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Grinding force control in an automatic surface finishing system

C.H. Liu [a,*], Adrian Chen [b], C.-C.A. Chen [c], Yin-Tien Wang [a]

[a] *Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, Tamsui, Taipei Shien 251, Taiwan, ROC*
[b] *Desktop Display Business Unit, Product Development, AU Optronics Corporation, L5 Fab, 23 Li-Hsin Rd., Science-Based Industrial Park, Hsinchu 300, Taiwan, ROC*
[c] *Department of Mechanical Engineering, National Taiwan University of Science and Technology, #43, Sec. 4, Keelung Rd., Taipei 106, Taiwan, ROC*

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Abstract

An automatic grinding system with grinding force control on a CNC machining center is developed to reduce surface roughness. This system includes an electric hand grinder mounted on a CNC machining center, a force sensor to measure the normal grinding force, and a force control sub-system to adjust the grinding depth. The CNC spindle vertical movement is produced by "external machine zero point shift".

The experiments performed in this study include: (1) Taguchi's parametric design to determine an ideal combination of the horizontal feed rate and the desired force value during force control and (2) grinding along an inclined surface. The results show that the force control technique may indeed reduce the average grinding force and grinding force variation.

Keywords: Grinding force control; Machining center; Hand grinder; Surface finishing; Grinding of mold and die; Taguchi method; Force measurement

1. Introduction

Grinding is an essential procedure in mold and die production performed on grinding machines, or, in a smaller factory, manually using electric hand grinders. Molds and dies are manufactured first using a CNC machine center. If grinding is performed on a grinding machine, an additional step may be needed to carry the molds and dies from the CNC machining center to the grinding machine. Automatic grinding (or surface finishing) systems using CNC machining centers have therefore been developed [1,2] and researched extensively. In this study an automatic grinding system based on a CNC machining center is developed. Grinding force control is imposed on this system to improve the grinding results.

It is well known that surface roughness may be improved by reducing the grinding force variation. Hahn [3] was the first person to propose the idea of controlled-force grinding. This has the advantage of eliminating errors due to machine deflections. Constant force grinding also has the advantage of preventing workpiece grinding from reduced material removal rate as wheel wear occurs [4]. For these reasons, grinding force control techniques have been proposed by many authors. Tönshoff et al. [5] developed a closed loop control technique to maintain a constant grinding force, applicable to internal as well as external grinding. To maintain the grinding force at a prescribed level, Liu et al. [6] developed a system with force feedback and robot arm position control. Jenkins and Kurfess [7,8] and Jenkins [9] developed a grinding force model that depended upon the material removal rate and grinding wheel feed velocity. Adaptive force control was imposed on the system to maintain uniform grinding force. The experimental results showed that adaptive control might produce better surface profiles (both flatness and roughness) than fixed-gain control.

While all of these force control techniques are for grinding machines using disk or cup wheels, rotary hand grinders with various grinding tools have also been widely used in the industry for surface finishing. The hand grinder has also been utilized in automatic surface finishing systems developed by Chen and Duffie [1] and by Hsu [2], in which rotary hand grinders are driven by CNC machining centers.

* Corresponding author. Fax: +886 2 2620 9745.
E-mail addresses: chaohwa@mail.tku.edu.tw (C.H. Liu), adrianchen@auo.com (A. Chen), artchen@mail.ntust.edu.tw (C.-C.A. Chen), ytwang@mail.tku.edu.tw (Y.-T. Wang).

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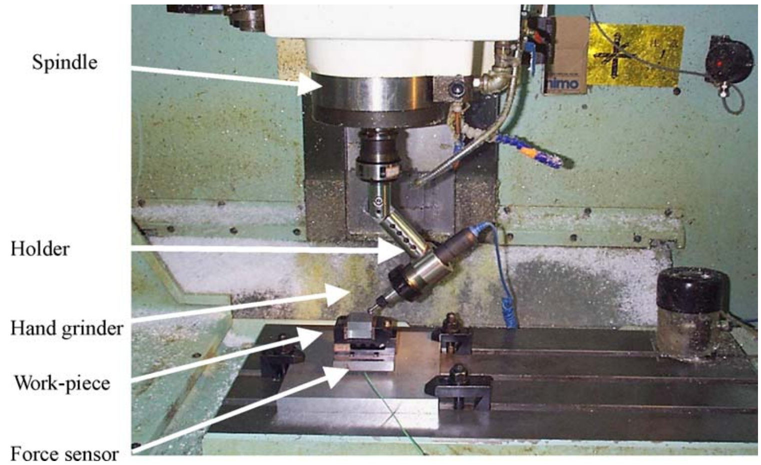

Fig. 1. Grinding system.

A constant force control technique for hand grinders driven by machining centers was developed by the authors. The proposed method is imposed on the automatic grinding system as shown in Fig. 1.

In this study the "external machine zero point shift" technique is used for fast CNC depth control. In this technique the amount of coordinate shift is sent to the PMC-M card register. After processing by the CPU, the message is sent to the position control circuit in the "axis card" for operation. This process is much faster than a process that alters the NC codes. The "external machine zero point shift" technique was developed to compensate for errors due to thermal deformation [10,11]. This technique is used in grinding force control for the first time in this study.

2. Signal measurement and the transfer process

The signal measurement and transfer process is shown in Fig. 2. As grinding forces are applied to the work-piece specimen, deformation in the quartz in the force sensor causes a charge release. The charge amplifier magnifies the charge signals and converts these signals into voltage signals. These voltage signals are converted into digital signals that are sent to the data acquisition software in a personal computer. The force control program (given in Appendix E of Chen [12]) makes calculations and the spindle position is obtained. Position data in the form of pulse signals is sent to a photo coupler through a 8255-card. The purpose of this photo-coupler is to convert the PC output voltage, with a magnitude of ± 5 V, into a value of ± 24 V for the CNC machining center. The spindle movement is carried out using a technique called "external machine zero point shift", which is discussed below.

3. External machine zero point shift

The CNC machine used in this study is model VC-65 of Victor Taichung Machinery Works Co. The spindle position data in the form of serial pulse signals were sent to an interface card, called the PMC-M card, in this CNC machine. The CNC controller then drives a servomotor to produce spindle

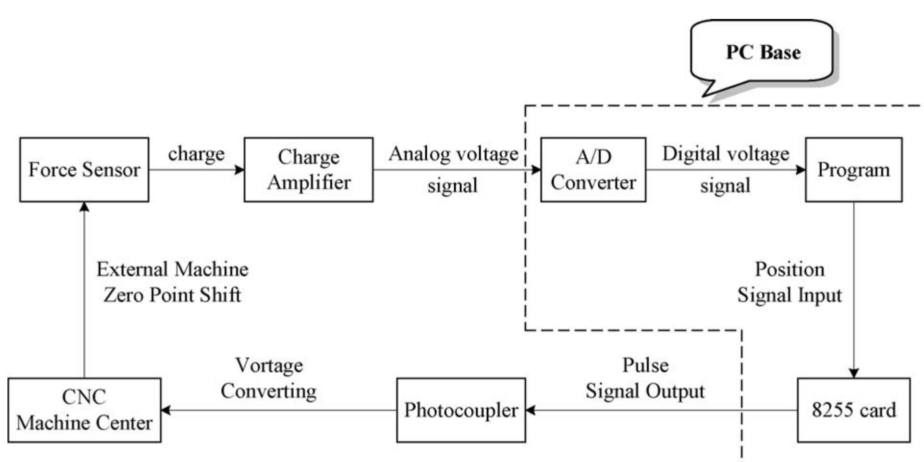

Fig. 2. Signal measurement and transfer process.

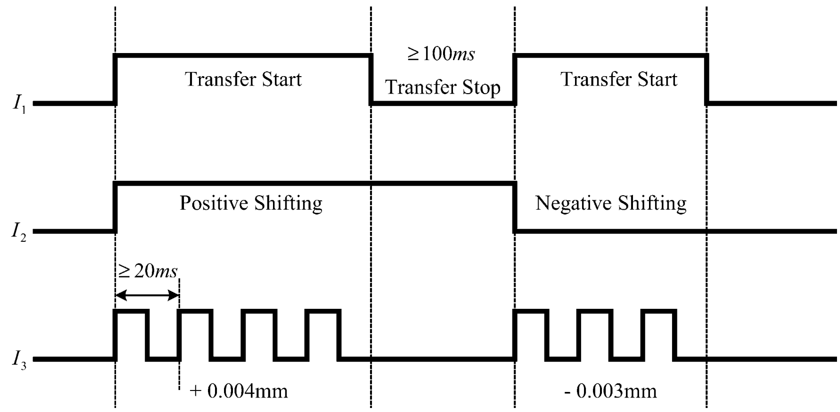

Fig. 3. Sequence of external machine zero point shift.

movement. The serial pulse signal sequences are shown in Fig. 3. The on and off of data transmissions are represented by the symbol I_1. Data transfer starts as the voltage is 24 V (i.e. the state HIGH) is reached, and terminates when the zero voltage state (i.e. the state LOW) is reached. Pulses I_2 and I_3 carry instructions for shifting the direction and the shift magnitude, respectively.

The CNC machining center controller requires that each pulse signal must last for a period longer than 20 ms. Data is transferred to and stored in the PMC interface card register. Each cessation of data transmission (i.e. the period I_1 is in the state LOW) must be longer than 100 ms. During this time data in the PMC register is sent to the controller to drive the spindle axis servomotor. Each pulse signal will cause the spindle axis to move 1 μm.

4. Photo-couple interface

As mentioned before, the purpose of the photo-coupler is to convert the output voltage at magnitude ±5 V into the ±24 V range required by the CNC input/output unit. A PC817 chip is used. The circuit for this chip is shown in Fig. 4. To ensure that the photo-couple output voltage is close to the value 24 V value, a suitable R_L value (see Fig. 4) is determined. A photo-couple interface was designed to check this value. The interface circuit is shown in Fig. 5.

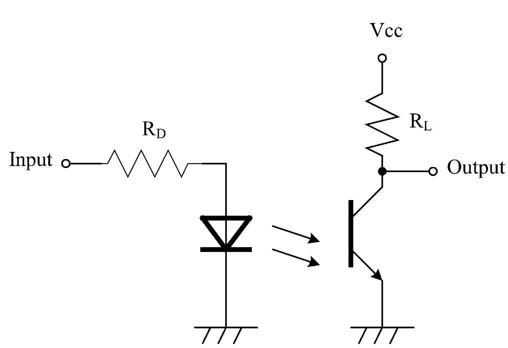

Fig. 4. Circuit in the PC817 chip.

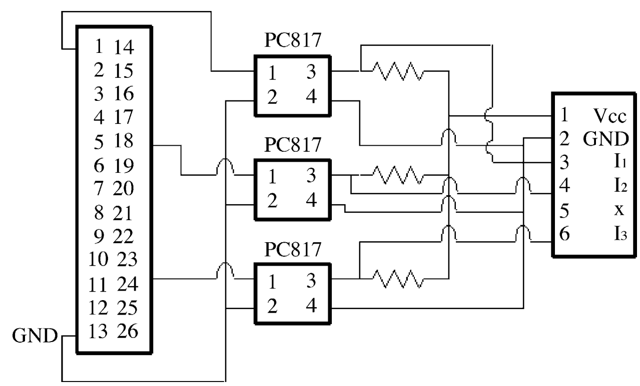

Fig. 5. Photo-couple interface.

Static tests were carried out to check the performance of the photo-couple interface. The Power supply supports 24 V voltage. The input pulse signals (0–5 V) are generated using a function generator. The output signals may be observed with an oscilloscope. The test results show that as R_L = 1.1 kΩ the output signals have the best shape. Input frequencies higher than 20 kHz make the output signals take irregular shapes, hence the value 20 kHz is approximately the maximum input frequency acceptable to this system.

5. Experiment preparation

The experiments discussed in this study include (1) Taguchi's parametric design, utilized to determine an ideal combination of grinding conditions, and (2) a special grinding case carried out to check the effectiveness of the force control technique, namely, grinding on an inclined work-piece.

In the following discussions, the Kistler_5295A force sensor is used. The force data was obtained at a 1000 Hz sampling rate. An average value was calculated for every 500 data points (i.e. two data points are obtained and sent out each second).

The initial contact point between the grinding tool and the work-piece was chosen as the origin for the NC code. More

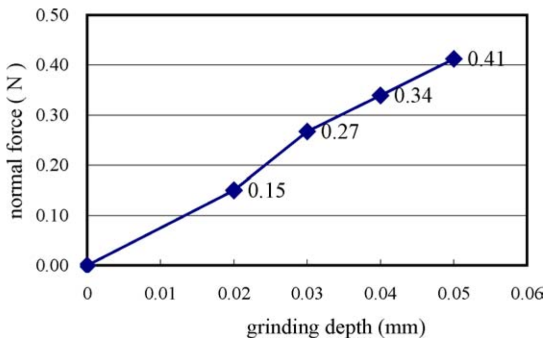

Fig. 6. Normal force vs. grinding depth (tool diameter is 9.5 mm, feed rate = 20 mm/min, and rotation speed = 20,000 rpm).

than one initial contact point may be found, however, especially in the static case (i.e. the hand grinder is not rotating). This is because carbide burs on the tool touch the work-piece at different elevations. In this study the initial contact point was determined while the hand grinder was rotating. This point may be higher than the static contact point by an amount 0.01–0.02 mm.

The goal of each grinding experiment was to maintain a desired grinding force value of by adjusting the grinding depth. The initial grinding depth to start the experiment may be estimated as follows. For a particular tool diameter, a certain feed rate, and a specific hand grinder rotation speed, the normal forces for various grinding depths were measured. The results were plotted as shown in Fig. 6. From this figure the initial grinding depth corresponds to a desired grinding force value may be estimated. At each time step the amount of shift in the CNC spindle was measured using this initial grinding depth position as the reference position (i.e. the distances the spindle shifts are measured with reference to this position). The authors also tried using the beginning contact point (with the hand grinder rotating) as the reference position. In this case the authors found that the pulse signals increased to such an amount that the system was seriously delayed.

A grinding process model for this grinding system was developed [13]. The model originally contained two masses and four springs. After simplification the model became a single spring-mass system. The spring constant is roughly the ratio of normal grinding force to grinding depth, and the mass includes the electric hand grinder and the holder. A corresponding PID controller to maintain a constant grinding force was also designed [13]. The following gain values were found: $K_d = 0.0443$, $K_p = 0.0891$, and $K_i = 11.762$. The numerical simulation results show that an overshoot of less than 3% was obtained using these gains [13]. These values will be used in the following grinding experiments.

6. Taguchi's parametric design

The purpose is to determine an ideal grinding condition. Taguchi's experimental design method was used. Grinding SKD61 specimens was performed. On each specimen a 3 cm path was produced. The grinding results were expected to depend upon the following four factors—*rotation speed* of the hand grinder, *horizontal feed rate*, *tool diameter*, and *desired value of grinding force*. Strong interactions were found among these four factors. In such a case the L_{18} orthogonal table could be used. However, previous results showed that *tool diameter* is such an influential factor on the surface roughness [14] that the effects of the other factors may become unimportant. The effect of the hand grinder *rotation speed* on surface roughness is already known, that is, the surface roughness decreases with an increasing *rotation speed*. The *feed rate* is a factor closely related to the force control system response rate. This means that a faster feed rate may prevent the system from controlling the force in time. This factor should therefore be included in the experiment. We maintained the *feed rate* and the *desired force* as two factors to be considered using an unsaturated L_9 array. The experimental design is shown in Table 1. Experiments were carried out using a 9.5 mm diameter carbide bur with a constant rotation speed of 20,000 rpm. The experimental results include *the average grinding force* measured by the force sensor, *the standard deviation in the grinding force*, and *the surface roughness*. These results are also shown in Table 1. Note that average forces measured by the force sensor were close to the desired force. The maximum percentage difference between the desired force and the average force was 8% shown in row 4. In the last column of Table 1 the "signal to noise ratio" (or

Table 1
Taguchi's L_9 (3^4) orthogonal table for parametric design

No	Factor *A* horizontal feed rate (mm/min)	Factor *B* desired force (N)	Average force (N)	S.D. of grinding force (N)	Surface roughness R_a (μm)	SN ratio for R_a, η_i
1	20	0.2	0.208	0.116	0.34	9.37
2	20	0.3	0.293	0.173	0.33	9.62
3	20	0.5	0.501	0.256	0.29	10.75
4	40	0.2	0.216	0.216	0.37	8.64
5	40	0.3	0.306	0.187	0.35	9.12
6	40	0.5	0.490	0.227	0.32	9.89
7	60	0.2	0.212	0.131	0.41	7.74
8	60	0.3	0.315	0.183	0.38	8.40
9	60	0.5	0.496	0.246	0.33	9.62

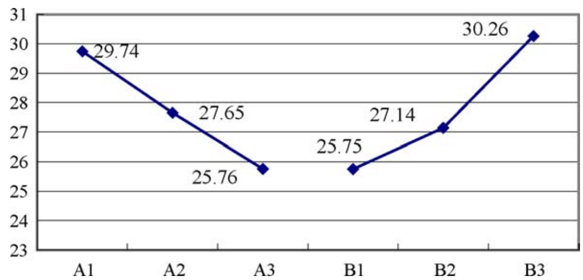

Fig. 7. SN ratios for various factors (feed rate—A_1: 20 mm/min, A_2: 40 mm/min, A_3: 60 mm/min; desired force—B_1: 0.2 N, B_2: 0.3 N and B_3: 0.5 N).

SN ratio) for the "smaller the better" case is shown, defined by:

$$\eta = -10\log(R_a^2) = -20\log(R_a) \quad (1)$$

Let A_1, A_2, A_3, denote three levels for factor A (i.e. three feed rates of 20, 40, and 60 mm/min, respectively), and B_1, B_2, B_3, denote three levels for factor B (i.e. three desired forces of 0.2, 0.3, and 0.5 N, respectively). From the results shown in Table 1 the SN ratio for each condition was calculated using the following equations:

$$\mathrm{SN}(A_1) = \eta_1 + \eta_2 + \eta_3; \qquad \mathrm{SN}(A_2) = \eta_4 + \eta_5 + \eta_6;$$
$$\mathrm{SN}(A_3) = \eta_7 + \eta_8 + \eta_9 \quad (2a)$$

$$\mathrm{SN}(B_1) = \eta_1 + \eta_4 + \eta_7; \qquad \mathrm{SN}(B_2) = \eta_2 + \eta_5 + \eta_8;$$
$$\mathrm{SN}(B_3) = \eta_3 + \eta_6 + \eta_9 \quad (2b)$$

The results are shown in Fig. 7. The best combination was therefore A_1B_3, i.e., at a feed rate of 20 mm/min, and a desired force of 0.5 N.

Fig. 8 is another way to express the experimental results shown in Table 1. From this figure we observe only mild interactions between the feed rate and desired force, suggesting that the results given in Table 1 reveal the general trends for each factor. With this understanding, note that the surface roughness decreases with the horizontal feed rate, and also decreases with increasing desired force, as Fig. 7 shows.

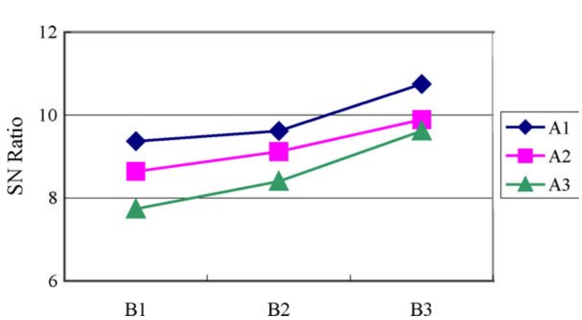

Fig. 8. Interaction effects between feed rate (factor A) and desired force (factor B).

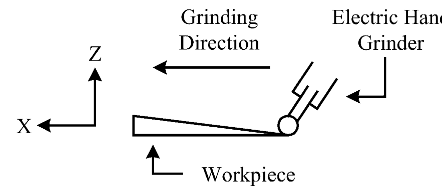

Fig. 9. Grinding on an inclined surface.

Table 2
Grinding forces for an inclined surface

Feed rate (mm/min)	Average force (N)		S.D. (N)	
	Force control	Without control	Force control	Without control
20	0.57	1.17	0.38	1.13
40	0.66	1.20	0.41	1.58
60	0.69	1.29	0.49	2.03

7. Grinding on an inclined surface

Grinding was performed on an inclined surface to check the effectiveness of the force control system. The grinding path was a 30 mm straight line in the x direction, with a 0.1 mm elevation difference from the starting point to the final point (see Fig. 9).

Experiments with no force control were performed under the same grinding conditions as experiments with force control. The only exception was that the z-coordinate of the tool head was kept at a fixed value. Hence both constant force experiments and constant z-coordinate experiments started with the same initial coordinate, as obtained from Fig. 6.

The experimental results are shown in Table 2 and Figs. 10–15. Comparing the results obtained with the force control, as shown in Figs. 11, 13 and 15, with the results obtain under the same conditions but with no force control, as shown in Figs. 10, 12 and 14, very apparent force reductions are indicated. The average grinding forces and their standard deviations are given in Table 2. Table 2 shows that both the average grinding forces and standard deviations for the controlled experiments are smaller than the corresponding values without force control. The average forces were reduced by approximately half. The force variations were reduced to 1/4–1/3 of the uncontrolled values. Therefore the

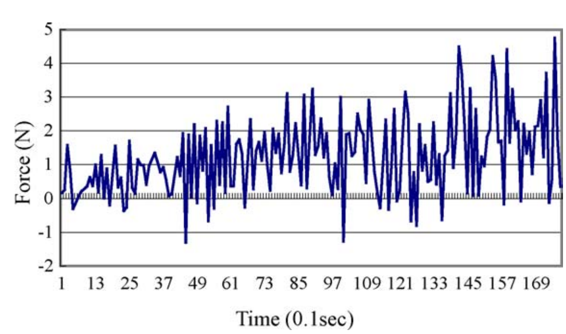

Fig. 10. Grinding force on an inclined surface—no force control (feed rate: 20 mm/min).

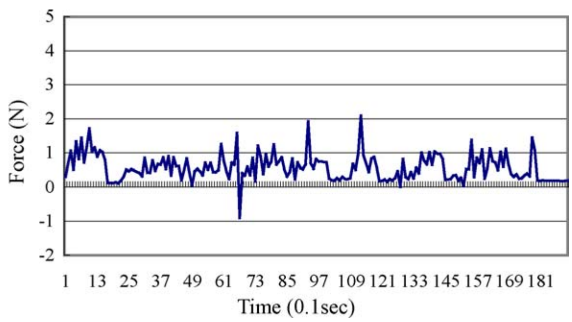

Fig. 11. Grinding force on an inclined surface—with force control (feed rate: 20 mm/min).

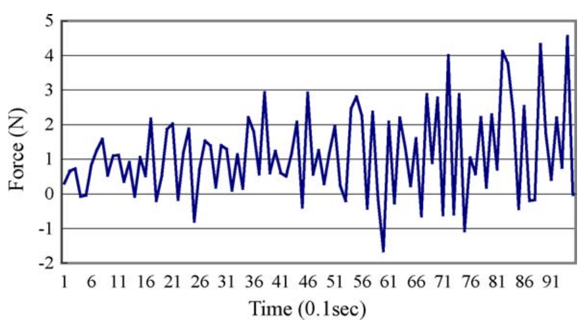

Fig. 12. Grinding force on an inclined surface—no force control (feed rate: 40 mm/min).

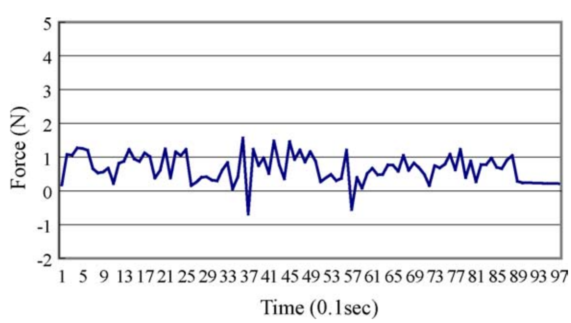

Fig. 13. Grinding force on an inclined surface—with force control (feed rate: 40 mm/min).

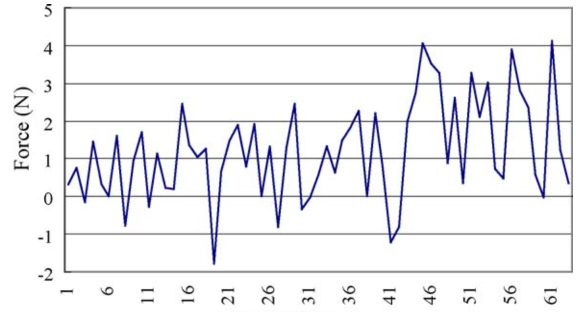

Fig. 14. Grinding force on an inclined surface—no force control (feed rate: 60 mm/min).

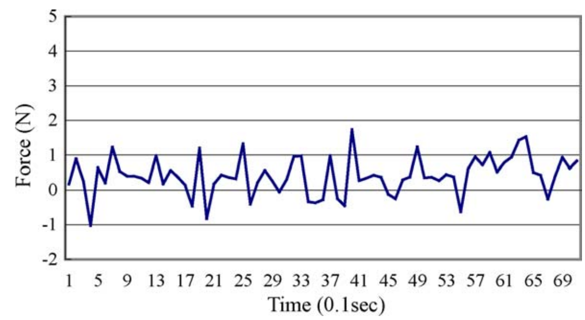

Fig. 15. Grinding force on an inclined surface—with force control (feed rate: 60 mm/min).

force control technique developed in this study does reduce grinding force variations.

8. Conclusions

In this study a force control system was designed and incorporated into a CNC machining center to reduce the grinding force variation and surface roughness. The proposed system includes an electric hand grinder, a force sensor, and a photo-couple interface. The "external machine zero point shift" technique was used to increase the speed of the system. A photo-couple interface was designed to facilitate the voltage conversion.

This system was used to perform a series of experiments. Taguchi's method for parametric design was carried out to determine an ideal feed rate and desired force combination. Although mild interactions exist between a horizontal feed rate and desired force, the experimental results showed the expected trends, namely that surface roughness decreases with a slower feed rate and also with larger grinding force. Comparisons were made between cases with force control and cases with fixed z-coordinate, as grinding was performed on an inclined surface. Results show both average forces and standard deviations for cases with force control were found to be much lower than those with fixed z-coordinates. These results lead us to conclude that the force control system developed in this study does reduce grinding force variation.

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