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The effect of Auxiliary Units on the Power Consumption of CNC Machine tools at zero load cutting

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Abstract— Electricity consumptions have attracted global interest in recent times. This is attributable to the increasing technological advancement and new machines and materials development hence, an urgent global call for energy efficiency and sustainable manufacture. The electricity consumption in the manufacturing sector especially at the process level stages is an increasing trend. This is partly due to the energy demand of the auxiliary units and machine features incorporated into the machine tools at the design and manufacturing stages and on the other, as a result of increased production activities (increased product demand) during the use phase. This resulted in an increased embodied product energy that affects the cost and life cycle assessment of the product. In view of this economic and environmental objectives, it is paramount to investigate the energy consuming activities during machining (i.e. tip energy and zero load cutting energy) in order to optimize electricity demand at the secondary processing stages. In this work, the electrical energy demand of the auxiliary units and machine features of three different machine tools were investigated and characterized. This is required in order to encourage symbiotic and sustainable manufacture of products for resource optimization and also to determine specific areas for energy savings. It was observed that the electrical energy demand for non-cutting activities dominate the machining processes at more than 70% and the zero load cutting energy, which is machine dependent, is also about 14%. A step change in axes motor designs for CNC machine tools could facilitate energy reduction in this direction.

Index Terms— CNC machines, cutting, energy efficiency, process level, sustainable machining, tip energy, zero load cutting.

1 Introduction

THE World Energy Outlook, WEO-2008 [1], reported that based on the trend of the global electricity consumption, especially the industrial electricity consumption, and that without any new energy policy, world primary energy demand will grow by 1.6% per year on average between 2006 and 2030 from 136,419.9 *TWh* to just over 197,826.3 *TWh*. This would lead to an energy demand increment of 45% between 2006 and 2030. Since carbon dioxide emission is attributable to electrical energy consumption, urgent action is required at all levels of electrical energy usage in order to cushion the impact of electrical energy consumption on the environment. The energy demand for manufacturing is increasing due to the demand for scientific and innovative products. Manufacturing processes have been reported to be an energy intensive process and as a result, they have high environmental impact [2] that leaves behind carbon footprint. Dang et al. [3] reported that manufacturing industries consumed 37% of the world total electrical energy generated in 2006. In 2011, the Energy Information Administration (EIA) [4] reported that 42.6% of the world total electrical energy was consumed by the industries. This therefore shows an increasing trend of electrical energy consumption within the manufacturing sector from 1971 to 2011. For example, in the United Kingdom UK, Digest of UK Energy Statistics' (DUKES) [5] reported that in 2012, the manufacturing industry consumed on average 17.9% (292 TWh) of the total energy consumption in the UK. Of this total, machine tools and accessories (i.e. metal products, machinery and equipment) being one of the most widely used processes consumed on average 38 *TWh*. Machine tools have previously been reported to have an efficiency of less than 30% [6] and were also included in the European Union EU ECO-Design directive [7] to be regulated in terms of its energy consumption characteristics and efficiency. The global call has been to reduce the CO_2 emission during the manufacturing processes. This will entail primarily, the optimization of the electricity consumption at the production and process level stages of manufacturing and encouraging a zero waste manufacturing process through the six sigma approach.

1.1 Electrical energy modelling of the machine tools

The machine tools are one of the most widely used manufacturing equipment globally [8]. Its production and consumption also varies especially within the developed countries. For example China accounted for approximately 33% of the world's machine tool consumption in 2013 followed by Germany at 9.3% and Japan at 5.3% [9]. The machine tools are equipped with varieties of components and accessories. These energy consuming components and accessories are called the

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auxiliary units and machine features. The auxiliary units and machine features are incorporated into the machine tools to reduce manufacturing errors at the process level and during the man-machine interactions. Recently, Balogun and Mativenga [10] classified the machining processes into three electrical energy states according to their operational characteristics during the use phase. These include the 'basic' state (a state at which electrical energy is consumed at zero load cutting for preparatory activities), 'ready' state (a state at which electrical energy is consumed to move the axes x, y and z to the about to cut position) and 'cutting' state (a state at which electrical energy is consumed for the actual cutting operations). Each of these states is controlled by the basic machine function units when the machine is switched 'ON' and throughout the cutting processes.

Few researchers have modelled the electrical energy and power consumption of machine tools with much emphasis at reducing the electrical energy consumption during the machining processes. For example Gutowski et al., [11] and Dahmus and Gutowski [12] reported that energy consumption of machine tools during actual cutting processes accounted for only 14.8% of the total energy consumed by the machine tools throughout the machining process of a unit and the auxiliary units consume 85.2% as shown in Figure 1. The auxiliary units' power consumption could be a reflection of the start-up, shut down, in-cycle and other spindle positioning processes which were not accounted for in the model. More energy is being used up during start-up and to maintain the machine tool in a 'ready state' [13]. Gutowski et al., [11] proposed the power model as stated in Equation (1) and stated that the idle power is a constant. This overstretched hypothesis needs to be investigated and tested.

$$P = P_o + k\dot{v} \quad (1)$$

Where, P represent the total power consumed in W, P_o is the idle power requirement in W, k is the specific cutting energy of the material in J/mm^3 and $\dot{v}$ is the material removal rate in mm^3/s

It can be observed that P_o could be constant for a particular machine tool and its value will definitely affect the overall energy consumptions during the production stages especially in the manual and semi-automated machine tools. More analyses are needed to determine the value and the contributing units of the auxiliary power consumptions that will eventually affect the total power consumption of the machine.

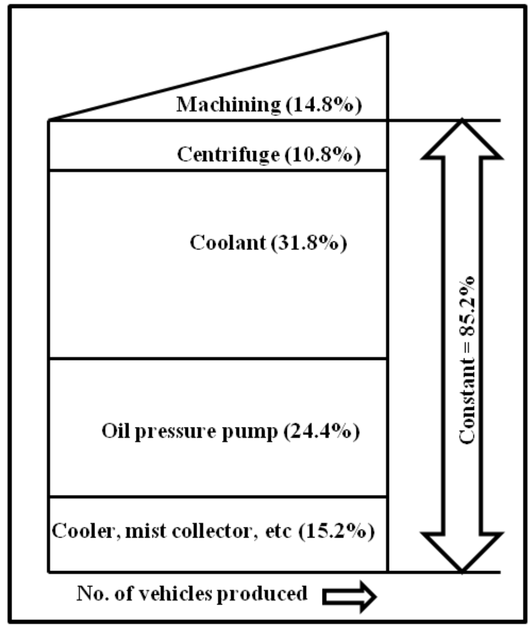

Fig. 1. Electrical energy used as a function of production rate for an automobile production machining line adapted from Gutowski et al., [12]

Also, Vijayaraghavan and Dornfeld [14] adopted the strategy of event streaming the energy demand in machining to predict the electrical energy requirement during the manufacturing process. The authors stated that event streaming strategy; system monitoring and data analysis software could be adopted for automated machines. These could encourage prompt manufacturing decision and effective optimization for electrical energy resource. In their analysis, the machining processes were monitored with the 'event clouding effects' that has the capabilities of live streaming of individual task and events. The output data shows spikes in the electricity consumption during the start-up and preparatory stages of the machine. Three machine tool states were identified as idle, low and high energy consumption stages. At these three stages, machine tools exhibit start up, shut down, idle and in-cycle stages. These stages however, have great impact on energy consumption of machine tools. Diaz, Nancy et al., [15] also reported that among the auxiliary units, the servo and the spindle consumes the most power in the basic and idle stages on a Mori Seiki NV1500DCG milling machine hence the need for assessment of the energy demand using other machine tools. Kara and Li [16] modelled energy consumption for material removal processes of a unit process with a simulated software LABView. They reported that during the mechanical machining on the Mori Seiki NL2000MC/500 machining centre, a spike occurred during machine start-up but what contributes to the spikes during the idle stages was not recorded. An energy model was proposed as shown in Equation 2.

$$SEC = Co + \frac{C1}{MRR} \quad (2)$$

Where SEC represents the specific cutting energy in J/mm^3, C_o and C_1 are the machine tool dependant constants and MRR

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is the material removal rate in mm^3/s.

In another approach, Mativenga and Rajemi [17] analysed the energy consumption of machine tools using the optimum cutting parameters based on minimum energy footprint. The authors reported that the idle energy can be disintegrated into auxiliary units and each of these units contributes to the total electrical energy consumption. Hence, they proposed a model as shown in Equation 3.

$$E = E_1 + E_2 + E_3 + E_4 + E_5 \quad (3)$$

Where, E is the total energy consumption, E_1 is the energy consumed by the machine during setup operation (Idle energy), E_2 the cutting energy, E_3 the tool change energy, E_4 is the embodied energy of the tool and E_5 the embodied energy of the material.

E_1 which can be equated as the idle energy of the machine or zero cutting energy represents the energy consumed during the setup and idling. This approach lumped together the zero cutting energy of the machine tools. This assumption which need further study, could aid the understanding of the energy contributing units of the idle stages. The study also reveals that a spike occurs during machine start-up. These spikes need clarification and adequate modelling.

In an attempt to categorise the energy consuming units of the machine tool, Mori et al., [18] modelled the total power consumption during the manufacturing processes with respect to time. It was reported that the electrical energy is consumed in several processes that includes; positioning and acceleration of the spindle following a tool change, actual cutting processes, returning the spindle to the tool exchange position after cutting, and stopping the spindle at machine stop. The authors also proposed an energy model as shown in Equation 4.

$$P = P_1(T_1 + T_2) + P_2 T_2 + P_3 T_3 \quad (4)$$

where, P is the total power hour or energy in Wh, $P_1(W)$ 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. The report also stated that improvement is on in reducing the idle power P_1, by machine tools designers. It is therefore clear that P_1 could vary depending on machine tools and the auxiliary units.

Rajemi et al., [19] investigated the power distributions for machine tools at different cutting speeds of 300, 400 and 500 *m/min* respectively. The data presented in this study suggest that machine modules are major power and electrical energy consumers during the use phase. The machine module and idle power consumption recorded are within the range of 34% to 38% for idle power and 25% to 36% for machine modules in non-cutting stages. This further shows the high consumption of energy in the idle mode which in this case goes up to 74% of the total energy demand of machining processes. It is clear from this report that non-cutting operations dominate the power consumption during the machining process. The percentage of power consumed by the actual machining process was 31%, 35% and 39% respectively for the cutting speeds investigated.

It is therefore obvious the need to clearly define the auxiliary unit's power consumption of machine tools to determine the contribution of each unit towards the total power consumption in a machining process. This is appropriate to enable adequate data gathering for life cycle analysis and evaluation of carbon footprints of manufactured products. This study will also provide adequate information on areas of further improvement in terms of machine tool designs and the need to reducing energy consumption throughout the product transitions from the concept stages to the end of life of a product. Hence, the needs for this research work.

1.2 Aim and objectives

The aim of this work is to understudy the auxiliary units and accessories of machine tools in order to evaluate the effect of such additional units on the total power demand. In view of this, three machine tools i.e. the Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre were investigated during zero cutting and cutting loads capacities. The auxiliary units of these machines were disintegrated into various sub-units and were studied more closely to ascertain the impact of the auxiliary units in the overall power consumption of the machine. Data were presented and analysed and recommendations proposed.

2 Experimental Methodology

The machining tests were conducted on three different machine tools i.e. the Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre. For cutting tests on the Roeders RFM 760 High speed milling machine, a carbide flat end mill of diameter 8 mm and four flutes was adopted. While the on Mikron HSM 400 machining centre, the cutting tool engaged was a 6 *mm* carbide end milling tool with two flutes. As the machines were switched 'ON', the electrical current was measured with the Fluke 345 power clamp meter and ELITEpro SP™ Power meter with set sample rate of 1 *second* for consistency and repeatability of the measured values. This initial electricity consumption is called the 'basic' electricity demand. After the basic power measurement, the NC codes generated with the Depocam CAD/CAM software were slightly modified as shown in Table 1 to suit the machine tool controller that is associated with the machine. A cutting test was conducted on the three machine tools. The workpiece material AISI1045 Steel alloy of 150 *mm* X 50 *mm* X 10 *mm* dimension was surface milled. The cutting parameters are as stated within the NC codes in Table 1. The zero load cutting tests were repeated three times on all the machine tools under investigations.

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3 Result and Discussions

The power consumption of machining operation according to CO_2PE! [20] and ISO 14955 [21] was divided into three groups including the basic, idle and cutting power. Each of these groups has an energy demand requirement on the machine tools. The basic and idle group are the power for zero cutting operations which is the scope of this study. The zero cutting operation includes the power required to switch 'ON' the machine modules and auxiliary units (for example, computer and fans, hydraulic pump, etc.) without cutting. The basic power demand for switching 'ON' the machine modules are 2.55, 2.06 and 2.90 *kW* for Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre respectively as tabulated in Table 3. Therefore, it can be deduced that the basic power demand is consumed at start up and to maintain the operational capabilities of the machine tool. It has been reported that at start-up, most of the auxiliary units are powered and that the machine is brought to a point 'just about to cut' position (ready state) in preparation for the actual cutting states.

Figures 2, 3 and 4 shows the power profile as measured with the ELITEpro SP™ Power meter for Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre respectively.

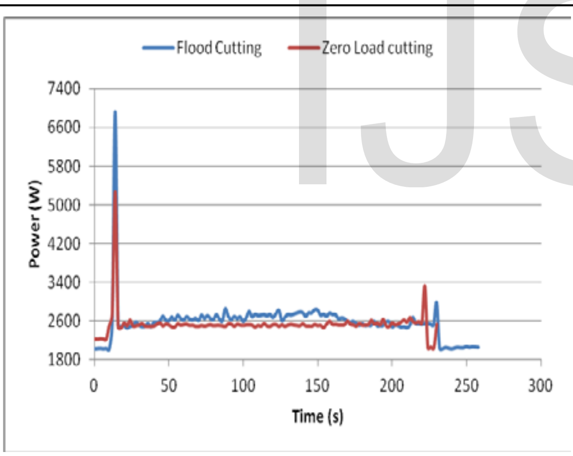

Fig. 2. Power profile for cutting on AISI 1045 steel alloy material on Hitachi Seiki VG-45 machine.

TABLE 1
Simple CNC Program for cutting on selected machine tools

Roeders RFM 760 High Speed Milling	Hitachi Seiki VG-45	Mikron HSM 400 Machining centre
G-code for Machining AISI1045 Steel	G-code for Machining AISI1045 Steel	G-code for Machining AISI1045 Steel
T1 // dia. 8mm	G90 G80 G40 H00 G00 G49 G17 G54	Begin PGM test 1
M3 S32000 TLC=$Tlc	T15	BLK FORM 0.1 X-150 Y-100 Z-15
WAIT=30	G00 X-42.5 Y25	BLK FORM 0.2 X+0 Y+0 Z+1
M8	G43 Z10 H5 M08	TOOL CALL 10 S8957; tool diameter 6 mm
RMAX=3 TOL=0.01 RADMAX=3000 SM=0.0	G01 Z-0.5 F75 S650 M03	L Z+360 FMAX
MOVCOOR=Y=3.8 // INITIAL offset-cutter radius size-0.2	G01 X192.5	L X+0 Y+10 R0 FMAX M3
WAIT=30	G01 Z10 F500	L Z+60 F11000
DO=125 XCALL Zig_Zag.TAP -W -F:12800 -nos MOVCOOR=Y=-0.4	G01 X-42.5 F1000	L Z+5 R0 F3000 M7 M38
ENDDO	G00 Z100 M09	LBL 1
WAIT=30	G90	L Z+15 R0 F200
M9	M05	
M5	G28	
M30	M30	
Zig_Zag.TAP G71 G90G00X-6.0Y0.0 G01Z-0.6 X106.0 Y0.2 X-6.0 M30		

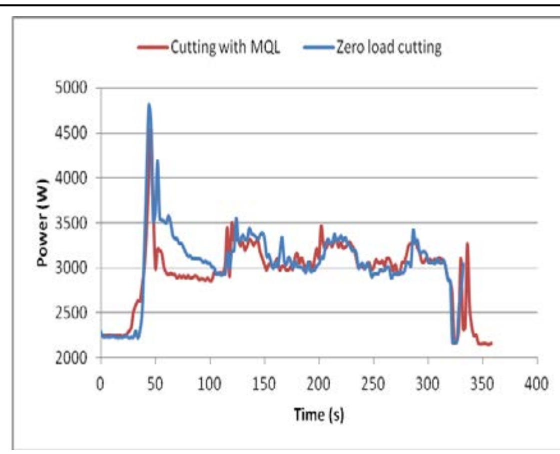

Fig. 3. Power profile for cutting AISI 1045 steel alloy material on the Roeders RFM 760 high speed milling machine.

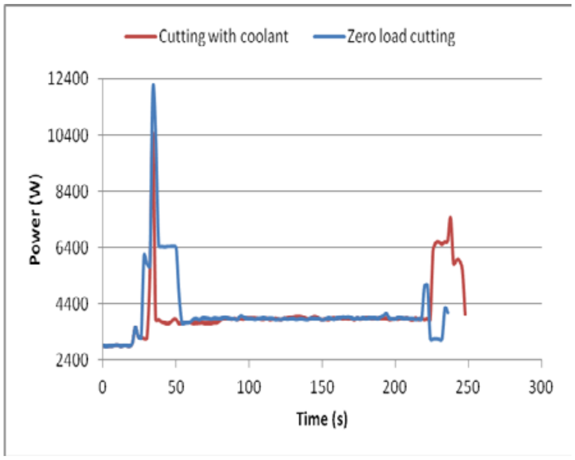

Fig. 4. Power profile for cutting of AISI 1045 steel alloy material on the Mikron HSM 400 machining centre.

It can be seen from Figures 2, 3 and 4, and as reported in literature [11], that the power consumption of the auxiliary units are comparatively higher compared to the actual cutting power consumption. This result is also a confirmation of literature [12] that the share of the electrical energy for machining processes varies from 0 up to 48.1% depending on the cutting variables and machining load. The results also show an interesting fact, that machine auxiliary units and start-up, (the 'basic and idle' states) consumes the bulk of the electrical energy of 80%, 80% and 69% of the total electrical energy demand on the Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre respectively as shown in Table 3. Thus switching 'ON' such a machine tool has major impact on the electrical energy consumption at zero load cutting. Energy reduction in this direction could adherently create an opportunity to optimise the economic objectives of manufactured products and hence reduces the carbon footprint for the entire process. It further proves that the Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre should not be left in the basic and idle position for a considerable amount of time.

TABLE 3

ELECTRICAL ENERGY COMPARISM FOR THREE DIFFERENT MACHINE TOOLS

Machine tools	Roeder	Hitachi	Mikron
Spindle Model	Fisher MFW-1230/42, max. 42,000 rpm	Hitachi spindle 4500/45 rpm (max/min) Main Motor: 15 hp	HVC140-SB-10-15/42-3F-HSK-E40
Controller Model	PC-based customized controller by Roeders	SEICOS MKIII controller , (similar to Fanuc 11M)	Heidenhain TNC 410
Basic Power requirement (kW)	2.55	2.06	2.9
Basic energy demand (Whr)	233.75	148.78	188.50
Area under graph for flood cutting (Whr)	292.65	185.40	274.77
Area under graph at zero load cutting (Whr)	279.07	159.98	265.81
Total Tip Energy (Whr)	58.9	36.62	86.27
Percentage of Tip Energy demand	20.1%	19.8%	31.4%
Zero Cutting Energy (Whr)	13.58	25.42	8.96
Percentage of the Zero load cutting energy.	4.6%	13.7%	3.3%
Percentage of Energy consumption of the Auxiliary units	79.9%	80.2%	68.6%

4 CONCLUSION

The research work investigated the effect of auxiliary units and machine features on the power demand of CNC machine tools at zero load cutting. It is shown that the auxiliary units and machine features dominate the power usage of the machine tool. It is specifically clear that more electricity is consumed for start up and preparatory activities of the machines at switch 'ON'. Thus switching 'ON' such a machine tool has major impact on the electrical energy consumption at zero load cutting. Therefore, electrical energy reduction in this direction would create an opportunity to optimize the economic

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objectives of manufactured products and hence reduces the carbon footprint for the entire process. This work, and in line with literature, also proves that the Hitachi Seiki VG-45, Roeders RFM 760 High Speed Milling and Mikron HSM 400 Machining centre should not be left in the basic and idle position for a considerable amount of time else, electrical energy resource could be wasted. Further conclusion deduced from the study is as follows:

1. Machine tool designers can improve on the design of the auxiliary and machine features through technological and innovative development to reducing power consumption of the preparatory units. However more research is needed in this direction to improve power consumption of the auxiliary units.
2. A step change in the design of machine tools and other manufacturing equipment will help to significantly bridge the gap in relation to energy efficiency of the machine tool at zero load cutting compared to material removal processes.
3. The auxiliary and zero load cutting energy vary with machine tools. The energy demand of the auxiliary units was 68.6%, 79.9% and 80.2% on Mikron HSM 400 machining centre, Roeders RFM 760 high speed milling and Hitachi Seiki VG-45 machining centre respectively. While their corresponding zero load cutting energy were 3.3%, 4.6%, and 13.7% respectively. This further confirms the need for auxiliary units and machine feature design improvement with respect to electrical energy efficiency during the use phase.
4. Also a step change in the design of machine tool axes motor will facilitate energy optimization and waste reduction if properly harnessed during the machine design stages.

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