CIRP Annals - Manufacturing Technology 60 (2011) 145–148

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A study on energy efficiency improvement for machine tools

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ARTICLE INFO

Keywords:
Energy
Machine tool
Machining

ABSTRACT

Energy consumption reduction is critical in various industrial environments. Machine tool manufacturers could contribute to this matter by developing advanced functions for machines. Power consumption of machining center was measured in various conditions. The conclusion was that modifying cutting conditions reduces energy consumption. This applies for either regular drilling, face/end milling or deep hole machining. Also, a new acceleration control method is developed to reduce energy consumption by synchronizing spindle acceleration with feed system. Experiments were performed to verify these methods and promising results were achieved.

1. Introduction

Energy savings is increasingly recognized as one of the most important features in consumer products and industrial equipment. This same trend applies in the machine tool industry. A survey of recent literature shows that many research efforts have been made towards this target in the machine tool industry. Inasaki [1] investigated reducing cutting oil usage during machining. Dornfeld proposed an efficient tool path and workpiece setup method [2] and explored power consumption monitoring on machine tools [3]. Diaz et al. [4] investigated the reuse of energy regenerated from the spindle motor. Neugebauer et al. performed comparison studies during drilling operations, varying tool and material removal rate in [5].

Modern machine tools rely on electricity as their main power source. The major components of machine tool power consumption are spindle rotation and servo-driven axis motion. Their power usage are both highly dependent on cutting resistance. Other energy demands come from the hydraulic unit, cutting oil pumps, cooling devices and peripheral devices like the controller unit. The power consumption of each of these varies mainly with operation time. Reduction of electrical energy for machining and peripheral devices plus shortening of the cycle time are the keys to reduce power consumption. Electrical energy can be reduced simply by shutting down unnecessary devices during set-up and/or minimizing wait times. This will not be addressed specifically in this paper. By advancing on the previous work in [6], this paper investigates more concrete ways to reduce power consumption, concentrating on spindle motors and servo motors, which have the highest energy demands in machine tools.

2. Formulation and evaluation function

Spindle motors and servo motors expend power for two reasons: (1) to accelerate/decelerate and move the spindle shaft and worktable against inertia, friction resistance and gravity, and (2) to provide the cutting force necessary to overcome cutting resistance.

The first item concerns the requirement to accelerate/decelerate the spindle and to position the worktable and therefore cannot be readily optimized in terms of power consumption. New acceleration/deceleration control was developed in order to reduce power consumption in this research.

For the second item, cutting conditions were examined for higher efficiency by minimizing the cutting resistance and shortening the machining time. In addition, conditions specific to deep hole drilling are investigated. In this paper, power consumption was measured while changing cutting conditions during drilling, end milling, face milling, which are typical process for machining centers. Machining parameters investigated included cutting speed, feed rate, and axial and radial cutting depth.

It is necessary to point out that excessive cutting speed and feed rate may cause rapid tool wear leading to premature tool chipping or may result in a rough work finish due to chatter. Therefore, although the primary goal of this study is to determine favorable running conditions in terms of power consumption, consideration is given to finding optimal cutting conditions that do not cause premature tool wear or unacceptable machining vibration.

Eq. (1) shows the model of power consumption P (Wh) of a machine tool during normal operation. It includes several processes: positioning and acceleration the spindle following a tool change, machining, returning the spindle to the tool exchange position after machining, and stopping the spindle.

$$P = P_1 \times (T_1 + T_2) + P_2 \times T_2 + P_3 \times T_3 \qquad (1)$$

where, P_1(W) is the constant power consumption during the machine operation regardless of the running state, T_1(h) is the cycle time during non-cutting state, T_2(h) is the cycle time during cutting state, P_2(W) is the power consumption for cutting by the spindle and servo motor, which fluctuates with cutting conditions, P_3(W) is the power consumption to position the work and to accelerate/decelerate the spindle to the specified speed, and T_3(h) is the time required position the work and to accelerate the spindle.

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0007-8506/$ – see front matter © 2011 CIRP.
doi:10.1016/j.cirp.2011.03.099

Reduction of the value of P_1, the constant power term in the above equation, has already been achieved in the machine tool industry by the development and adopting of more efficient devices for machine tools. Thus it is not a subject of this paper. As for P_2, the goal is to find the cutting condition which consumes the least energy per material removal rate as well as to decrease the value of the term, $P_1 \times (T_1 + T_2)$ by shortening the machining time, T_1. For P_3, methods to determine feedrates and spindle acceleration/decelerations which minimize power consumption are to be investigated.

Here define a variable y (Wh/cc) as P(Wh) divided by the material removal volume M_R (cc). The result is an evaluation function for power consumption reduction as given as Eq. (2).

$$y = \frac{P}{M_R} \tag{2}$$

3. Case study 1: power consumption change by cutting conditions

3.1. Experiment device and method

To determine the impact of the cutting conditions on power consumption, the total machine power consumption and spindle power consumption of a vertical machining center were measured by connecting a clamp-type ammeter to the input power source cable. The major specifications of the test machine are shown in Table 1. Measurements of power consumption were conducted for three cases: (1) drilling, (2) end milling, and (3) face milling. A specific tool was used for each machining case: (1) for drilling, a 10 mm diameter drill, multi-layer coated with TiAlCr + TiSi, with a point angle of 135° and a helix angle of 30°, (2) for end milling, a 10 mm diameter two-fluted carbide end mill, multi-layer coated with TiAlCr + TiSi, and (3) for face milling, an 80 mm diameter face mill with carbide alloy inserts, multi-layer coated with TiAlN + AlCrN. The work material was S45C carbon steel.

The measurements were carried out varying 4 parameters, the cutting speed V (m/min), feed rate per revolution Fr (mm/rev) or per tooth F_t (mm/t), cutting depth in axial direction A_p (mm), and cutting depth in radial direction A_e (mm), in three stages, the median, minimum, and maximum values of the tool manufacturer's recommended range. Changing four parameters in three stages would require 81 experiment combinations. In this study, by applying Taguchi Method with an L9 orthogonal table, the optimal parameter values were obtained with 9 experiments, and were compared to the initial condition (set to the median value within the recommended range). The experiment #10 shows the initial conditions for end milling and face milling.

Table 1
Specification of machining center.

Spindle motor power, kw	18.5
Spindle speed, min^{-1}	14,000
Spindle diameter, mm	65
Type of spindle taper	7/24 taper, No. 40
Maximum feed rate, m/min	42
Feed acceleration, G	0.43/0.39/0.74

Table 2
Experimental result (drilling).

	Parameters		P (Wh)	Y (Wh/cc)	Material removable (cc/min)	Cycle time (s)
	V (m/min)	F_r (mm/rev)				
Experimental number						
1	50	0.20	28.1	3.0	25.0	32
2	30	0.28	23.5	2.5	35.0	24
3	50	0.35	20.9	2.2	43.8	21
4	90	0.20	23.8	2.5	45.0	21
5	90	0.28	20.9	2.2	63.0	16
6	90	0.35	19.8	2.1	78.8	14
7	130	0.20	21.5	2.3	65.0	16
8	130	0.28	19.1	2.0	91.0	13
9	130	0.35	16.5	1.8	113.8	12

3.2. Experimental results and discussion

Tables 2–4 show the power consumption data for each cutting condition. After measuring power consumption of the spindle and the servo, total power consumption, P, was studied. Using the

Table 3
Experimental result (end milling).

	Parameters				P (Wh)	Y (Wh/cc)	Material removable (cc/min)	Cycle the (s)
	V (m/min)	F_t, (mm/t)	A_P, (mm)	A_e (mm)				
Experimental number								
1	50	0.05	5	0.5	38.6	133.0	0.4	60
2	50	0.10	10	1.0	21.8	18.8	3.2	32
3	50	0.15	15	1.5	17.1	6.5	10.7	22
4	90	0.05	10	1.5	28.2	16.2	4.3	35
5	90	0.10	15	0.5	16.3	18.7	4.3	19
6	90	0.15	5	1.0	11.9	20.5	4.3	14
7	130	0.05	15	1.0	22.7	13.0	6.2	25
8	130	0.10	5	1.5	14.1	16.2	6.2	14
9	130	0.15	10	0.5	11.9	20.5	6.2	11
10	130	0.15	15	1.0	10.9	6.3	18.6	11

Table 4
Experimental result (face milling).

	Parameters				P (Wh)	Y (Wh/cc)	Material removable (cc/min)	Cycle time (s)
	V (m/min)	F_t, (mm/t)	A_P, (mm)	A_e (mm)				
Experimental number								
1	175	0.1	1.0	30	38.4	5.5	8.4	98
2	175	0.2	1.5	45	30.4	1.9	37.6	51
3	175	0.3	2.0	60	31.2	1.1	100.3	36
4	200	0.1	1.5	60	48.8	2.3	28.6	87
5	200	0.2	1.0	30	26.4	3.8	19.1	45
6	200	0.3	1.0	45	19.8	1.9	43.0	32
7	250	0.1	2.0	45	43.8	2.1	35.8	70
8	250	0.2	1.0	60	23.7	1.7	47.7	37
9	250	0.3	1.5	30	17.6	1.7	53.7	26
10	200	0.2	1.0	60	28.1	2.0	38.2	46
11	250	0.3	1.5	60	23.1	1.1	107.4	26