tool geometry, ASME Journal of Manufacturing Science and Engineering 119 (1997) 1–9.

[4] W.K. Luk, The direction of chip flow in oblique cutting, International Journal of Production Research 10 (1) (1972) 67–76.

[5] Society of Manufacturing Engineers. Fundamentals of Tool Design, Second ed., SME, Dearborn, MI, 1984.

[6] H.Y. Young, P. Mathew, P.L.B. Oxley, Allowing for nose radius effects in predicting the chip flow direction and cutting forces in bar turning, IMechE Proceedings of the Institution of Mechanical Engineers 201 (C3) (1987) 213–226.

[7] C.Y. Jiang, Y.Z. Zhang, Z.J. Chi, Experimental research of the chip flow direction and its application to the chip control, Annals of CIRP 33 (1) (1984) 81–84.

[8] F. Kiyasawa, Observation on the chip entanglement, in Proceedings of the 5th International Manufacturing Conference, Guangzhou, China, Vol. A, 1991, pp. 49–52.

[9] V.C. Venkatesh , Computerized machinability data, in: Proceedings of the 1986 Automach Conference, Sydney, Australia, 1, SME, Dearbon, Vol. 1. 1986, pp. 59–73.

[10] X.D. Fang, I.S. Jawahir, Predicting total machining performance in finish turning using integrated fuzzy-set models of the machinability parameters, International Journal of Production Research 32 (4) (1994) 833–849.

[11] R. McCormack, Manufacturing trade associations form a virtual organization to pursue next generation manufacturing, Manufacturing News 2 (18) (1995) 1–7.

[12] The Editor, Industry, academia team up in engineering, Manufacturing News 3 (12) (1996) 7.
[13] J. Lee, Overview and perspectives on Japanese manufacturing strategies and production practices in machinery industry, International Journal of Machine Tools and Manufacture 37 (10) (1997) 1449–1463.
[14] S. Kaldor, A. Ber, A criterion to optimize cutting tool geometry, Annals of the CIRP 39 (1) (1990) 53–56.
[15] X.D. Fang, S.M.R. Najmossadat, Mechanical design of a new tooling mechanism with on-line controllability of inclination angle, International Journal of Machine Tools and Manufacture 36 (1) (1996) 103–113.