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Modelling of direct energy requirements in mechanical machining processes

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ABSTRACT

The aim of this research was to contribute towards the development of a new mathematical model and logic for predicting direct electrical energy requirements in machining toolpaths. This model will track the visibility and process dependence of energy and hence carbon footprint in machining process. This study includes a critical review of similar existing models and their limitations. The effect that machine modules, auxiliary units and machine codes have on power and energy consumption during machining was studied and the electrical current consumption measured. A mathematical model for electrical energy use in machining was developed addressing the limitations of existing models and validated on a milling tool path. The paper provides valuable information on the impact of machine modules, spindles, auxiliary units and motion states on the electrical energy demand budget for a machine tool resource. This knowledge is fundamentally important in evaluating toolpaths and re-designing machine tools to make them more energy efficient, to reduce electricity costs and associated carbon footprints.

1. Introduction

In the year 2010, 27% of electrical energy consumption in the United Kingdom (UK) was attributable to industrial sectors (DUKES, 2010). In most cases this electricity is predominantly generated through the use of fossil fuel. The use of carbon rich electricity generation sources is of critical global concern as these processes produce CO_2 emissions. This implies that the higher the consumption of electricity in manufacturing industries, the higher the carbon footprints left by such end products. As a result, the UK government and other worldwide leaders are making an increasing demand for energy efficiency.

A machine tool plays a major role in manufacturing. The European Commission has cited it as being in a top three priority for inclusion into the product categories regulated through the eco-design directive (EPTA, 2007). As such there is urgent need for manufacturing sectors, particularly machine shops, to reduce energy use per product manufactured, to help meet eco-design directives and CO_2 emission targets. Some relevant targets were set by Kyoto protocol (1997) (Kyoto protocol, 2007). This calls for machine tool designers to increase their understanding of energy use by different design features of a machine tool. There is also a need for the manufacturing industry to understand the impact of machine tool motions and toolpaths on energy requirements for machining.

1.1. Research aim and motivation

At present the research community and industry do not have a robust method of calculating the energy that is going to be used in machining a given product. Existing models are focussed on specific energy or treating the machine tool as a black box. There is need to relate the machining numerical control (NC) commands to the energy requirements in machining for process planners to be able to select minimum energy machining strategies. The motivation for this work was to contribute towards an improvement in the modelling capability for energy requirements in mechanical machining and to develop a new model for explicit modelling of the machine tool states, workpiece machinability and the impact of cutting variables. It is essential to produce such a model and to raise the integrity of energy prediction models so that they can be used in eco-friendly process planning to estimate the electricity footprint for machined products.

1.2. Machine tool states and proposed improvements

The Cooperative Effort in Process Emission (CO2PE!) proposed a unified taxonomy (Ostaeyen, 2010) and methodology (Kellens et al., 2012) so that in manufacturing, energy data collection can be standardised and presented in a globally compatible approach. CO2PE! classified machine tool states into two categories: ‘Basic State’ and ‘Cutting State.’ The states are based on operational characteristics of the processes. In the ‘basic state’, electrical energy is needed to activate required machine components and ensure the

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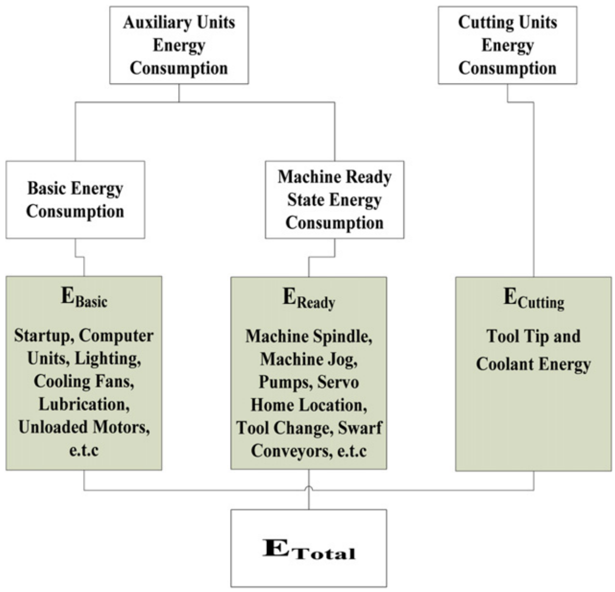

Fig. 1. Machine tool electrical energy consumption estimation model.

operational readiness of the machine tool. In the 'Cutting State' the energy is demanded at the tool tip to remove workpiece material as well as for modes of energy loss e.g. through machine noise, friction etc.

While COP2E! sets the framework, it does not clarify the existence of a transitional state between the 'Basic State' and 'Cutting State.' In this paper the authors define a third and intermediate state called the 'Ready State'. This additional state is required to clarify the process that takes place after the machine is started. This stage of the process requires more energy for the drives and spindle movement to bring the tool and workpiece to the correct, about to cut position and to set-up the necessary cutting velocity. Examples for such activities could include 'G00', 'S' and 'T' (rapid, spindle speed and tool change machine features respectively). Fig. 1 shows the extended machine tool electrical energy states proposed by the authors.

In order to establish focus for electrical energy improvement, it is important to understand how the electrical energy use or power demanded is distributed during machine use. A small number of researchers have explored the critical aspects of electrical energy use in machine tools. Some of these results are summarised in Table 1.

Table 1 clearly shows that the machine tool is the dominant consumer of electrical energy in machining compared to the actual chip forming process. It is important to further understand how this electrical energy requirement by the machine is distributed. This can then help to develop more accurate models of energy demanded by machine tools which could be used by machine tool designers and process planners. A good basis for analysing energy use in machining is through Gutowski et al. (2006) mathematical model for direct energy requirement in machining as shown in Equation (1).

$$E = (P_0 + k\dot{v})t \tag{1}$$

Where, E is the direct energy in J or Ws required in machining processes, P_0 is the power in W, consumed by the machine before it starts cutting, k is the specific energy requirement in Ws/mm^3 for machining a particular workpiece material, $\dot{v}$ is the material removal rate in mm^3/s, while t is the cutting time in s.

Considering both Equation (1) and Table 1, it can be noted that P_0 dominates the direct energy requirement in machining. This demonstrates how the selection of machine tools can have significant impact on direct energy requirement in machining. Equation (1) also enables modelling of the machine tool energy requirements to be done distinctly from the energy required for the chip formation process. This mathematical model is very valuable for supporting process planning as it enables comparison and selection of machine tools and workpiece materials.

After this early work by the MIT group, a number of mathematical models for energy in machining have been proposed and these are summarised in Table 2.

From Table 2a, the modelling approach used by Mori et al. (2011) has some resemblance to Gutowski et al's (2006) but Mori et al., split P_0 into basic and idle power. This is in line with the proposal put forward by this paper in Fig. 1, assuming that the idle power can be described as the 'Ready State' power. Calling it idle power suggests an unnecessary step, while the term ready state clarifies the need to bring the system to an about tool to engage position. In the current paper, authors further propose, that the cutting power demand P_3 in the model developed by Mori et al. (2011), can be expanded to take into account the specific cutting energy coefficient as introduced by Gutowski et al. (2006). Diaz et al. (2011) produced an interesting approach acknowledging that during the machining process the tool engage and disengage with the workpiece and that the total cycle time is not devoted to the actual material removal. Thus, modelling the air cutting time reduces the chance of over estimation of the energy demand. Ultimately there is need to quantify the air cutting time for toolpath in order to estimate its impact on total energy

Table 1
Machine tool contribution to electrical energy demand.

Authors	Observations
Kordonowy (2001)	The constant energy on a Cincinnati Milacron 7VC Automated milling machine was 51.9% of the total energy requirements in machining.
Dahmus and Gutowski (2004) and Gutowski et al. (2006)	The energy consumption of machine tools during actual cutting processes was 85.2% for 'Idle' or machine tool auxiliary function and 14.8% for 'Cutting'.
Devoldere et al. (2007)	The idle or stand-by mode consumed 1.7 kW energy on a five-axis milling machine and the biggest consumer was the hydraulic pump, using nearly 0.9 kW of energy.
Diaz et al. (2009)	Among the auxiliary units on a Mori Seiki NV1500DCG milling machine, the servo and the spindle consumed the most energy in the basic and idle states.
Vijayaraghavan and Dornfeld (2010)	For a Mori Seiki NV1500DCG milling machine, energy consumption was dominated by start-up and idle states.
Rajemi et al. (2010)	In an MHP CNC Lathe during dry cutting, the machine module and idle power consumption was 61–69% of the total power, in the cutting speed range of 500 to 300 m/min.
Anderberg et al. (2010)	Reported that energy demand by machine tool auxiliary units dominated the cost components and CO_2 footprint of a manufactured product.
Avram and Xirouchakis (2011)	Reported that the machine tool system consumed 45% and 55% of energy at low and high spindle speeds respectively when in a non-cutting mode on executing a part program on a C.B. Ferrari A152 machining centre.

Table 2
a: A summary of other models for direct energy requirements in machining. b: A summary of specific energy models in machining

Author(s)	Direct energy in machining model	
Mori et al. (2011)	$E = P_1(T_1 + T_2) + P_2(T_2) + P_3(T_3)$ Where, E is the total direct energy requirements, P_1, P_2, P_3 represent basic, idle and cutting power demand in Whr and T_1, T_2, T_3 are the corresponding time.	(2)
Diaz et al. (2011)	$E = P_{avg}*\Delta t = (P_{cut} + P_{air})*\Delta t$ Where, E is the total direct energy requirements, P_{avg} is power demand, Δt processing time, P_{cut} is the cutting power and P_{air} is air cutting.	(3)
He et al. (2012)	$E_{total} = E_{spindle} + E_{feed} + E_{tool} + E_{cool} + E_{fix}$	(4)
	This expanded to $E_{total} = \int_{t_{me}}^{t_{ms}} P_m dt + \int_{t_{ce}}^{t_{cs}} P_c dt + \sum_{i=1}^{m} \int_{t_{fs}}^{t_{fe}} P_i dt + P_{tool} t_{tool} + P_{cool}(t_{coe} - t_{cos}) + \left(P_{servo} + P_{fan}\right)(t_e - t_s)$	(5)
	Where, E_{total} is the total direct energy requirements, P_m is the power for enabling the operating state of the spindle transmission module, P_c is the power for material removal from the workpiece, t_{ms} and t_{me} are respectively the starting time and the ending time for spindle running, and t_{cs} and t_{ce} are respectively the starting time and the ending time for cutting, P_i, t_{fei}, and t_{fsi} are, respectively, the power, the starting time, and the ending time of the ith-axis feed motor, P_{tool} is the power of the tool change motor, and t_{tool} is the turret rotation time, P_{cool} is the power of the coolant pump motors, and ($t_{coe}-t_{cos}$) represents the running time of the coolant pump motor, P_{servo} and P_{fan} are the power of the servos system and fan motors, respectively and (t_e-t_s) denotes the running time of the machine tool throughout the entire NC file.	

Author(s)	Energy in machining model	
Diaz et al. (2011)	$e_{cut} = k*\frac{1}{MRR} + b$ Where, e_{cut} is the specific cutting energy, k is a constant and has units of power and b represents the steady-state specific energy.	(6)
Draganescu et al. (2003)	$E_{cs} = \frac{P_c}{60\eta z}$ Where, E_{cs} is the specific energy consumption, P_c is the cutting power, η is machine tool efficiency and z is the material removal rate.	(7)
Li and Kara (2011)	$SEC = C_0 + \frac{C_1}{MRR}$ Where SEC in kW/cm^3 is the specific energy consumption; MRR is the material removal rate; C_0, and C_1 are empirical coefficients and are not the same as the specific cutting energy and idle power because the empirical approach considered the machine tool to be a single holistic system. Unfortunately this hides vital information about the machine tool design and workpiece machinability.	(8)

demand. However, Diaz et al's model was not focused on process planning and does not explicitly model the impact of machine tools, workpiece materials and cutting variables.

Unlike Gutowski et al. (2006), He et al. (2012) used cutting forces instead of specific energy to model the energy required for the chip formation process. The utility of using specific energy is better because it is a simple concept to apply to a range of machining processes. It enables an assessment of the energy efficiency of materials based on their machinability. The limitation of the model developed by He et al. is that modelling the fixed energy simply based on power for servo drives does not present a complete picture as other equipment features are required to support the machining process. For example this model ignores energy demand for the computer used by the machine, the lights, lubrication of the machine, swarf conveyors and chillers. As such, this model is not generic for all machine tools and needs to be improved. The energy used by machine equipment features in the unloaded state, need to be characterised according to the machine design and energy losses. Additionally, He et al., 2012's part of the energy model for tool change does not consider the number of tool changes required to finish a machining job and the fact that turret indexing can be done using the shortest route. Additionally, on a milling machine, the axis have to be engaged to take the spindle from its current location on the workspace to the tool magazine pick up position and back which requires energy. Ultimately, the model does not incorporate cutting conditions of cutting speed, feed and depth of cut which prevents it from being an information source for process planning.

There are also other approaches to modelling of energy consumption in machining as shown in Table 2b. These are based on different methods used to measure efficiency. This can be total energy normalised by the volume machined. While these may be interesting as a benchmarking measure, Diaz et al. (2011); Draganescu et al. (2003); and Li and Kara (2011) specific energy models do not directly give the energy footprint for a machined component nor do they render themselves supportive to process planning which needs cutting speeds, feeds and depth of cut information to be modelled explicitly.

2. New improved model for direct electrical energy requirement in machining

Considering Equation (1) and the new classification in Fig. 1, the model for direct energy requirements in machining can further be improved into Equation (9a)

$$E_t = P_b t_b + (P_b + P_r)t_r + P_{air}t_{air} + (P_b + P_r + P_{cool} + k\dot{v})t_c \quad (9a)$$

Where, E_t is the direct total energy requirement, P_b, P_r and P_{cool} in W are the basic and ready state power (power increment above basic power to bring the machine to the about to cut position) and coolant pumping power requirements respectively, t_b and t_r in s are the basic and ready time respectively and k with units of kJ/cm^3 is the specific cutting energy which is closely related to the workpiece machinability and the specifics of the cutting mechanics; $\dot{v}$ in cm^3/s is the rate of material processing; and t_c is the cutting time in s. Taking into account Diaz et al's (2011) approach, P_{air} represents the average power requirements for a non cutting approach and retract moves over the component and t_{air} represents the total time duration in s of these non-cutting moves. Obviously in machining the objective is to keep the non-cutting time as short as possible in order to improve machine actual cutting utilisation.

Equation (9a) can further be re-organised into Equation (9b).

$$E_t = P_b(t_b + t_r + t_c) + P_r(t_r) + P_{air}t_{air} + (P_r + P_{cool} + k\dot{v})t_c \quad (9b)$$

3. Experimental investigation

To validate the mathematical approach suggested by Equation (9), cutting tests were done in milling to characterise energy requirements and further develop the model according to observed electrical energy demand patterns. This was extended into the application of the model for facing off a x–y plane surface on a component on vertical axis milling machines. The machines used were a MHP lathe, Takisawa CNC milling machine and a Mikron HSM 400 High Speed Milling Centre.

A Fluke 345 Power Quality Clamp Meter was clamped on the power bus at the back of the machine tool system under investigation and used for current measurement. Fluke 345 has in-built functions for power measurement, Oscilloscope and Data Logger in a single, hand-held tool. True-rms ac and dc current measurements up to 2000 A can be measured.

4. Results and discussions

4.1. Energy consumption for machine modules and auxiliary units without cutting

A direct assessment of the energy demand of machine modules was undertaken to identify the energy demand of the machine modules and to understand the dominant energy consumers. A CNC MHP lathe with Open MDSI architecture, Takisawa CNC milling machine and Mikron HSM 400 high speed machining centre were tested. To measure the electrical current drawn by the machines using the Fluke 435 power clamp meter, current flow was recorded when the machine was switched ON and then individual auxiliary units were identified through the electrical circuitry. To characterise the electrical energy requirements by the machine, the current readings were recorded without any cutting operation. The servos and spindle were then manually indexed through the jog mode to measure the current during home positioning and tool change.

The power needed for switching on the machine modules of the CNC MHP lathe with Open MDSI architecture was 1229 W. The machine start-up consumed 3537 W of power. This was due to the fact that at start-up, most of the auxiliary units are powered. The rapid movement to home location (axes jog) required 2394 W. Rotating the spindle without cutting (idle condition with spindle on) at a speed 1000 rpm required 3594 W.

Fig. 2 shows the distribution of power consumption of the machine modules, auxiliary units and essential motions based on machine tool states of 'Basic' and 'Ready'. The tip or cutting state is not shown since this is a study for a non-cutting operation. The results show that the power demand of the 'Basic states' is 53%, 72% and 63% for CNC MHP lathe, Takisawa CNC milling machine and Mikron HSM 400 High Speed Milling Centre respectively, of the total power requirements for a machine operating at no cutting load. The 'Ready states' power budget is 47%, 28% and 37% respectively. This shows that the intermediate actions of getting the machine ready have a significant power demand though lower than start-up.

Therefore, it is important that the power demand of the 'Ready state' is included in the estimation methodology of the total energy demand for machine tool system as shown Equation (9). Hence, the total energy demand of machine tool system could be estimated using Equation (9).

The power requirements for individual aspects of the CNC MHP lathe, MAC-V2 Takisawa Milling Machine, and Mikron HSM 400 high speed machining centre are shown in Figs. 3–5. For example taking the MHP CNC lathe, it is noted that the machine start-up (24.04%), spindle running (24.43%), servo home location (16.27%), fluid pumping (14.85%) and main switch (8.35%) dominate (>80%) the power demand of the 'Basic' and 'Ready' states of the machine tool under investigation. These are the key areas for improvement for eco-design of this type of machine tool for machine utilisation and optimisation.

In the cutting state, other auxiliary modules are activated which also consume electricity. This includes the tool change system, spindle speed acceleration or deceleration and coolant pumps.

4.2. Tool change and spindle speed–power characteristics

The tool change process accesses the tool magazine for tool selection processes based on the programmed NC codes. In the event of a machining task, as the machine tool is switched 'ON', electrical current flows through the system to activate the machine modules to get to the basic state as previously described. Just before actual cutting starts, there will be a tool change action (could be null in some machine tools system as in the case of fixed spindle machine tool, vertical or universal milling machines), at which the machine tool now completes the rapid axis movement to a point

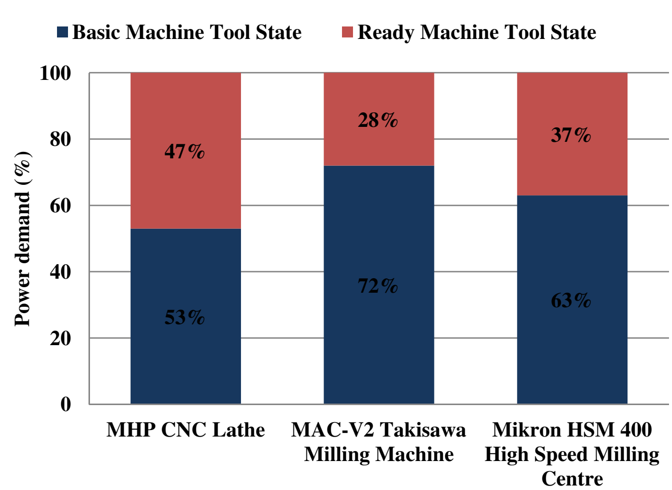

Fig. 2. Basic and ready states power relationship.

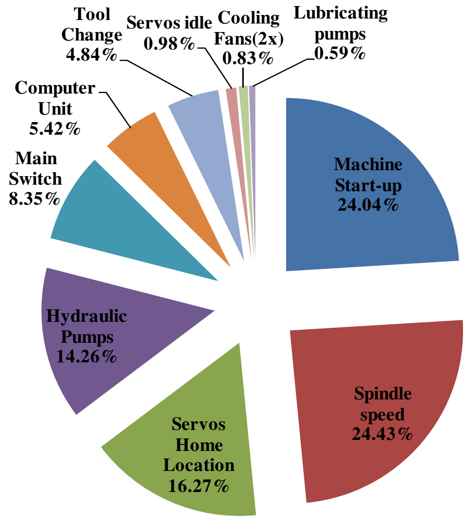

Fig. 3. Non-cutting power consumption distribution of the MHP MDSI CNC open lathe machine.

where the machine tool is in a Ready state. The energy demand for tool change task E_{tc}, can be estimated as shown in Equation (10).

$$E_{tc} = P_{tc}t_{tc} \tag{10}$$

Where, P_{tc} and t_{tc}, represents power demand in W and time in s respectively for tool change.

The next energy consuming unit of a machine tool system is the spindle. Its analysis is complex (Hu et al., 2012). However, direct measurement and/or statistical modelling of the spindle power demand characteristics can be estimated with simplifications such as neglecting the power loss due to friction, vibration of the bearing units, heat, and viscosity of the spindle lubricant. The assembled spindle of a machine tool generally consist of drives, motor and mechanical transmissions. The energy efficiency of drive component and power output characteristics depends on the ratio of delivered power to consumed power and it is therefore the efficiency of the system. The spindle does accelerations and decelerations during machining processes. This characteristic affects power demand.

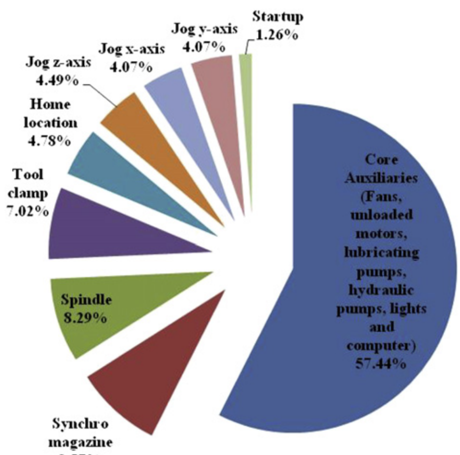

Fig. 4. MAC-V2 Takisawa Milling Machine auxiliary units power demand.

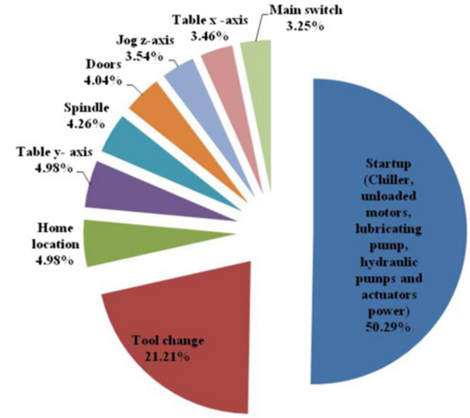

Fig. 5. Mikron HSM 400 high speed machining, auxiliary units power demand.

4.2.1. *Effect of spindle speed on energy required by a DC motor driven MAC-V2 Takisawa Milling Machine*

Current consumption at different spindle speeds was recorded at no cutting on the MAC-V2 Takisawa Milling Machine using the Fluke 435 power clamp meter. A tool holder diameter of diameter 50 mm with four uncoated carbide tool inserts, TPKN1603PPTR-P30, and model number Bristol Erickson 10-527-008-1.P5030 with overhang of 105.16 mm. The material and process parameters used are as shown in Table 3.

During the analysis, it was observed that the spindle exhibits three different characteristics when running in non-cutting mode. These can be related to the power spindle characteristics curve as shown in Fig. 6. The zones were identified as zone A, B and C. The rate at which the spindle power required rises with increase in spindle speed depends on the spindle design and spindle power characteristics as shown in Figs. 6–9. The influence of spindle speed on spindle power demand was evaluated and a regression equation with R-squared of between 97 and 100% obtained. It is therefore, possible to estimate the power demand of the spindle at each zone using the power equation as shown in Equations (11)–(13). The spindle power consumption equation to be used depends on the spindle speed selected during machining processes.

From Figs. 6 and 7, for the power-spindle speed characteristics for spindle speed ranges between 600 and 1500 rpm, the power model in Equation (11) should be used for MAC-V2 Takisawa CNC milling machine.

$$P_s = 0.8518N - 345.26 \tag{11}$$

Where, P_s is the spindle power and N, is the spindle speed.

For Zone B, spindle speeds ranges 2000–5000 rpm,

Table 3
Workpiece type and process parameters used.

	Takisawa Milling Machine (with DC servo motor model 20M, spindle A06B-0652-B)	Mikron HSM 400 machining centre (with HVC140-SB-10-15/42-3F-HSK-E40 spindle)
Workpiece	Stainless steel T316L	Stainless steel T316L
Hardness	220 Vickers	220 Vickers
Spindle speed	650 RPM	650 RPM
Feed rate	75 mm/min	500 mm/min
Cutting depth	0.5 mm	0.5 mm
Cutting fluid	Blasocut BC25	Blasocut BC25
Tool holder diameter	50 mm	8 mm

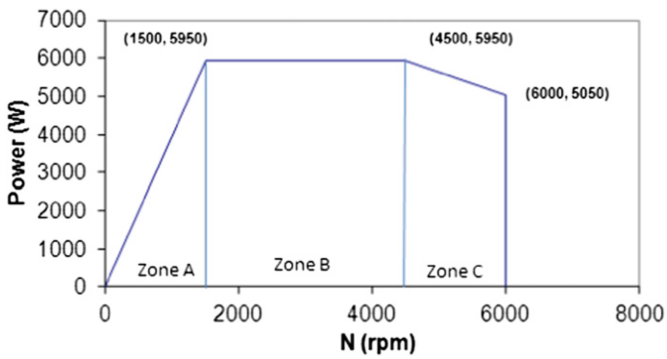

Fig. 6. Power-speed characteristics of a MAC-V2 Takisawa Milling Machine tool and 3 zones for energy profile.

$$P_s = 1.181N - 1682.5 \tag{12}$$

Likewise, for Zone C, spindle speeds ranges 4800–5600 rpm,

$$P_s = -1.5513N + 11423 \tag{13}$$

It is therefore clear that the spindle power consumption equation to be used depends on the spindle speed selected during machining processes as shown in Equations (11)–(13). Hence, a generic model was formulated for the spindle speed power demand as shown in Equation (14).

$$P_s = mN + C \tag{14}$$

Where P_s, is the spindle power demand, m, represent the spindle speed coefficient and N, represent the spindle speed in revolution per minute and C, a constant.

4.2.2. Development of an improved and new energy model for milling processes

The workpiece type and process parameter in Table 3 was used to undertake a face cleaning cutting toolpath and the generated power–time graph shown is shown in Fig. 10. The area under the graph equates to the total energy demand of machining the workpiece which was categorised into three zones thus; 'Basic', 'Ready' and 'Cutting' energy states as previously explained.

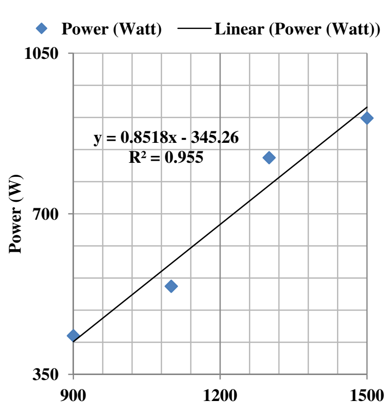

Fig. 7. MAC-V2 Takisawa Milling Machine no load power-spindle speed characteristic in zone A to 1500 rpm.

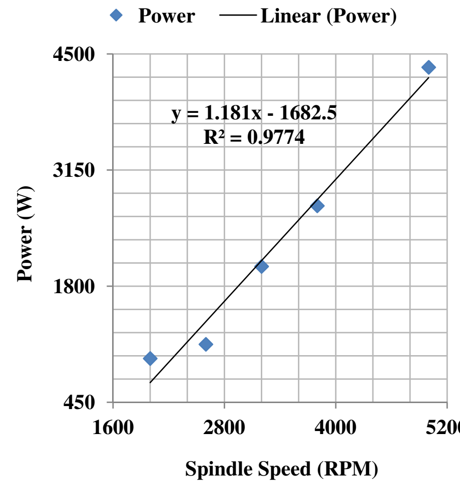

Fig. 8. MAC-V2 Takisawa Milling Machine no load power-spindle speed characteristic in zone B to 5000 rpm.

Based on the analysis of the three states of machine tools as depicted in Fig. 10, the energy demand of each state can be summed and the total energy demand of a machine tool predicted.

The tool life is an important characteristic in machining processes. It needs to be used to effect a tool change so that surface finish and product precision is not compromised. Thus incorporating tool life into the energy equation:

Total energy demand equation can therefore be re-written thus:

$$E_{\text{total}} = E_b + E_r + P_{\text{tc}} t_{\text{tc}} \left[\text{INT}\left(\frac{t_2}{T}\right) + 1 \right] + P_{\text{air}} t_{\text{air}} + (P_s + P_{\text{cool}} + k\dot{v}) t_c \tag{15a}$$

Incorporating spindle power demand, P_s from Equation (14) then;

$$E_{\text{total}} = E_b + E_r + P_{\text{tc}} t_{\text{tc}} \left[\text{INT}\left(\frac{t_2}{T}\right) + 1 \right] + P_{\text{air}} t_{\text{air}} + (mN + C + P_{\text{cool}} + k\dot{v}) t_c \tag{15b}$$

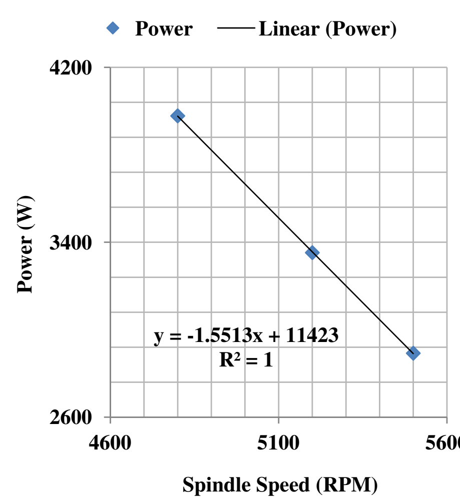

Fig. 9. MAC-V2 Takisawa Milling Machine no load power-spindle speed characteristic in zone C to 5500 rpm.

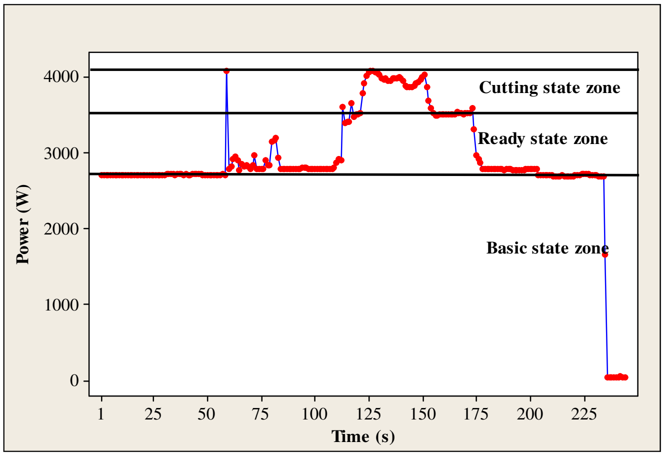

Fig. 10. Total power consumption trend for machining toolpaths.

Where P_{tc}, t_{tc} represent tool change power and tool change time respectively.

The cutting time, t_c and Tool life T and material removal rate can be modelled for turning and milling as a function of cutting velocity variables thus enabling the use of the equation in process planning.

5. Validation of direct energy model during milling processes

In order to validate the energy model in Equation (15), machining trials were conducted on the Takisawa Milling Machine. A Bristol Erickson 10-527-008-1.P5030 tool holder of diameter of 50 mm with overhang of 105.16 mm was used with a four uncoated carbide tool inserts, TPKN1603PPTR-P30. The testpiece was then also machined on a Mikron HSM 400 High Speed Machining Centre. An SHR-161-6160K 8 mm diameter carbide mill end cutter and an HSK40E-VC13-90 tool holder were used. The material and process parameters are stated in Table 3. Since the spindle speed is a dominant parameter for energy consumption, tests on both machines were done at the same spindle speed. The power consumption of the corresponding power states of the machine tools system were measured with the Fluke 435 power meter and the result shown in Table 4.

The total energy demand on MAC-V2 Takisawa Milling Machine and Mikron HSM 400 machining centre calculated using Equation (15) was 399 Whr and 415 Whr. The Fluke 435 Clamp meter gave measured values of power and cycle time which led to an area under the graph of 391 Whr and 402 Whr respectively for the Takisawa and Mikron HSM 400 CNC machines. The deviation of the prediction from the energy calculated from the experimental measurement of current demand was only +2% and +3% for the Takisawa and the Mikron CNC milling machine respectively. These values further prove that the energy model as stated in Equation (15) can be used as a generic and robust estimate of the energy requirements in machining.

Table 4
Power and total energy demand estimation of machine tools under investigation.

	Takisawa CNC machine	Mikron HSM 400 machine
Basic state power (W)	2760	2904
Ready state power (W)	648	401
Tool change power (W)	0[a]	920
Air cutting power (W)	2955	2917
Coolant power (W)	776	1790
Spindle no load power (W)	184	184
Specific energy power (W)	125	333
Total energy calculated from new model (Whr)	399	415
Total energy from measured current and time (Whr)	391	402
% Difference between model predicted and measured energy	+2	+3

[a] Zero represents 'do need' for event i.e. tool already in spindle and single pass tested.

6. Conclusions

The electrical energy requirements for a machining process needs to be modelled in order to account for and optimise the monetary and environmental impact of electricity usage in manufacturing. This paper classified three categories for the energy states of machine tools. In addition, to the start-up and tip (cutting) energy an intermediate step of the 'Ready state' was proposed. The ready state brings the cutting tool and workpiece to a proximity state or an about to cut state. Current measurements were then done on an MHP CNC lathe, MAC-V2 Takisawa Milling Machine and Mikron HSM 400 Milling centre and some conclusions can be drawn from the study.

1. There is growing evidence from literature that the tool tip energy is typically lower than the energy required by a machine tool operating at no load. For this reason it is important to further understand what constitutes the power requirements and hence energy usage for a machine tool. The study shows that machine tools should not be left in a no-cutting mode for a longer time otherwise its energy footprint is significantly increased.
2. On a CNC MHP lathe machine, the power requirement of the basic machine state (the machine start-up state) was 53% of the total power requirement for a machine running at no load. At 47% the ready state power is smaller but significant and hence should be modelled more explicitly and accurately. The significance of the Ready state was also confirmed for the Takisawa and Mikron HSM CNC machine tools.
3. The case study on the MHP CNC lathe machine show an interesting fact that in a no-cutting mode, the bulk of the power demand arises from machine start-up (45%), spindle power (15%), servo home location (10%), hydraulic pumps (8.9%) and coolant pumps (8.2%). These are the key areas of focus on the redesign of the MHP lathe to target a lower energy footprint resource. Fluid pumping is a major energy consumer as it required 17.1% of the total power. The design of more energy efficient pumps should be a target.
4. Total energy demand can be estimated using the generic model presented. The model was developed to consolidate the following key machine tool energy trends:
   a. In addition, to the Basic and Cutting States, explicitly modelling the energy required to take a machine tool from the Basic State to a state where the axis and tool is ready for action and about to cut. This has been named the Ready State.
   b. Modelling of energy requirements for spindles based on spindle speed used and machine tool spindle – power characteristic zones.
   c. Accounting for the number of tool changes required and associated energy for tool change by incorporating the tool life.
   d. Modelling energy demand for air cutting during toolpath execution to account for repositioning the cutting tool.

e. Modelling energy with an explicit consideration and incorporation of cutting speeds, feed and depth of cut to support process planning.
f. Acknowledging that there are differences in number and design of machine tool accessories/modules.

5. Further work is required to compare the data presented here with other machine tools and to model the energy consumed by machine axis and its dependence on G01, G02 and G03 axis as well as plane of interpolation.

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