Investigation into Energy Efficiency of Outdated Cutting Machine Tools and Identification of Improvement Potentials to Promote Sustainability

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Abstract

Cutting machine tools have a significant impact on manufacturing and sustainability. There exist a large number of outdated cutting machine tools especially in developing and emerging countries which are still taking a considerable share in global value creation. Furthermore, an increasing trend in field of reuse, retrofitting and upgrading can be observed. For Life-Cycle-Assessment and analyses of end-of-life behavior of such machine tools in context of sustainability, reliable values for energy consumption and machining efficiency under realistic machining conditions are indispensable. In the present paper the energy consumption and machining efficiency of an exemplary outdated milling machine have been measured and analyzed under consideration of different influences such as process parameter, machining material and ratio of primary to secondary time. Additionally a comparison between a newer and the outdated milling machine has been carried out in order to identify and quantify possible improvement potentials of outdated machine tool concerning energy consumption and machining efficiency. Based on obtained results more accurate and realistic decision can be made by enterprises who aim to promote sustainable manufacturing.

1. Introduction

1.1. Motivation

Manufacturing sector is one of the major energy consumer on global scale [1,2]. The resulting waste and the resulting pollution as well as the energy consumption of manufacturing sector have a huge environmental impact. The growing world population on one hand and the change in consumption conduct of population in developing and merging countries on the other hand will intensify the current situation. The magnificent and almost incessant growth of machine tool production, as major carriers of global manufacturing network, in last two decades affirms the above assumption [3]. According to International Energy Agency (IEA) [4], there exist significant potential for further energy savings through the application of proven technologies in manufacturing sector. Nevertheless, sustainability is becoming increasingly important beside classical decision making attributes like cost, quality and flexibility [5].

In this context SCHISCHKE et al. [6] have carried out a comprehensive study on existing and missing norms and guidelines for energy consumption of machine tools. Different machine tool systems were evaluated in terms of annual energy consumption and consequently potential environmental impact. Over 60 technical suggestions for reducing the environmental impact of the machine tools, were presented.

The demand for new products including machine tools itself lead to great need on raw material and energy resources as well as financial resources. This demand can hardly be met sustainably by means of existing technologies merely. Simultaneously, there exist a large number of outdated machine tools which can still be used effectively [7,8]. In field of machine tools, the retrofitting and remanufacturing industry has experienced a fast growth within last decade [9]. UHLMANN [10] has investigated the upgrading potentials of outdated cutting machine tools. They proposed alternative approaches for upgrading of milling machine tools without
changing the core components to provide sustainable value creation in global scale.

Upgrading, remanufacturing and reusing of existing machine tools affect the life cycle assessment significantly. For more reliable evaluation of economical and environmental impact of reusing and upgrading of machine tools, the energy consumption and energy efficiency of such machine tools comparing to modern machine tools have to be known. To the authors’ knowledge, there exist very few studies which compare the energy efficiency and energy consumption of outdated and new machine tools.

### 1.2. State of art in energy efficiency of machine tools

There exist a various number of studies in the field of energy consumption and efficiency of machine tools. The main objective is to estimate and to reduce the energy consumption. The specific energy consumption, SEC, is defined as the energy consumption of the machine tool for removing 1 cm³ material. SEC is used in this context as an index for energy efficiency of machine tool or process. Two central approaches can be observed in existing studies:

- Energy demand estimation by using empirical or analytical models
- Energy demand reduction on process level or/and on component level.

MATIVENGGA et al. [11] have used an analytical model for estimation of total energy demand by turning process. By using a minimum energy criterion, they found the optimum process parameter under consideration of tool life for minimum energy footprint. Li et al. [12] have developed an empirical model for estimation of energy requirement of a milling machine based on thermal equilibrium. MORI et al. [13] have carried out a study for determination of optimal process parameters by regular drilling, face milling and end milling. They have also developed new acceleration control method for energy demand reduction [14].

It is important to mention that the main objective of the present study is providing a reliable comparison between outdated and new machine. This information shall be used for more accurate life cycle assessment. Furthermore, the results can be used to modify existing models for outdated machine tools and to optimize the energy efficiency of similar machine tools.

### 2. Approach

In order to make a realistic comparison, an outdated and modern conventional midsize CNC milling machine tool have been investigated regarding the energy consumption. The reason for investigation of cutting machine tools is their important role among other manufacturing processes like forming and joining. Milling machine tools and machining centers made up of 30 % of German machine tool production in 2011 [14]. At the same time the metal working machine tools experience a continuous shift from non-CNC machine tools to CNC-machine tools [15]. Therefore results of the present study can be applied to a large number of exciting milling machine tools.

The outdated machine tool, FP4NC, DECKEL GmbH, Germany, is a vertical knee-type CNC milling machine with 4 simultaneously controlled axis built in year 1986. The newer machine tool, DMU-50, DECKEL MAHO GmbH, Germany is a vertical universal 3+2 axis CNC milling machine manufactured in year 2008.

Both compared machine tools have common working space for stand-alone solutions of between 450 mm and 560 mm per linear axis and are suitable for machining of single parts and small series. Concerning age (27 years) and technology, the FP4 milling machine has been considered as a representative example for an outdated machine tool. Further technical information available for these machine tools including main drive, feed drives, working space, control system, power of main spindle and maximum velocity of feed drives are shown in Table 1.

| Machine type       | CNC Milling Machine | CNC Universal Milling Machine |
|--------------------|---------------------|-------------------------------|
| Manufacturing year | 1986                | 2008                          |
| Manufacturer (GmbH)| Deckel              | Deckel Maho Seebach           |
| Designation        | FP4NC               | DMU 50                        |
| Base area [m]      | 2 x 1.6             | 1.2 x 1.4                     |
| Number of machine axes | 4          | 3 + 2                         |
| CNC control system | Grundig/Dialog 4   | Heidenhain/ITNC 530           |
| Travels X/ Y/ Z [mm] | 560/ 500/ 450    | 500/ 450/ 400                 |
| Feed speed [mm/min] | Up to 3600         | Up to 24000                   |
| Max spindle power [kW] | 4.0           | 13.0                          |
| Spindle revolution [RPM] | Up to 3150 | Up to 10000                   |
| Tool holder system | SK 40              | SK 40                         |

At first step the energy consumption of major machine tool components such as spindle, feed drives and control unit under idle condition has been determined. In order to minimize the measurement effort, only the total required electrical power of machine tool as a function of time has been measured. By activating the components successively, the energy consumption of each component could be determined. Additionally such an approach can be applied by enterprises worldwide, which might be interested in evaluation and optimization of energy efficiency. At second step the required electrical power of different operations such as tool changing, air cutting, roughing and finishing have been measured under identical condition for both machine tools. At third step, the energy consumption of each machine tool for a specific volume of removed material has been determined for different materials and process parameters. The motivation is not the determination of optimal process parameters but the comparison of efficiency increase due to available spindle rotation and feed speed.

The total energy consumption of machine tool depends on temporal share of a sequence of operations, which are required for manufacturing of a specific part or a series of part. This share of required energy depends on geometry of part and manufacturing chain.
3. Experimental Setup and measurements

Two types of tests have been carried out on both machine tools; (1) Test for determining the energy consumption of components and operations; (2) Tests for measurement of energy efficiency at different process parameters. The objective of both test categories is comparison of two milling machine as representative examples of outdated and updated machine tools. Following sequence of operations have been carried out by first test type:

- Startup
- Standby
- Ready
- Axis jog
- Spindle
- Air cutting
- Roughing
- End milling
- Shutdown

By applying the above sequence of operations, the power profile of each machine tool has been determined. The power profile can be used for estimation of power demand of major operations and main components. Table 2 shows a number of operations and the corresponding components which consume energy.

Table 2. Main operation and corresponding power demands.

| Operation          | Main electronic controlling | Spindle | Coolant Pump | Door | Tool-change system | Mechanical cutting power |
|--------------------|----------------------------|---------|--------------|------|--------------------|--------------------------|
| Standby            | X                          |         |              |      |                   |                          |
| Ready              | X                          | X       |              |      |                   |                          |
| Positioning (axis jog) | X                        | X       | X            |      |                   |                          |
| Tool changing      | X                          | X       | X            | X    |                   |                          |
| Air cutting        | X                          | X       | X            | X    |                   |                          |
| Material removal   | X                          | X       | X            | X    |                   | X                        |

All tests have been applied to both machine tools with comparable parameter and identical NC-program. NC-codes have been generated by CAE software NX 8.0 and uploaded on machine CNC-unit by means of proper interface. For more comparability, the duration of defined operation has been kept similar. Figure 1 shows the path of tool center for a test work piece.

By second test type, the required power for material cutting has been determined for sets of process parameter and two materials. Table 3 and Table 4 show the test parameters. The goal of present test is estimation of differences of energy efficiency which are given through the technical limitation of both machine tools.

Table 3. Test parameters used by roughing.

| Parameter set | Test 1 | Test 2 | Test 3 |
|---------------|--------|--------|--------|
| Spindle revolution [RPM] | 1114   | 2500   | 3183   |
| Cutting velocity [m/min] | 70     | 157    | 200    |
| Feed velocity [mm/min] | 267    | 500    | 673    |
| Feed per tooth [mm] | 0.06   | 0.04   | 0.05   |
| Cutting width [mm] | 12     | 12     | 12     |
| Overlap [%] | 60     | 60     | 60     |
| Cutting depth [mm] | 3      | 3      | 3      |
| Material number | 1.0038 | 3.4365 | 3.4365 |
| Wet machining | +      | +      | +      |

Table 4. Test parameters used by finishing.

| Parameter set | Test 4 | Test 5 | Test 6 |
|---------------|--------|--------|--------|
| Spindle revolution [RPM] | 1273   | 2600   | 3183   |
| Cutting velocity [m/min] | 80     | 182    | 200    |
| Feed velocity [mm/min] | 317    | 300    | 300    |
| Feed per tooth [mm] | 0.04   | 0.02   | 0.02   |
| Cutting width [mm] | 14     | 14     | 14     |
| Overlap [%] | 70     | 70     | 70     |
| Cutting depth [mm] | 0.3    | 0.3    | 0.3    |
| Material number | 1.0038 | 3.4365 | 3.4365 |
| Wet machining | +      | +      | +      |

The specification of tools, which has been applied for roughing and end milling, are shown in Table 5. In order to avoid additional effects of tool wear, a new tool has been used by each test.

Table 5. Tool specification for roughing and end milling.

| Description                   | Diameter [mm] | Number of teeth | Item number | Producer |
|-------------------------------|---------------|-----------------|-------------|----------|
| HSS roughing cutter Coating: TiAlN | 20            | 4               | 192850      | Garant   |
| HSS PM finishing cutter Coating: TiAlN | 20            | 6               | 191420      | Garant   |
4. Evaluation and Results

The energy efficiency of above milling machines have been determined by measuring and evaluating of total energy consumption. The total required electrical power of milling machines have been determined by measuring the value of voltage $U$ [V], current $I$ [A] and phase shift per each power supply line as time function. The active power $P$ [W] and reactive power $Q$ [VAR] has been calculated according to equation (1) and equation (2):

$$ P = \sum_{i=1}^{n} U_i I_i \cos(\varphi_i) $$  

(1)

$$ Q = \sum_{i=1}^{n} U_i I_i \sin(\varphi_i) $$  

(2)

Using above values the apparent power $S$ [VA] as time function can be calculated by means of equation (3):

$$ S = \sqrt{P^2 + Q^2} $$  

(3)

The value of apparent power has been used for evaluating of energy consumption and energy efficiency. Figure 2 and Figure 3 illustrates the power demand profile of both milling machines for the set of representative operations as described in section 3. In this way the required power of main components can be determined under operative condition. It is important to notice that the duration of above operations deviate for both machines. So that power profile shall not be used directly for comparison of energy consumption. Instead the mean power demand of components and operation can be calculated correctly.

The total power demand of machine tools can be decomposed in a fixed part and temporal variable part. According to equation (4):

$$ P_{tot}(t) = P_{fix} + P_{opr}(t) $$  

(4)

Here $P_{tot}(t)$ is the total power demand at time $t$, $P_{fix}$ is the fixed part due the main electronic and controlling systems and $P_{opr}(t)$ is the variable share of required power at time $t$. $P_{opr}(t)$ is dependent on running operation. The energy consumption of machine tool $E$ in time period from $t_1$ to $t_2$ is calculated as followed:

$$ E = \int_{t_1}^{t_2} P_{tot}(t) dt = P_{tot}(t)(t_2 - t_1) $$  

(5)

Here $P_{tot}$ is the mean value of required power. Figure 4 shows a comparison of the mean required power for main components of both investigated machine tools. Concerning the fact that the measurements have been carried out under similar condition, the differences in values is a reliable measure for energy efficiency of components. Figure 5 illustrate the mean required power of representative operations.

It can be assumed that the process chain for manufacturing of a specific part can be decomposed into sequences of above operations. By knowing the time duration of each operation, the total energy consumption which is required for manufacturing a part or a set of parts can be estimated.

In order to determine energy efficiency of a process or component, the energy consumption per material or material removal rate has been calculated. The removed material volume and energy consumption have been measured for each test. Table 6 shows the results of measurements and calculation of SEC. Since the process parameters and NC-codes are identical for both machine tools in each test, the SEC values can be compared directly as a measure for process efficiency. The process parameter of test 5 and test 6 cannot be applied to the FP4-Deckel milling machine due to the limitation of spindle speed to 3000 RPM.
Fig. 4. Comparison of required power of major components of investigated machine tools without material removal.

Fig. 5. Comparison of total required power of milling machine by defined test parameters.

From Table 6 it can be seen that the milling machine DMU-50 has higher energy efficiency for all test parameter. However, the difference in energy efficiency is more significant by cutting of aluminum alloy 3.4365 comparing to cutting of steel 1.0038. Considering above information, it can be assumed that the outdated machine tools would have higher energy efficiency by cutting of materials which allows lower cutting velocity like high strength steels and nickel-based alloys.

5. Summary and outlooks

It can be seen from the component’s power demand that energy consumption of main electronic and coolant pump is by DMU-50 milling machine up to 40 % higher than by FP4-Deckel milling machine.

In contrast, power demand of spindle and feed drives under idle running condition by FP4-Deckel are significantly higher than by DMU-50. The lower fixed energy consumption in combination of shorter time for modus-change represents a high potential for reduction of energy consumption by FP4-Deckel. As an example energy reduction can be carried out by using a graph-based optimization method for control parameters which has been applied by EBERSPRÄCHER and VERL [16].

By comparing the results of milling tests with different process parameters it can be seen that the specific energy consumption of outdated milling machine is in average 40 % higher than the newer one. Due to limited maximum available spindle speed and spindle power, the outdated machine tools are not able to reach high removal rate. This leads additionally to lower energy efficiency by cutting of materials which allow higher cutting speed such aluminum alloys. On other hand there exist materials which can be processes with only low cutting speed like nickel-based alloys. Here it can be assumed that the outdated machine tools can be applied with higher energy efficiency for cutting of such materials. Though, the requirements for realizing such a process like sufficient spindle power and adequate structural stability have to be considered.

The results of the present paper can help enterprises considerably for more reliable life cycle analysis of outdated machine tools. In this way more economically and ecologically sustainable decision can be made in the field of remanufacturing, retrofitting and upgrading of outdated milling machine tools. It is important to notice that there exists a great necessity for further investigation and performance comparison in this field in order to meet the future manufacturing demands sustainably.

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