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INVESTIGATION OF SEQUENTIAL MACHINING PROCESSES IN TERMS OF POWER CONSUMPTION AND SURFACE QUALITY

This paper presents the practical application of a power measurement system based on computer processing of signals generated by current and voltage sensors connected with spindle and axis driving electric motors. By using LabView data acquisition system, the total power and its components were recorded during machining operations. The experimental study concerns the power consumption and surface roughness produced in a sequential machining process consisting of hard turning and ball burnishing operations under variable machining parameters. In particular, some machining routines including finish hard machining and both single and multi-pass ball burnishing of hard surfaces were performed and compared. Finally, the optimization procedure based on these technological criteria was proposed.

1. INTRODUCTION

Energy savings is increasingly recognized program in all manufacturing industry sectors including the machine tool industry because modern machine tools are powered by electricity as the main power source [1]. The energy consumed by manufacturing industry accounts for 30% of the total world energy and 36% of the global CO_2 emission. The reduction of electrical energy consumption for machining and peripheral devices along with shortening the technological cycles are the key challenges. It can be done not only by the processes designed and employed directly by manufacturers but also the product design decisions made by manufacturers [2].

For instance, it was documented [2] that the cutting energy consumed by a modern automatic machine tool during machining is less than 15% of the total energy demand. It is an important argument for R&D centers to investigate accurately all components of machine tools in terms of energy consumption in all phases of their utilization.

Filippi et al. [3] had investigated the energy consumption by computer numerical controlled (CNC) machine tools above thirty years ago and concluded that the greatest loss of efficiency in machining results from non-machining utilization. Later, predictive modelling of energy consumption by various machine tools was distinctly developed in

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order to achieve its reduction by both construction and technological improvements and innovations [4],[5],[6]. Because the energy profile is very much dependent on machining conditions, this work is directed towards integrating energy and surface finish in sequential machining operations.

2. EXPERIMENTAL DETAILS

2.1. EXPERIMENTAL SET-UP

In this study the machining power was measured in an in-process mode using a special set-up installed on a CNC turning center, Okuma Genos L200E-M. In general, three types of energy flows into the machine tool including spindle/axis NC drives, peripherals and air compressor can be distinguished in a CNC machine tool. Accordingly, three machine tool electric circuits should be taken into account to obtain the energy profile of a machine tool. The layout of electric circuits and power measuring points are presented in Fig. 1.

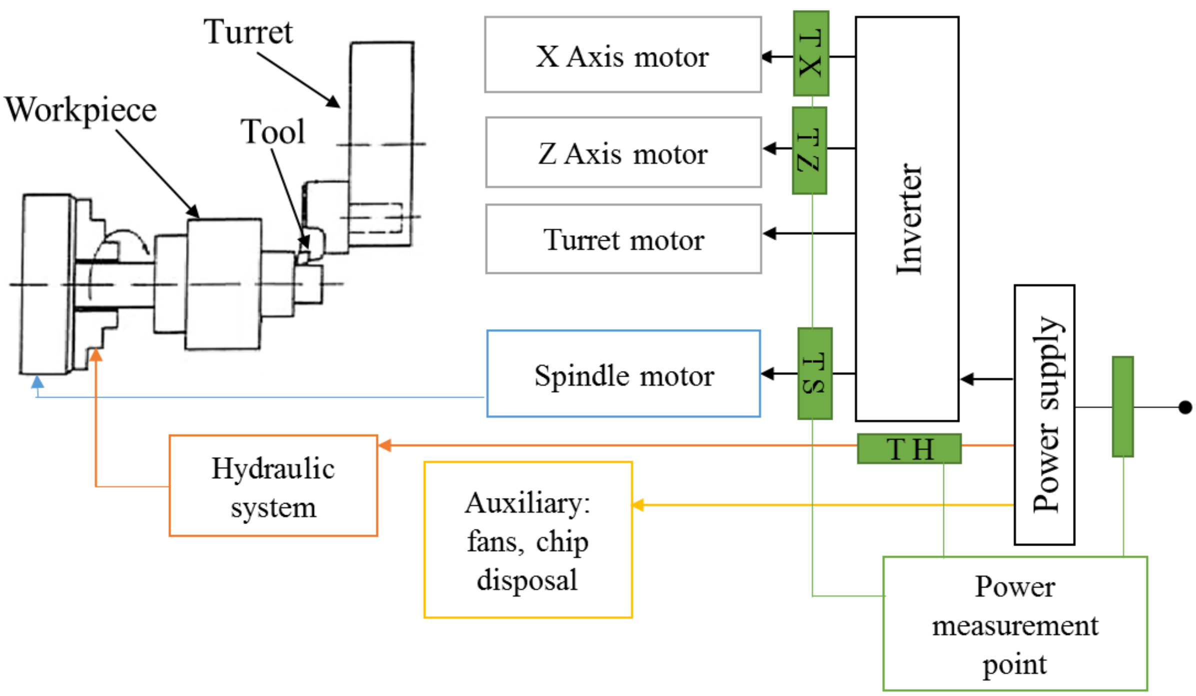

Fig. 1. Scheme of experimental set-up with location of sensors

As shown in Fig. 1, powers of all three electric motors, i.e. the spindle motor (TS) and two drive axis motors (TX and TZ) were controlled using the frequency inverter. The actual power consumption was measured using a three phase power transducer on the incoming power lines into the CNC lathe and a three phase power transducer on the lines to the spindle motor (TS), drive axis motors (TX and TZ) and hydraulic system (TH). Both current and voltage transducers were tested and calibrated before studies in order to ensure their proper functions appropriate signals were measured and recorded using a custom LabView program. The power signals were recorded and analysed for each series of machining tests.

2.2. CHARACTERIZATION OF MACHINING CONDITIONS

In this study, a 41Cr4 (AISI 5140) steel of the Rockwell's hardness of 50±2 HRC was hard turned and ball burnished [7]. All sequential machining operations were performed on a CNC turning center, Okuma Genos L200E-M shown in Fig. 1. In the case of initial hard turning passes a low content CBN, grade CB7015 by Sandvik Coromant was used as the cutting tool material. All machining conditions are specified in Table 1. First, hard turning operations were performed with the constant cutting speed of 200 m/min and the depth of cut of 0.2 mm but variable feed rate ranging from 0.075 mm/rev to 0.25 mm/rev (other feeds are selected in Table 1).

Table 1. Hard turning and burnishing conditions

Hard turning before burnishing v_c *=200 m/min;* a_p *=0.2 mm*							
Number, feed rate and code							
1	2	3	4	5	6	7	8
0.075	0.1	0.125	0.15	0.175	0.2	0.225	0.25
T1	T2	T3	T4	T5	T6	T7	T8
Burnishing v_b *=50 m/min; load* F_n*=300N*							
First pass, feed rate and code							
0.05	0.075	0.1	0.125	0.15	0.175	0.2	0.225
1B1	2B1	3B1	4B1	5B1	6B1	7B1	8B1
Second pass, feed rate and code							
0.05	0.075	0.1	0.125	0.15	0.175	0.2	0.225
1B2	2B2	3B2	4B2	5B2	6B2	7B2	8B2

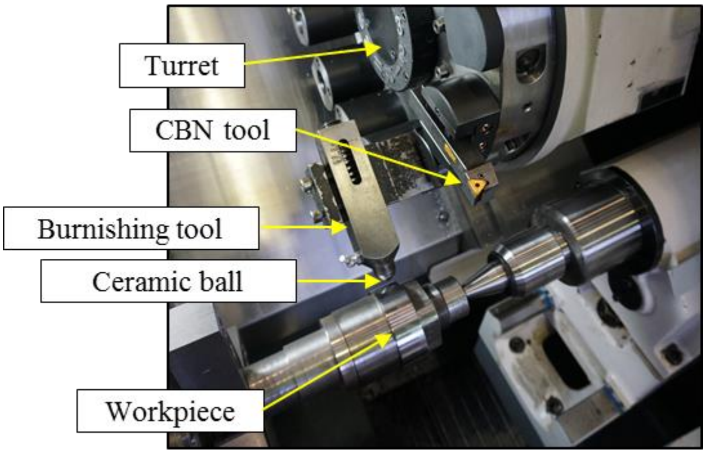

Fig. 2. Machining operations used in the technological sequences tested in this study hard turning and ball burnishing

Burnishing was performed with constant speed of 50 m/min and variable feed ranging from 0.05 mm/rev to 0.225 mm/rev for both one-pass and two-pass burnishing operations (other feeds are selected in Table 1). As shown in Fig. 2b the roller burnishing head equipped with a polished Si_3N_4 ceramic ball of 12 mm diameter was mounted in the turret. The desired normal load was controlled using a spring-based pressure system (Fig. 2b). In this part of experimental study the constant normal load of F_n=300 N was employed. After each machining tests the surface roughness was measured using a Hommel Tester T1000 profilometer.

3. EXPERIMENTAL RESULTS

This experimental study was focused on the power and energy consumption in finishing removal and non-removal machining operations performed on a 41Cr4 hardened alloy steel and its correlation with the surface finish characteristic for precision and high-precision operations, i.e. when the Rz roughness parameter is below 1 μm [8]. Power measurement routines using variable feed rate and keeping constant cutting speed of 200 m/min for hard turning and 50 m/min for burnishing series were carried out (see Table 1). In total, eight machining tests for each of the two variants of sequential machining operations were carried out. Experimental results include both the power and energy consumptions and surface finish characterized by the mean roughness Ra and the maximum roughness height Rz. Moreover, the energy consumed by hard turning and ball burnishing to obtain the surfaces with the Ra parameter of about 0.15 μm was compared.

3.1. CHARACTERIZATION OF POWER AND ENERGY CONSUMPTION IN SEQUENTIAL PROCESSES

The dependence of the power and energy consumption in hard turning and additional one-pass and two-pass burnishing operations on the feed rate is shown in Figs. 3 and 4 respectively. The depth of cut in hard turning was changed depending on the operation type, i.e. at a_p=0.2 mm for initial turning, at a_p=0.15 mm for finish turning and at a_p=0.05 mm. for precision turning.

As a result, keeping the feed rate at 0.075 mm/rev for finish turning and 0.05 mm/rev for precision hard turning the value of Ra parameter was reduced to about 0.30 μm and 0.15 μm respectively. Such a comparison allows comparing the energy consumption required to obtained the surfaces with comparable surface finish characterized by the roughness average Ra [9],[10].

The changes of the power consumption resulting from hard turning increase of the feed rate for hard machining and ball burnishing operations are presented in Fig. 3. It is evident in Fig. 3 that for hard turning the total power increases from about 3.5 kW to about 4.0 kW (the increase is about 0.5 kW) depending on the feed rate applied. On the other hand, the power utilized for both one-pass and two-pass ball burnishing is practically constant independently of the feed rate used.

Different energy consumption profiles are obtained for the same machining operations as depicted in Fig. 4. In contrast, the energy consumed during hard turning with variable feeds is evidently lower than for ball burnishing processes and decreases from about 130 kJ for the lowest feed of 0.075 mm/rev to 45 kJ for the highest feed of 0.25 mm/rev. This results from the fact that smaller feeds prolong the machine tool usage, i.e. machining time tends to increase and all motors work longer. The energy consumption profile recorded for burnishing operations are strongly feed dependent and increases distinctly (approx. by 80%) when two-pass burnishing is performed (course #3 vs. course #2 in Fig. 4).

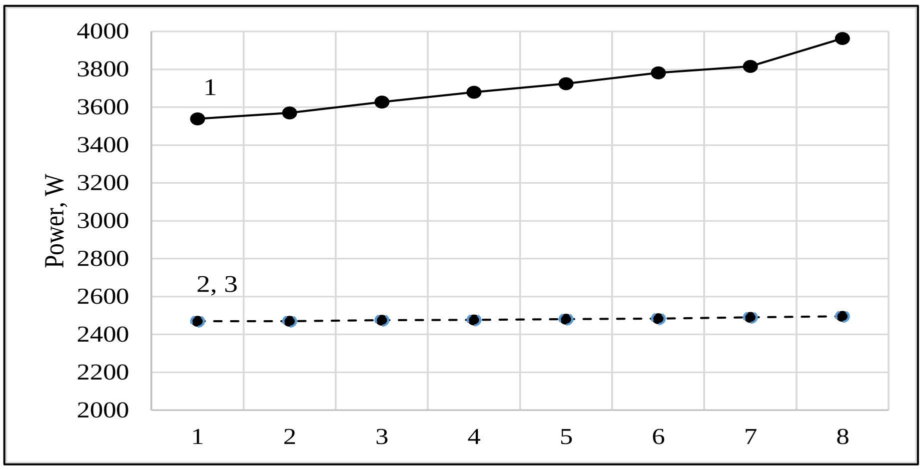

Fig. 3. Power consumption of hard turning (1) and burnishing (2, 3) operations

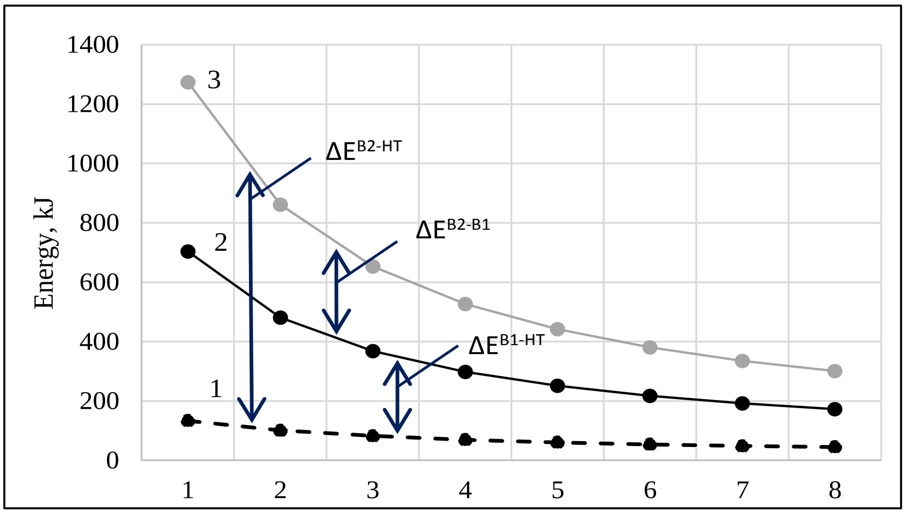

Fig. 4. Energy consumption in hard turning-HT (1) and sequential processes including one-pass-B1 (2) and two-pass-B2 (3) burnishing

Fig. 4 suggests that in sequential processes the energy savings are possible by increasing the feed rate in ball burnishing and decreasing the initial surface roughness in hard turning. In case of hard surfaces two-pass ball burnishing is a very energy consuming process and can only be recommended for parts with special functional properties, for instance exceptional fatigue life. In Fig. 4 symbols $\Delta E^{B2\text{-}HT}$, $\Delta E^{B2\text{-}B1}$ and $\Delta E^{B1\text{-}HT}$ denote the differences between energy consumption in two-pass burnishing (B2) and hard turning (HT), two-pass (B2) and one –pass (B1) burnishing, and one-pass burnishing (B1) and hard turning (HT).

For comparison, Fig. 5 includes the energy values for three various precision machining sequences after which a comparable surface finish of about 0.15 μm was produced. It is clear, that the sequential process with one-pass burnishing is more energy consuming than hard cutting processes because producing extremely low surface roughness needs the smallest feeds of 0.05 mm/rev or lower to be used (700 kJ vs. 330 kJ). This, of course, causes that the machining time and, in turn, the energy consumption, increases. According to Fig. 5 producing the surface finish of about Ra=0.15 μm requires the energy consumption of about 330 kJ (two turning passes), 700 kJ (initial turning and burnishing passes) and 650 kJ (initial turning and two burnishing passes). When the demanded surface roughness Ra=0.30 μm the appropriate energy values are distinctly lower and equal to 130 kJ, 300 kJ and 440 kJ.

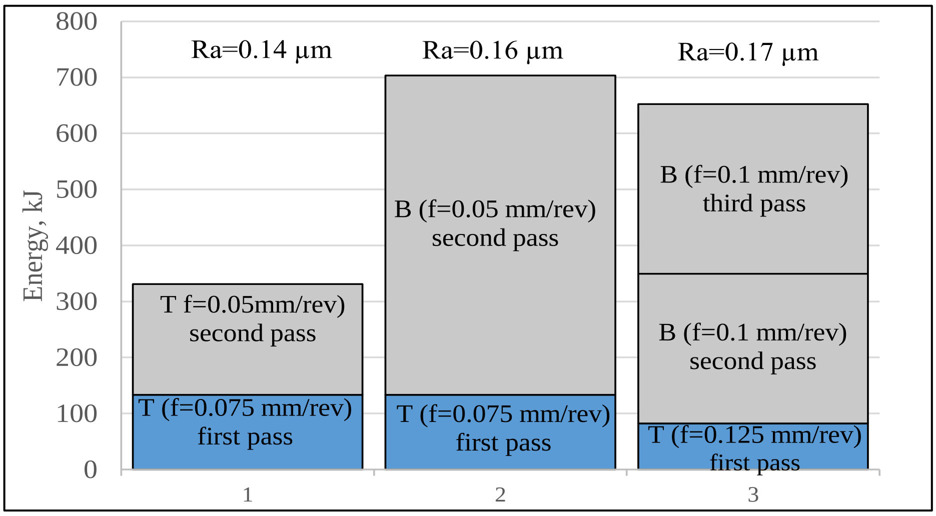

Fig. 5. Energy consumption in two-pass hard turning (1) and sequential processes including one-pass (2) and two-pass (3) burnishing

3.2. CHARACTERIZATION OF SURFACE ROUGHNESS PRODUCED IN SEQUENTIAL PROCESSES

The reduction of the turned surface roughness by one-pass and two-pass ball burnishing characterized by the Ra and Rz parameters is shown in Figs. 6 and 7 respectively. Fig. 6 depicts that the most effective are burnishing processes performed with medium (6B1, 6B2) and higher feeds. For instance, for the one-pass burnishing with the feed of 0.175 mm/rev the reduction of Ra parameter is about 1.1 μm. On the other hand, the second burnishing pass causes that the Ra parameter is reduced down to 0.36 μm. It should be noted that the Ra reduction due to the second burnishing pass is practically the same independently of the feed rate applied.

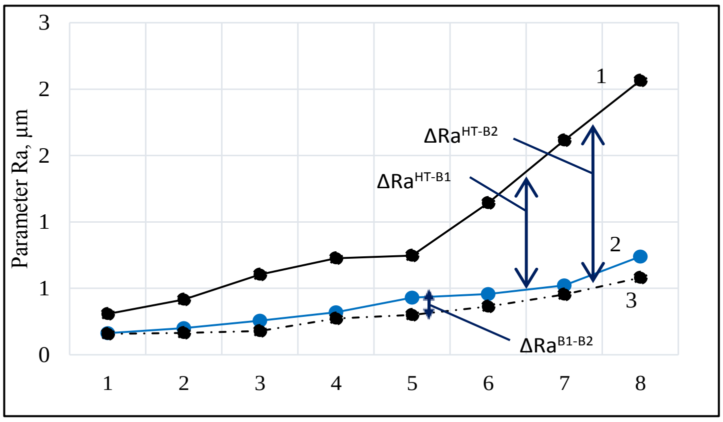

Fig. 6. Values of Ra parameter for hard turning (1), sequential process T+1B (2) and sequential process T+2B (3)

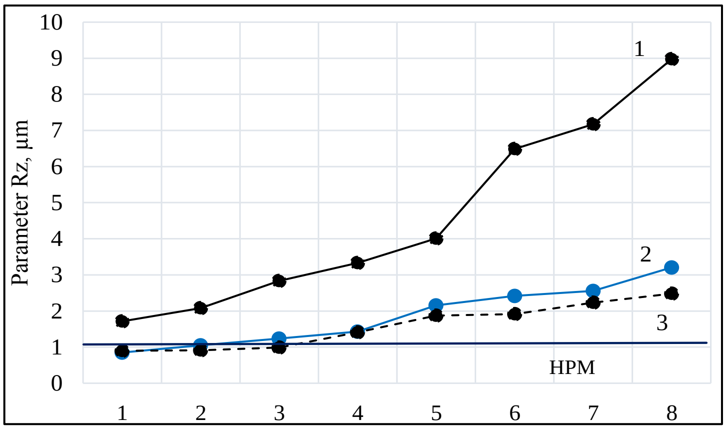

Fig. 7. Values of Rz parameter for hard turning (1), sequential process T+1B (2) and sequential process T+2B (3)

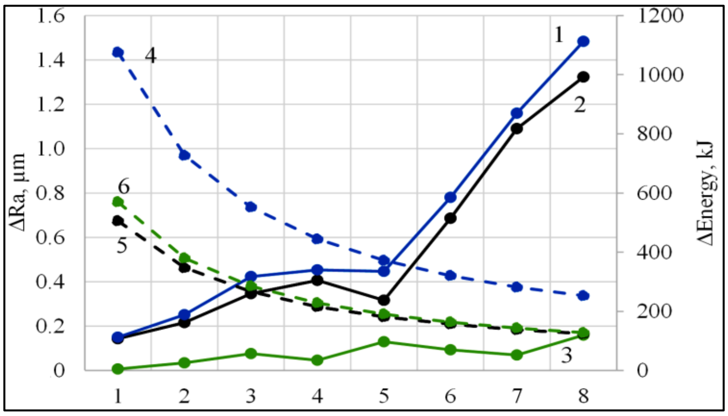

Fig. 8. Comparison of the reduction of Ra parameter (ΔRa) and energy consumption (ΔE): 1) $\Delta Ra^{HT\text{-}B2}$, 2) $\Delta Ra^{HT\text{-}B1}$, 3) $\Delta Ra^{B1\text{-}B2}$, 4) $\Delta E^{B2\text{-}HT}$, 5) $\Delta E^{B1\text{-}HT}$, 6) $\Delta E^{B2\text{-}B1}$

The main advantage of the two-pass burnishing is shown in Fig. 7. Accordingly, the Rz value below 1 μm (corresponding to high precision machining-HPM) can be obtained for higher feed rates, which, in turn, reduces the energy consumption. This effect is discussed in Fig. 8.

Fig. 8 clearly indicates that in terms of the energy consumption and surface roughness the most effective sequential processes should be performed with feed rates higher than 0.175 mm/rev for hard turning (6T) and 0.15 mm/rev for burnishing (#1B6 and #2B6). For this case study, the values of energy consumed for burnishing $\Delta E^{B1\text{-}HT}$ and $\Delta E^{B2\text{-}HT}$ are equal to 190 kJ and 380 kJ, whereas for the smallest feeds of f_t=0.075 mm/rev and f_b=0.05 mm/rev these energy values increase up to 570 kJ and 1140 kJ respectively. This comparison also suggests that producing surfaces with the smallest surface roughness are very energy consuming processes.

4. CONCLUSIONS

1. In sequential machining processes the energy consumption depends on the values of machining parameters which influences machining time [11],[12].
2. Burnishing operations consume less machining power but more energy because the cutting speed and feed rate are evidently lower than for removal cutting operations
3. The sequential machining operations can save the energy consumption in cases when the demanded surface roughness is above 0.3-0.5 μm. Further energy saving can be achieved by performing two-pass burnishing operations with optimized load and feed.
4. When surfaces with a very high quality (Rz lower than 1 μm) should be produced less energy is required by two-pass hard turning than for sequential processes.

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