Int. J. Engng Ed. Vol. 11, No. 6, pp. 435–440, 1995
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Application of Computer Aided Animation of Machining Operations in Support of a Manufacturing Course*

X. D. FANG
Department of Mechanical Engineering, University of Wollongong, NSW 2500, Australia

This paper presents details of the development of a computer animation system for maching operations to be used to enhance the teaching effect of a manufacturing course for mechanical engineering students. Such a computer animation system is particularly useful for the situation where it is difficult to arrange appropriate machining experiments due to the large size of class, or the limitation on laboratory facilities, etc. It has been shown that using such a computer animation system can greatly help students understand the machining mechanism because each student can 'operate the machine' on his/her own and observe the dynamic machining process performance by varying the process parameters through the computer keyboard control. It has also been shown, through teaching practice, that the teaching effect can be greatly enhanced by the use of this computer animation system.

1. INTRODUCTION

MECH305 Manufacturing Technology is a third-year subject in the Department of Mechanical Engineering at the University of Wollongong. The class size is normally about 80 students. The subject covers different methods of manufacturing processes with machining operations as the main content. Due to the limitations on laboratory facilities (machine-tools and technical staff) and the size of class, it is difficult to organise some appropriate machining experiments. Thus students do not have opportunities to observe the machining performance and understand the metal cutting principle from actual machining operations. Due to lack of physical understanding about the machining process it will affect students' learning effectiveness on this subject, in particular in the case that most of the students taking this subject come directly from high school and have no practical experience in metal machining.

It has been shown that using computer-aided experimentation can either enhance students' understanding on scientific phenomena and reduce the deficiencies in the existing laboratories to a large extent [1], or improve students' learning efficiency in experiment-related courses [2]. Computer simulation techniques are becoming more popular in assisting the teaching of engineering courses. Representative successful applications of computer simulation in teaching machinery kinematics and dynamics have been reported recently [3, 4], which greatly reinforce students' basic mechanics background.

In our undergraduate course of manufacturing technology (Mech305), two computer programs have beeen developed in an effort to enhance the teaching effect and help students understand the machining processes. The designed computer animation lab work has been well received by students as they can 'operate the machine' on their own and observe the dynamic machining process performance by selecting different process parameters.

2. COMPUTER LAB WORK I—COMPUTER ANIMATION OF BAR TURNING OPERATIONS

The objective of designing computer Lab Work I is to animate the actual machining of round-shape workpiece in terms of dynamic graphic presentation incorporating with the on-line display of predicted machining performance. Students can 'operate the machine' and change cutting conditions through the use of computer keyboard. Shown in Fig. 1 is the schematic diagram of the computer animation of bar turning operations with the details being discussed below. C language was used for developing the computer program for animation.

2.1 *Theoretical background for machining performance prediction*

Cutting power consumption. It is important to predict cutting power consumption, which in practice may best be done in terms of total specific energy (u), since this tends to remain approxi-

---

* Paper accepted 15 February 1995.

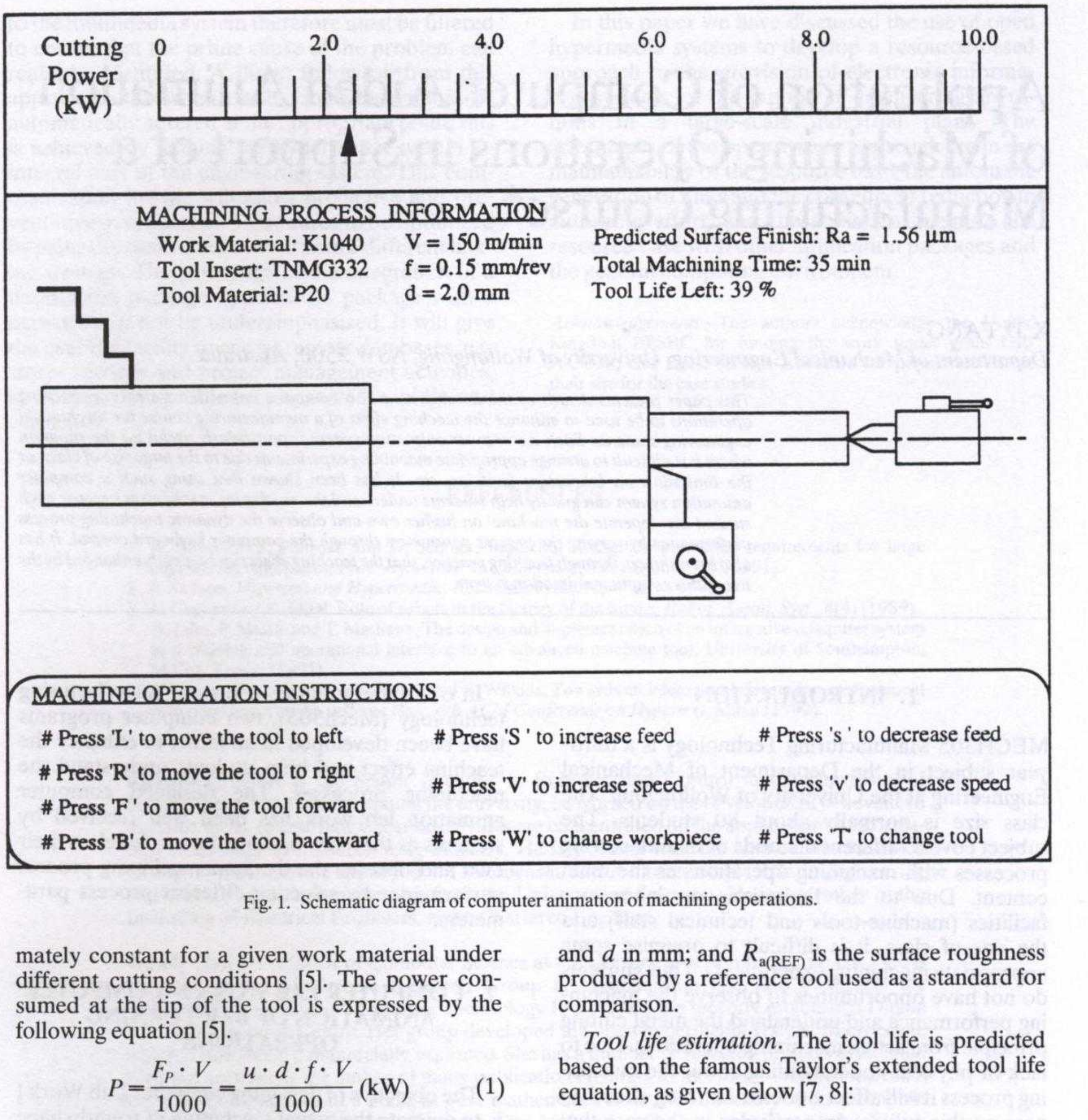

Fig. 1. Schematic diagram of computer animation of machining operations.

mately constant for a given work material under different cutting conditions [5]. The power consumed at the tip of the tool is expressed by the following equation [5].

$$P = \frac{F_P \cdot V}{1000} = \frac{u \cdot d \cdot f \cdot V}{1000} \ (\mathrm{kW}) \qquad (1)$$

where: u is the value of specific energy in Jm^{-3}, depending on different work materials; F_p is the cutting force (N); d is depth of cut (mm); f is feed (mm/rev); and V is cutting speed (m/min).

Surface roughness. The estimation of surface roughness is based on an empirical equation developed from a series of machining experiments [6], as shown below.

$$\begin{cases} R_{a_{ij}} = W_{0_j} + W_{1_j}(C_{0_i} + C_{1_i}(R_{\mathrm{a(REF)}}) \\ R_{\mathrm{a(REF)}} = 6.252 \cdot V^{-0.173748} \cdot f^{0.284038} \cdot d^{0.029483} \end{cases} \qquad (2)$$

where: $R_{a_{ij}}$ is the surface roughness produced using the ith tool insert and the jth work material; W_{0_j} and W_{1_j} are work material coefficients; C_{0_i} and C_{1_i} are tool insert coefficients; V is in m/min, f in mm/rev and d in mm; and $R_{\mathrm{a(REF)}}$ is the surface roughness produced by a reference tool used as a standard for comparison.

Tool life estimation. The tool life is predicted based on the famous Taylor's extended tool life equation, as given below [7, 8]:

$$T = \frac{C}{V^p f^q d^r} \qquad (3)$$

where: T is the tool life in minute; V is in m/min, f in mm/rev and d in mm; and C, p, q and r are the constants which are experimentally determined, mainly depending on the combination of work-tool materials.

For each individual machining operation with varying cutting conditions, the tool life can be expressed as

$$T_i = \frac{C}{V_i^p f_i^q d_i^r} \qquad (4)$$

where the subscript i represents different machining operations using the same tool insert, $i = 1, \ldots, k, \ldots, n$. Let t_i be the machining time for the ith operation. As $\Sigma(t_i/T_i) = 1$ or 100% means that the tool is at the end of its life, the following equation can be used in machining operations to indicate the tool life left in terms of percentage (%),

$$(T_{\mathrm{LEFT}})_k = \left(1 - \sum_{i=1}^{k} \frac{t_i}{T_i}\right) \times 100\% \qquad (5)$$

where the subscript k represents the kth machining operation and $(T_{\mathrm{LEFT}})_k$ means the tool life left after the kth machining operation. When $(T_{\mathrm{LEFT}})_k = 0\%$, it indicates the end of tool life and thus the operator should change the tool insert.

2.2. *Algorithms for computer animation of turning operations*

In order to animate the dynamic relation between the cutting tool and the workpiece being machined, a dynamic graphic matrix *DGM* is introduced as shown below for its initial state DGM_0,

$$DGM_0 = \begin{bmatrix} SC & 0 & 0 \\ W & CT & 0 \\ 0 & 0 & T \end{bmatrix} \qquad (6)$$

where *SC*, *W*, *CT*, and *T* are sub-matrices, representing self-centering chuck, workpiece, center tailstock and tool respectively. All the elements in the matrix are of two values, i.e. 0 and 1.

In the *X–Y* coordinates shown in Fig. 2, which corresponds to a state of dynamic graphic matrix *DGM*, the contents of tool sub-matrix *T* (i.e. the shape of tool) are fixed while its position depends on the operator's operation. The position of workpiece sub-matrix *W*, once its axis has been determined, is unchanged while the contents (i.e. workpiece shape) will be changing with the progress of machining.

Suppose that *T* is a sub-matrix with *n* rows and *m* columns, then, the position of *T* in *DGM* can be expressed by the following one-step equation which indicates the new position of *T* after moving a coordinate unit,

$$\begin{cases} t_{i,j-1} = t_{i,j} \text{ and then } t_{i,j} = 0, \text{(when tool moves left)} \\ t_{i,j+1} = t_{i,j} \text{ and then } t_{i,j} = 0, \text{(when tool moves right)} \\ t_{i-1,j} = t_{i,j} \text{ and then } t_{i,j} = 0, \text{(when tool moves forward)} \\ t_{i+1,j} = t_{i,j} \text{ and then } t_{i,j} = 0, \text{(when tool moves backward)} \end{cases} \qquad (7)$$

where $i = Y_A, Y_A + 1, \ldots, Y_A + n - 1$ and $j = X_A, X_A + 1, \ldots, X_A + m - 1$ by assuming that the coordinates of the tool tip, i.e. Point A in Fig. 2, are (X_A, Y_A).

For the workpiece sub-matrix *W*, suppose that the intersection of workpiece center line and the cross-section being cut is at Point B (X_B, Y_B) shown in Fig. 2, the diameter being cut is ϕ_B and depth of cut is d, then, the new shape of W after being cut for a coordinate unit can be expressed by the following one-step equations.

For longitudinal turning (the tool moves left):

$$\begin{cases} w_{i,j-1} = w_{i,j} \text{ (for newly formed cross-section)} \\ \quad i = Y_B - \frac{\phi_B}{2}, Y_B - \frac{\phi_B}{2} + 1, \ldots, Y_B + \frac{\phi_B}{2} \\ \quad \text{and } j = X_B \\ w_{i,j} = \overline{w_{i,j}} \text{ (for newly formed up and low outlines)} \\ \quad i = Y_B - \frac{\phi_B}{2}, Y_B - \frac{\phi_B}{2} + 1, \ldots, Y_B - \frac{\phi_B}{2} \\ \quad + (d-1) \text{ and } j = X_B \\ \text{and} \\ \quad i = Y_B + \frac{\phi_B}{2}, Y_B + \frac{\phi_B}{2} - 1, \ldots, Y_B + \frac{\phi_B}{2} \\ \quad - (d-1); \text{ and } = X_B. \end{cases} \qquad (8)$$

for face turning (the tool moves forward):

$$\begin{cases} w_{i,j} = w_{i,j-d} \text{ (for newly formed cross-section)} \\ \quad i = Y_B - \frac{\phi_B}{2}, Y_B - \frac{\phi_B}{2} + 1, \ldots, Y_B + \frac{\phi_B}{2} \\ \quad \text{and } j = X_B \\ w_{i+1,j} = 1 \text{ and } w_{i,j} = 0 \text{ (for newly formed up outline)} \\ \quad i = Y_B - \frac{\phi_B}{2} \text{ and } j = X_B - (d-1), X_B \\ \quad - (d-2), \ldots, X_B \\ w_{i-1,j} = 1 \text{ and } w_{i,j} = 0 \text{ (for newly formed low outline)} \\ \quad i = Y_B + \frac{\phi_B}{2} \text{ and } j = X_B - (d-1), X_B \\ \quad - (d-2), \ldots, X_B. \end{cases} \qquad (9)$$

3. COMPUTER LAB WORK II—COMPUTER ANIMATION OF CHIP FORMATION AND CURLING PATTERNS

The computer animation converts the parametric prediction into a series of animated images of chip flow and chip curling during the machining process. By 'operating the machine' under different machining conditions, students may obtain an intuitive and physical understanding about the mechanism of chip formation, which is fundamental to the machining process. In the computer Lab Work II, the software MATHEMATICA has

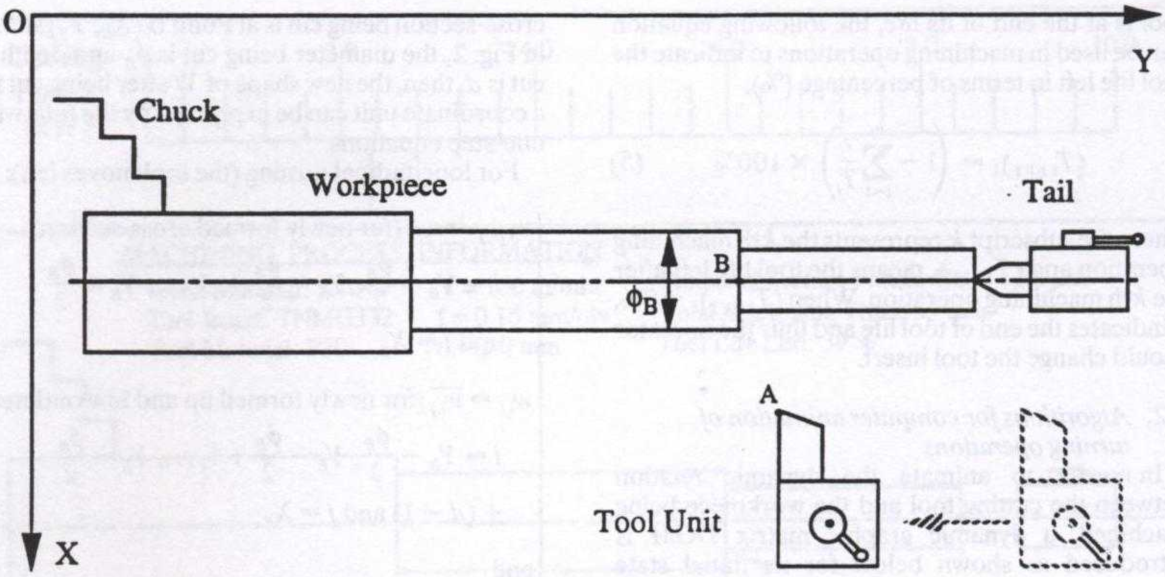

Fig. 2. *X–Y* coordinates for graphic animation of turning operations.

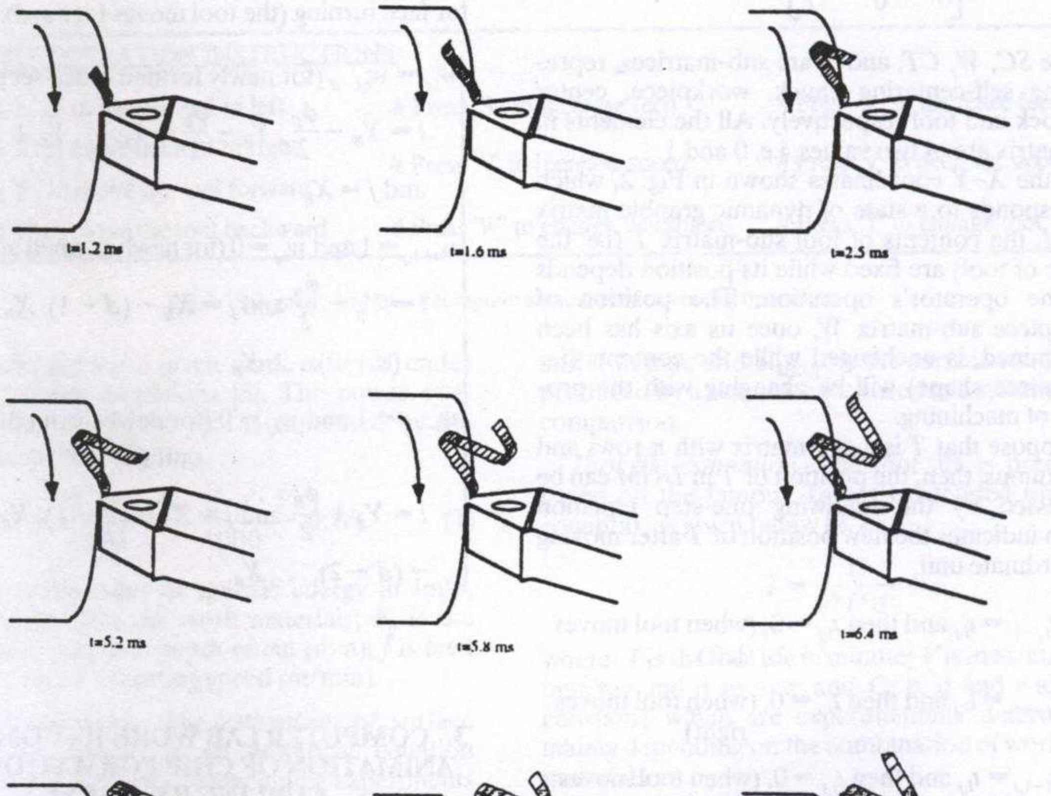

Fig. 3. Animation of chip forming progression (cutting conditions: $V = 150$m/min, $f = 0.2$mm/rev and $d = 2.0$mm).

been selected for computer animation due to its powerful function to convert mathematical formulae into a 3-D graphic animation [9]. Another reason for choosing MATHEMATICA is because the Department of Mechanical Engineering has a site license and students have the easy access to MATHEMATICA through a computer terminal.

3.1. *Theoretical background of chip formation*

In recent research work, Nakayama and Arai [10] have made a comprehensive classification of all possible chip forms and formulated them into a mathematical function of four chip parameters, i.e. radius of upward curvature, radius of sideward curvature, the chip flow angle and chip helix angle with respect to tool rake face, as shown below,

$$\text{Chip radius: } R = \sqrt{\frac{1-\sin^2\eta\cos^2\theta}{(\cos^2\eta/\rho_x^2)+(1/\rho_z^2)}} \tag{10}$$

$$\text{Chip pitch: } p = \frac{2\pi R\sin\eta\cos\theta}{\sqrt{1-\sin^2\eta\cos^2\theta}} \tag{11}$$

where ρ_x and ρ_z are radii of upward and sideward curvatures respectively, θ is the angle between the axis of chip helix and the rake face, and η is the chip flow angle relative to the line of tool–chip separation. All these parameters can be theoretically predicted using some basic assumptions and the given operation conditions including tool insert type, work material and cutting conditions [10, 11].

3.2. *Animation of chip forming progression*

To animate the progression of chip formation, the following equation is derived to describe the relationship between the chip curls and the time consumed

$$\text{Time} = \frac{\text{Chip length produced}}{\text{Chip velocity}} = \frac{2\pi RN}{V_{\text{ch}}} \tag{12}$$

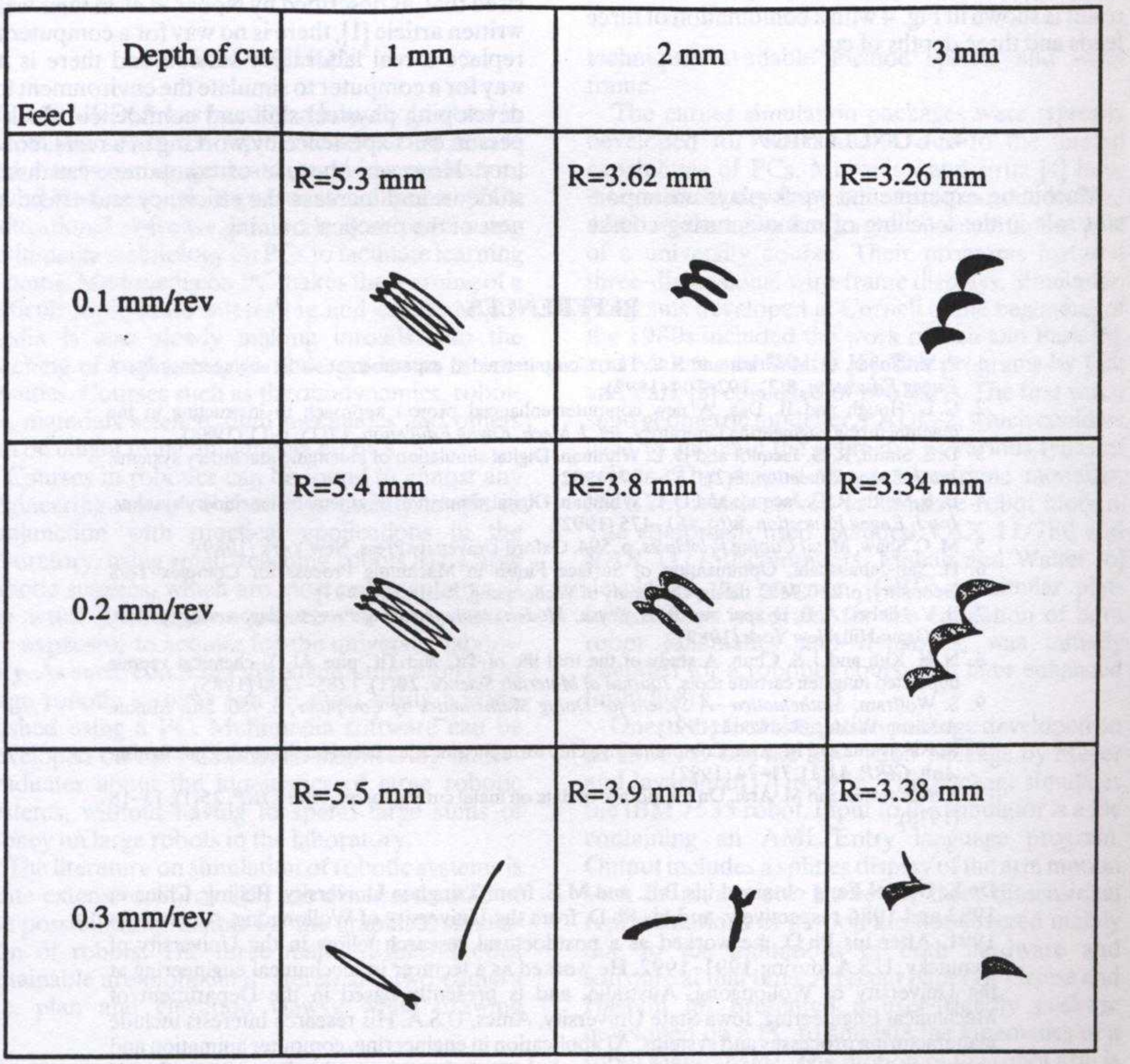

Fig. 4. An example of chip curling animation for different cutting conditions.

where N is the number of chip turns and V_{ch} is the chip velocity determined by the following equation,

$$V_{\mathrm{ch}} = \frac{V \sin\phi}{\cos(\phi - \alpha)} \tag{13}$$

where ϕ is the cutting shear angle which can be theoretically predicted [5] and α is the tool rake angle. Shown in Fig. 3 is the animation results based on the above equations.

3.3. *Animation of chip forming with different machining operations*

Chip forming and curling patterns vary when using different cutting conditions and tool inserts. For example, the feed (f) and depth of cut (d) determine the actual chip flow angle (η) thus change the chip forming and curling pattern, as shown below [11]

$$\eta = \tan^{-1}\frac{r_n + f/2}{d} \tag{14}$$

where r_n is the tool nose radius. A representative result is shown in Fig. 4 with a combination of three feeds and three depths of cut.

4. CONCLUSION

Machining experimental work plays an important role in the teaching of manufacturing course for mechanical engineering students. However, it is often the case that some appropriate experiments are difficult to organize for a number of possible reasons such as large size of class, limited funds, deficiency of laboratory facilities or technicians.

Therefore, as an alternative, this paper has presented a computer simulation-based strategy which utilises machining theories for modelling the maching process and computer programming techniques for generating dynamic graphs. The well-designed computer lab work provides all students an opportunity to 'operate the machine' on their own while observing what will happen in the machining operations with different cutting conditions. In addition, the computer lab work enables students to study the effects of different process parameters on machining performance through the control of computer keyboard input. Such lab work has been well received by the students as it enhances their understanding of the mechanisms of machining operation and chip formation.

As a last concluding remark, it should be emphasised that, as described by Nobar *et al.* in their well-written article [1], there is no way for a computer to replace a real laboratory session and there is no way for a computer to simulate the environment for developing physical skill and confidence which a person can experience by working in a real laboratory. However, the use of computers can assist students and increase the efficiency and effectiveness of the practical training.

REFERENCES

1. P. M. Nobar, G. McGrath and S. S. Tan, Computer aided experimentation in engineering, *Int. J. Engng Education*, **8**(3), 192–204 (1992).
2. C. L. Hough and B. Das, A new computer-enhanced project approach to instructing in the manufacturing engineering laboratory, *Int. J. Mech. Engng Education*, **17**(1), 1–11 (1988).
3. D. S. Smith, R. G. Jacquot and D. L. Whitman, Digital simulation of kinematic machinery systems, *Int. J. Engng Education*, **8**(2), 132–137 (1992).
4. D. S. Smith, R. G. Jacquot and D. L. Whitman, Digital simulation of kinematic machinery systems, *Int. J. Engng Education*, **8**(6), 461–475 (1992).
5. M. C. Shaw, *Metal Cutting Principles*, p. 594. Oxford University Press, New York (1989).
6. H. Safi-Jahanshahi, Optimization of Surface Finish in Machining Process for Complex Tool Geometry, p. 210. M.E. thesis, University of Wollongong, Australia (1993).
7. B. V. Niebel, A. B. Draper and R. A. Wysk, *Modern Manufacturing Process Engineering*, p. 466, McGraw-Hill, New York (1989).
8. N. H. Kim and J. S. Chun, A study of the tool life of TiC and TiC plus Al_2O_3 chemical vapour deposited tungsten carbide tools, *Journal of Materials Science*, **20**(1), 1285–1290 (1985).
9. S. Wolfram, *Mathematica—A System for Doing Mathematics by Computer*, p. 960, 2nd edition. Addison-Wesley, Redwood (1991).
10. K. Nakayama and M. Arai, Comprehensive chip form classification based on the cutting mechanism *Ann. CIRP*, **41**(1), 71–74 (1992).
11. K. Nakayama and M. Arai, On the storage of data on metal cutting forces, *Ann CIRP*, **25**(1), 13–18 (1976).

Dr X. Daniel Fang obtained his B.E. and M.E. from Tsinghua University, Beijing, China in 1983 and 1986 respectively, and his Ph.D. from the University of Wollongong, Australia in 1991. After his Ph.D., he worked as a postdoctoral research fellow in the University of Kentucky, U.S.A. during 1991–1992. He worked as a lecturer in mechanical engineering at the University of Wollongong, Australia, and is presently based in the Department of Mechanical Engineering, Iowa State University, Ames, U.S.A. His research interests include manufacturing processes and systems, AI application in engineering, computer animation and computer control. His teaching activities include manufacturing technology, CAD/CAM/CIM, computer control and engineering instrumentation.