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COMPARISON OF POWER AND ENERGY CONSUMPTION FOR HARD TURNING AND BURNISHING OPERATIONS OF 41CR4 STEEL

This paper presents a new power measurement system which allows recording the power consumption profile and determining its components related to all the controlled axes. The system is based on computer processing of signals generated by current and voltage sensors connected to spindle and axis driving electric motors. It should be noted that these motors are controlled independently with different frequencies and voltages. By using LabVIEW data acquisition system, it is possible to record total power consumption and its components during a typical machining operation. This study concerns the power consumption in a sequence machining process consisting of hard turning and ball burnishing operations under variable machining conditions.

1. INTRODUCTION

Manufacturing industry sectors emit CO_2 indirectly through the consumption of electricity and directly through the use of fossil fuels. It is obviously known that manufacturers play a critical, multi-faceted role in controlling the material and energy resources in modern society. It can be done not only by the processes designed and employed directly by manufacturers but also the product design decisions made by manufacturers. Moreover, they influence the energy and material resources consumed by products across their life cycle [2]. In all these aspects, the efficiency of energy and material resources saving depends on the technological level of manufacturing equipment including machine tools.

One of the first studies on the energy use by computer numerical controlled (CNC) machine tools was done by Filippi *et al*. [3] above thirty years ago. This study clarified that the greatest loss of efficiency in machining was due to machine under-utilization. During next decades, several researchers have focused efforts on developing models to predict energy consumption of various machine tools and to achieve its reduction by both construction and technological methods [8].

For instance, Dahmus and Gutowski [1] documented that the cutting energy consumed

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by a modern automatic machine tool during machining is less than 15% of the total energy demand. It is then important to investigate accurately all components of machine tools in terms of energy consuming in all phases of their utilization.
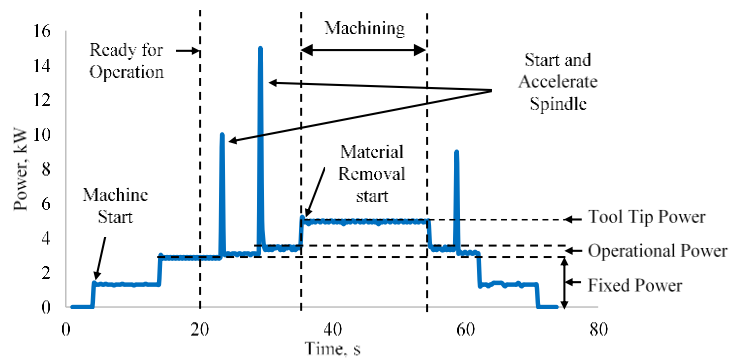

Fig. 1. Typical power profile of a lathe [7]

For instance, Fig. 1 illustrates a typical power profile of a turning process [7], which divides the total machine tool power in three levels:

- Fixed power: power demand of all activated machine components ensuring the operational readiness of the machine;
- Operational power: power demand to distinctively operate components enabling the cutting as performed in air-cuts;
- Tool tip power: power demand at tool tip to remove the workpiece material.

It is evident in Fig. 1 that the power profile is strongly dependent on all factors related to planning and machining conditions. Hence, it is a very important source of knowledge about the states of machining system and, as a result, is an essential information which can support the process planning and optimizing.

2. EXPERIMENTAL DETAILS

2.1. EXPERIMENTAL SET-UP

The set-up for measurements of the machining power is installed on a CNC turning center, Okuma Genos L200E-M, which is classified among energy-saving machines on the Polseff list (Programe of Financing of Sustainable Energy in Poland). This list covers all machines/equipment which enable to make at least 20% energy savings [9]. The structure of the experimental set-up is shown in Fig. 2. Powers of all three electric motors are controlled using the frequency inverter. The power signals were recorded and analysed for each series of machining tests. 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). Signals were measured and recorded using a custom LabView program. Both current and voltage transducers were tested and calibrated to ensure their proper function.
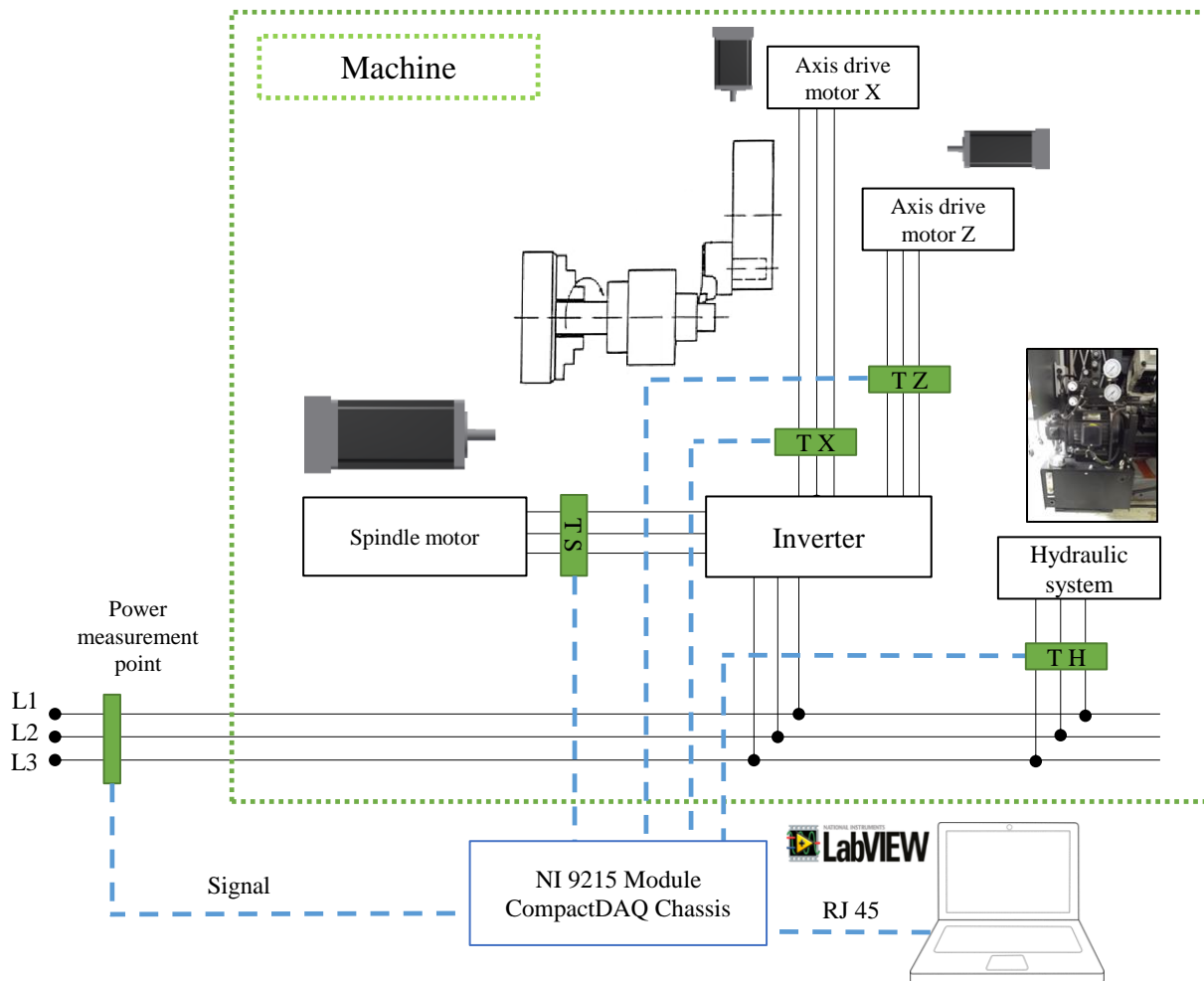

Fig. 2. Scheme of experimental set-up with location of sensors

2.2. CHARACTERIZATION OF MACHINING CONDITIONS

In this investigation, machining trials were performed on the specimens made of 41Cr4 (AISI 5140) steel with Rockwell's hardness of 55±1 HRC. Hard turning and ball burnishing operations were performed on a CNC turning center, Okuma Genos L200E-M. Low content CBN tools grade CB7015 by Sandvik Coromant, were used to perform turning passes. Hard turning conditions were as follows: variable cutting speed of 150, 200, 250 and 300 m/min, variable feed rate of 0.1 (HT1), 0.15 (HT2) and 0.2 mm/rev (HT3) and depth of cut of 0.3 mm. Burnishing conditions were as follows: burnishing speed of 30 m/min, burnishing feed of 0.05 mm/rev (B1), 0.01 mm/rev (B2) and 0.15 mm/rev (B3). The burnishing head was mounted in the turret. Roller burnishing was performed under

static ball-workpiece interaction using special burnishing tool equipped with Si_3N_4 ceramic ball of 12 mm diameter and controlled spring-based pressure system to generate desired normal load. Constant load of 300 N were used in the experiment. Surface roughness was measured using a Hommel Tester T1000 profilometer.

3. EXPERIMENTAL RESULTS

The main goal of this experimental study was to explain how the machining conditions of the sequential process influence the power and energy consumption and how the surface finish corresponds to the energy consumption. Four power measurement routines using variable feed rate and keeping constant cutting speed of 150, 200, 250 and 300 m/min for each series were carried out. As a result, three initial surface roughness values produced by hard machining were selected for the subsequent ball burnishing operations.

3.1. CHARACTERIZATION OF POWER AND ENERGY CONSUMPTION

The dependence between the power consumption in hard turning and the feed rate and cutting speed is shown in Fig. 3. The depth of cut in hard turning was constant at a_p=0.2 mm.
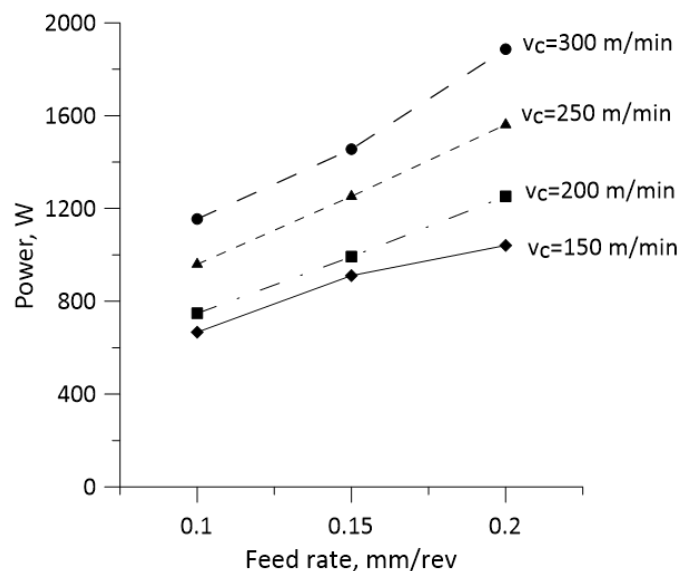

Fig. 3. Comparison of power consumption for variable cutting speed and feed rate and depth of cut a_p=0.2 mm

As it can be seen in Fig. 3 the cutting power increases distinctly with the increase of both the cutting speed and feed rate. When the feed rate increases from 0.1 mm/rev to 0.2 mm/rev the cutting power increases about two times for all cutting speeds used.

It is assessed [6] that the cutting power is about 30% of the total power consumed by a machine tool but in case of machine tools equipped with additional units, for example with high pressure cooling unit, the cutting power is reduced to about 15%. In this case study, the cutting power measured in three hard turning operations (HT1, HT2 and HT3) is assessed at the level of 20-30% of the total power consumed by the CNC lathe employed. On the other hand, the power required for three ball burnishing operations (B1, B2 and B3) is substantially less and 2-4% of the total power measured. This relationship between power consumptions in two machining passes in sequential machining processes is shown in Fig. 4. In addition, burnishing is a chipless process which eliminates additional power for chip disposal from the machine tool. Different process behaviour can be observed in Fig. 4 in relation to the energy consumption.
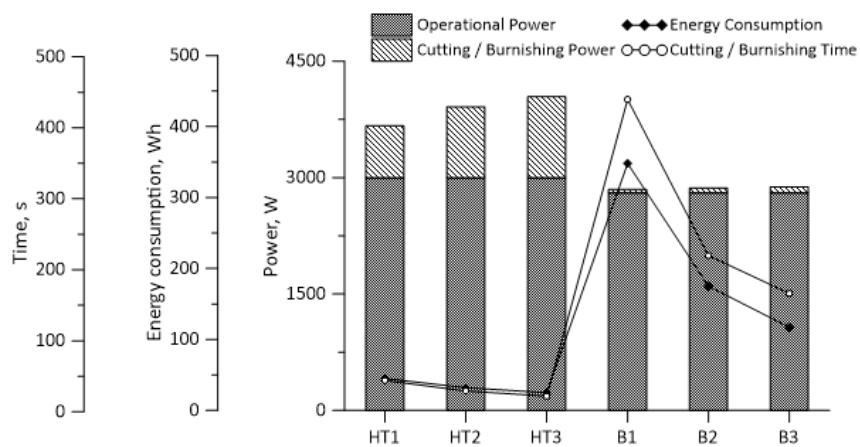

Fig. 4. Power and energy consumption *vs*. process time in cutting and burnishing passes (hard turning: f=0.1 mm/rev (HT1), f=0.15 mm/rev (HT2), f=0.2 mm/rev (HT3)), cutting speed v_c=150 m/min

It is clear in Fig. 4 that for burnishing passes the power consumption is extremely low but at the same time the energy consumption is substantially higher than for hard turning. This discrepancy results from the fact that the burnishing speed is very low in comparison to the cutting speed in turning and the burnishing time is longer. This is also due the fact that additional portion of energy is consumed by chip disposal necessary in all cutting operations (see Fig. 5a). In addition, the fixed power also increases because the machine tool should be maintained in operational readiness. It should also be noticed that turning with a higher feed causes the cutting energy to decrease but at the same time the surface roughness increases. This means that the technologist should find an optimal relationship between energy consumption and the initial surface roughness for the subsequent burnishing operation.

Exemplarily, the power distribution determined for the HT2+B2 sequential process performed on the CNC lathe used along with relevant energy consumption are shown in Figs. 5a and 5b. It is interesting that the fixed power is about 80% of the total power measured independently of the machining conditions applied. In particular, the most important variable power component with 40% input is the power consumed by hydraulic system, which is necessary for the workpiece clamping and the tailstock operating.
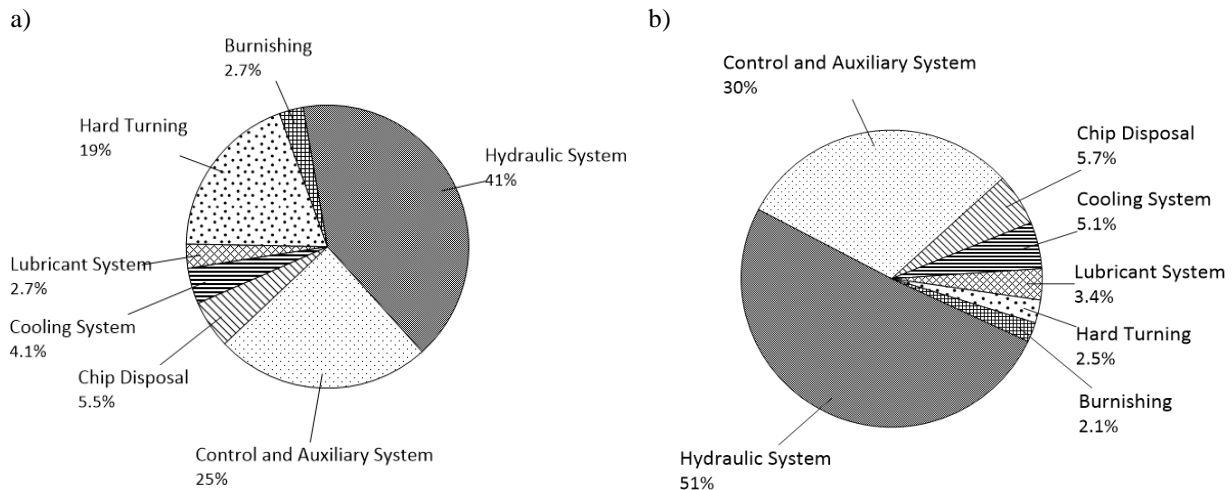
a)

b)

Fig. 5. Pie diagrams of power (a) and energy (b) consumption in turning and burnishing operations (case HT2+B2), cutting speed v_c=150 m/min

It should also be seen in Fig. 5b that the energy consumption determined for machining operations is equal to 2.5% and 2.1% for hard turning and burnishing operations respectively (in summary about 5% for sequential operation HT2+B2). In comparison, the total power consumption is about 22% (Fig. 5a).

3.2. CHARACTERIZATION OF SURFACE ROUGHNESS AND ITS CORRELATION WITH ENERGY CONSUMPTION

Fig. 6 presents the measured values of the Ra and Rz roughness parameters obtained for the initial hard turning with variable feed rate of 0.1 mm/rev (HT1), 0.15 mm/rev (HT2) and 0.2 mm/rev (HT3) and relevant values measured after finishing burnishing passes with variable feed rate of 0.05 mm/rev (B1), 0.1 mm/rev (B2) and 0.15 mm/rev (B3) respectively. In addition Fig. 6b illustrates the changes of the maximum peak height Rp and the maximum valley depth Rv. It can be noticed that the maximum roughness height Rz is the sum of the Rp and Rv components.

It can be reasoned based on Fig. 6a that the average roughness Ra is reduced 2-3 times when additional burnishing is performed on the hard turned surface. The maximum reduction of the Ra parameter is documented for sequential technological process with minimum turning and burnishing feeds of 0.1 and 0.05 mm/rev respectively. This is due to the fact that feed marks produced by turning with a low feed are relatively narrow and sharp, so its deformation is relatively easy. On the other hand, irregularities produced at a higher feed are wide, so its deformation is not so effective if the normal load was comparable at 300 N.

Based on the obtained surface smoothing effects one can conclude that the ball burnishing of hard surfaces with deterministic feed marks is a very effective technology which, in addition, can be easily performed on a CNC lathes without advanced software [4].

In general, under machining conditions used, the reduction of the Ra and Rz roughness parameters resulting from the burnishing effect is in the range of 50-60%. The most visible deformation effect, 3 times for the case HT3+B3, is related to the maximum peak height, as shown in Fig. 6b. The deformation scale of the material in the area of valleys is not so high and about 1.5 times.
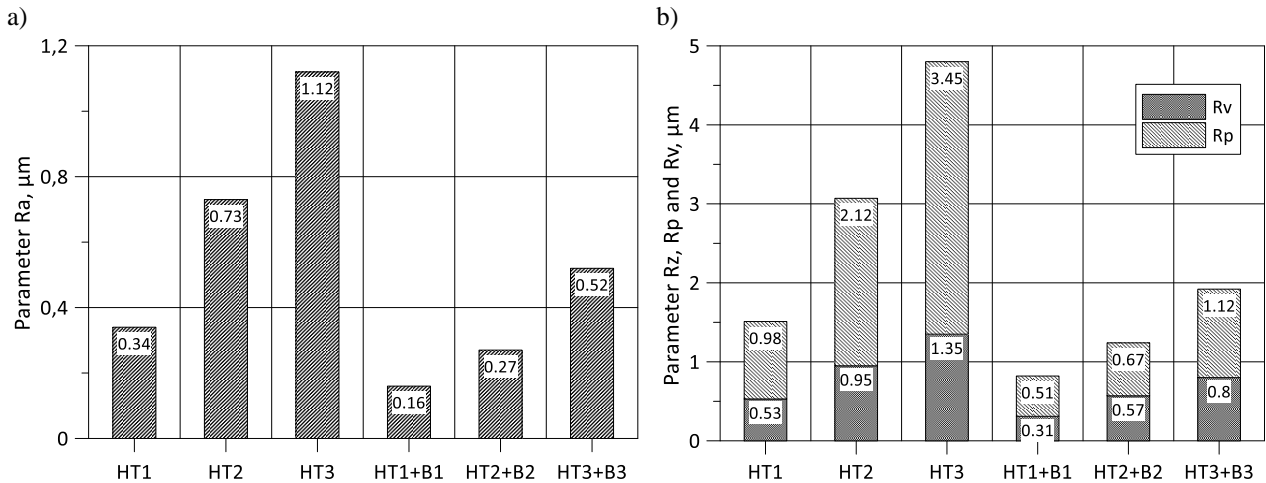

Fig. 6. Comparison of roughness parameters for hard turned and burnished surfaces, a) Ra, b) Rz, Rp and Rv, cutting speed v_c=150 m/min, depth of cut a_p=0.2 mm

In order to relate the energy consumption to the reduction of surface roughness Fig. 7 presents the relationship between the total energy needed to perform the sequential processes and the roughness reduction ratio K_{Ra} which relates the initial Rat value measured after hard turning to the final R_{ab} value obtained after ball burnishing. The reduction of the surface roughness during burnishing in relation to the initial roughness expresses the effectiveness of sequential machining processes [5].
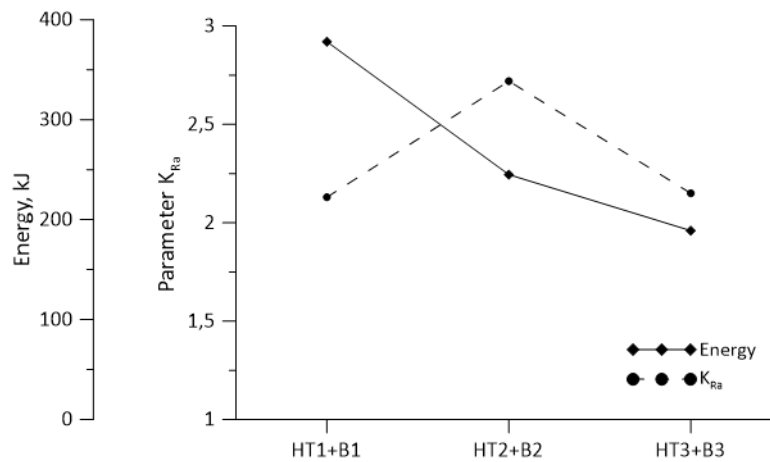

Fig. 7. Relationship between total machining energy and K_{Ra} parameter; cutting speed v_c=150 m/min, depth of cut a_p=0.2 mm

As shown in Fig. 7 the value of the K_{Ra} ratio ranges between 2.2 and 2.7 depending on the conditions of the sequential process. The maximum value of K_{Ra} ratio of 2.7 is recorded for the HT2+B2 sequence when the turning and burnishing feeds were equal to 0.15 mm/rev and 0.1 mm/rev respectively. It is also evident that the total energy decreases when both feeds increase and the most energy efficient process is performed at the maximum feed selected. In general, the process variant depends on the demanded surface finish which defines the initial surface roughness after hard turning and subsequent burnishing strategy. Also multi-pass burnishing should be investigated in terms of the power/energy consumption.

4. CONCLUSION

The following conclusions can be formulated based on this experimental study:
1. Under machining condition used the turning and burnishing power components are of 20% and 3% of total power consumption recorded on a CNC lathe.
2. The most important variable power component with 40% contribution is the power consumed by hydraulic system.
3. The power consumption is extremely low for burnishing passes but at the same time the energy consumption is substantially higher than for hard turning.
4. The total energy consumption decreases when turning and burnishing feeds increase and the most energy efficient process is performed at the maximum feed selected. This relationship is related to the process time.
5. Power/energy consumption criterion should be considered along with the surface finish criterion in order to generate surfaces with demanded functionality. This effect can be related to the K_{Ra} factor.

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