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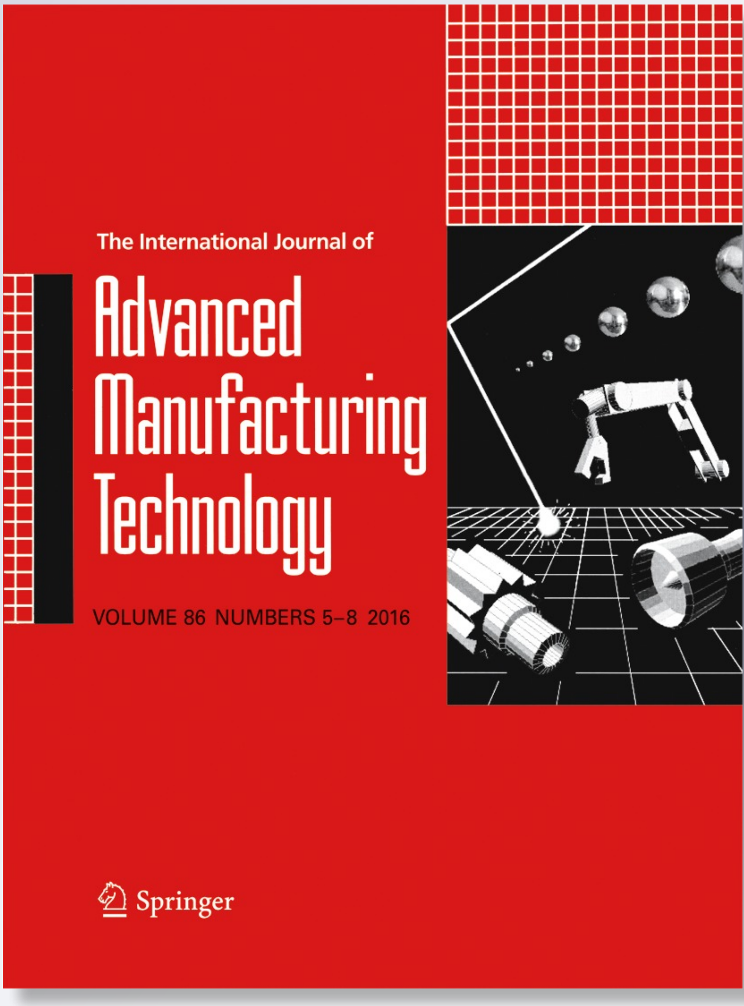

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ORIGINAL ARTICLE

E-smart toolpath machining strategy for process planning

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Abstract The environmental impact of conventional machining processes as influenced by the consumption of electrical energy resources is one of the contributing factors to global warming potentials and pollution. This is as a result of CO_2 emission in the manufacturing process. Mechanical machining is one of the most commonly used processes and a major electrical energy consumer in manufacturing sector. In this paper, a framework is presented to validate the energy consumption model previously proposed using the computer numerical control (CNC) tool path and numerical control (NC) code characteristics. The CNC architecture was decomposed into energy-consuming units, and NC codes were parsed to estimate the electrical energy consumption. A test piece was designed in accordance with the ISO14955-3 standards on energy consumption estimation and followed through the CAD/CAM software to generate NC codes which were used in the machining trials on the Takisawa milling machine. The validation was carried out pre-process and post-process machining. The result shows that the e-smart software compares well with the actual machining operation when milling stainless steel 316L.

Keyword Energy efficiency · Toolpath · NC code · Resource efficiency · Sustainable manufacture

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1 Introduction

The impact of global warming, resource efficiency and sustainable manufacture are some of the major factors that mitigate electricity demand globally. There are urgent calls to reduce and/or optimise electrical energy consumption in all facets of electrical energy generation, transmission, distribution and consumption. The Energy Information Administration (EIA) [1] reported that 42.6 % of the world's total electrical energy was consumed by the industries in 2011. Dang et al. [2] reported that manufacturing industries consumed 37 % of the world's total electrical energy generated in 2006. Manufacturing is an industrial production process of tangible goods which entails the input of raw materials in combination with machines, human resources, energy and output of products from the synthesis of the inputs. Manufacturing processes have been reported to be energy intensive and as a result, they have high environmental impact [3].

In the UK, Digest of UK Energy Statistics' (DUKES) [4] reported that in 2012, the industry consumed on average of 17.9 % (292 TWh) of the total energy consumption in the UK. Machine tools and accessories (i.e. metal products, machinery and equipment) is one of the most widely used processes that consumed on average 38 TWh. This amounted to 13 % of the average UK industrial energy consumption. This generated on average 16 million tonnes of CO_2 emitted to the environment in the UK in 2012. Therefore, a reduction of energy usage in this domain (machining) would reduce the CO_2 emission globally and in the UK.

Numerical control (NC) is a means of controlling the movements of machine tools by directly inserting coded instructions into the system in the form of numbers and letters. These codes are interpreted through the computer numerical control (CNC) controller software interface. The commercially available CNC controller software is designed to drive the various axes (i.e. *x*-axis, *y*-axis, *z*-axis, *i*-axis, *j*-axis etc.) of a machine tool with precision and speed. In general terms, NC codes consist of a sequence of directions which governs the operational behaviours of numerical control machine tools and consist primarily of G codes, M codes, T codes, S codes and F codes [5]. The functional characteristics of NC codes are governed by the machine tool controllers.

In recent years, different controller architecture has been developed. This improvement allows rapid sustainable machining/manufacturing strategy to be incorporated in the product during the design stages. For example, Mazatrol Fusion controllers allow Mazak machines communicate over wireless networks for applications that includes real-time machine tool monitoring and diagnostics [6]. In their analysis, Wang, et al. [6] proposed monitoring approach for remote real-time CNC machining. It is implemented as a Web-based system on top of the Wise-ShopFloor framework with three-tier architecture. Other commercially available NC controllers include: Fanuc, Fagor, Acu-rite, Anilam etc. Some of these controllers may include fault diagnosis routines and additional algorithms to avoid collisions when two or more axes are moving simultaneously. There is no major consideration of the electrical energy usage in the current incarnation of these controller systems. Theoretically, the developments of more intelligent controllers (that can predict the electricity usage at various interpretations of the control instructions, i.e. G codes), could enhance the possibilities of selecting the most efficient machining strategy (given the speed and precision requirements). This could lead to electrical energy saving within the process [7].

For a NC machine tool, the energy-consuming components generally consist of spindle, axis feed (*x*-axis, *y*-axis and *z*-axis), servos system, tool change system and other auxiliary equipment such as coolant pump, fans, light, computers, air pump, lubricating pumps etc. Researchers have previously classified these energy-consuming components into 'basic', 'ready' and 'cutting' energy states [8]. It is important to group each energy-consuming state into their various NC code groups. The 'basic state' is the energy demand of the machine tool resource and auxiliary units at zero load, for example start up, lights, computers etc. as shown in Fig. 1. The basic state energy-consuming units are controlled by programme initialisation NC code, i.e. G97, G90, G21 etc. The 'ready-state' energy demand represents the energy consumed for all transitional movement of the machine axes up to the point the tool is just about to cut. These are controlled by, for example T00, G00, M30 etc. The 'tip' or 'cutting state' energy are controlled by G01, G02, G03 etc. The cutting state energy is the specific energy demand for the actual material-removing operations.

1.1 Electrical energy demand and efficiency analysis in CNC machining

Machine tools are the main equipment used during a machining process for material removal operations [5, 9]. He et al. [10] reported that the energy efficiency of machine tools is generally less than 30 % and hence reported to be energy intensive [11]. The intensity of electricity demand is due to the new improvements and additional auxiliary features within the machine tool that are incorporated to improve its performance. For example, in the analysis of a Toyota automobile production line, Gutowski et al. [12] and Dahmus and Gutowski [11] reported that 85.2 % of the total electrical energy consumed was used up by the auxiliary units of the machine tools. The actual cutting process consumed between 14.8 and 22 %. By this analysis, it can be deduced that the maximum tip energy (energy demand for material removal operation) is averagely 25 % of the total electricity consumption. It also show that machine tools, machine features and process optimization strategies differ in their electrical energy consumption, automation levels, complexity and intended use [13].

In the past, CNC machines were designed based on speed and accuracy as the main objectives. However, a high speed and accurate machine is not necessarily an energy efficient and sustainable one. In theory, the introduction of energy efficiency objective as a criterion in the design and development process of CNC machine tools, could improve their energy efficiency. However, this would only improve the 'basic' (electricity demand when the machine is switched 'ON') and possibly the ready (electricity demand when the machine is 'just about to cut') energy states [8]. The tip or cutting states is dependent on the optimisation of the process parameter [14]. Several EU research projects such as DEMAT [15] and NEXT [16] together with International initiatives like CO2PE! [17] all aimed at achieving this goal of energy and resource efficiency and sustainable manufacturing for e-smart operations. The specific cutting energy which is about 25 % of the total energy demand of current machine tools are controlled by numerical data input known as G codes. Therefore, improvements through these initiatives, i.e. e-smart machining with G codes can be beneficial for electrical energy efficiency.

Few researchers also proposed different methodology to estimate the electrical energy demand of machining. For example, Gutowski et al. [11] proposed a fundamental approach to the understanding of energy intensity in machining processes by establishing an electrical energy model. Also, Behrendt et al. [18], after a survey of 232 machine tools, proposed three assessment methods for estimating the electrical energy demand of machining operations, i.e. idle mode, operational sequences and machining operations. In an alternative approach, Mori et al. [19] modelled the total power consumption during the manufacturing processes with respect to time. They

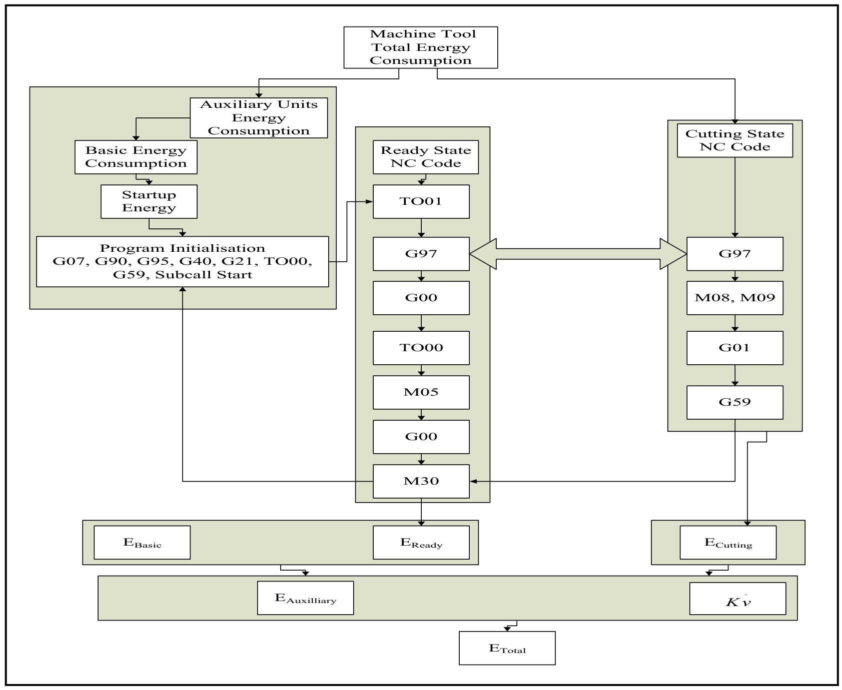


Fig. 1 Machine tool numerical code energy state model

reported the power consumption variation while changing cutting conditions for drilling, end milling and face milling operations on machining centres.

In the analysis of Avram and Xirouchakis [20], the relationship between energy consumption of machine tool state, the transient state and fixed energy consumption of the peripheral units were established through the use of an automatic programming tool (APT) file which can be generated through any commercially available CAD/CAM software. They developed and proposed a software called Global Reasoning for Eco-evaluation of Machining (GREEM). The software was based on Visual Basic for Application (VBA). With this software, a methodology was developed and adopted to estimate the variable energy requirements of machine tool system through machining toolpath. Although this work is an additional contribution to understanding energy demand of machining processes through APT file generated from CAD/CAM software, however, NC codes (G codes) were not integrated into the software-based analysis of the electrical energy demand.

He et al. [10] investigated the electrical energy consumption for NC machining and presented a model based on tool path criteria. The authors reported that since machine tool and features can be controlled through the NC codes, it is therefore possible to estimate their energy consumption using the related codes that governs the relative movement of machine features in order to perform specified operations. They approached the energy estimation based on the linear interpolation of NC. In their paper, the general understanding of energy classifications, i.e. fixed part and a variable part [21] was adopted. They presented an energy estimation model. Although this work is also an additional contribution to understanding electrical energy demand of NC machining processes, it does not categorically developed software that took into cognisance the G codes exclusively. In addition, Aramcharoen and Mativenga [22] proposed a method for predicting the energy consumption of mechanical machining processes based on NC codes with regards to toolpaths and energy states.

Hu et al. [23] reported that the energy required for actual machining is a function of the machine tool spindle states, i.e. start up, idle and cutting states. Lv et al. [24] proposed a methodology to model the energy demand of CNC machine tools based on Therbligs (i.e. a set of fundamental motions required for machine tool to perform an operation). In their study, they established energy supply models of CNC machine tools by developing the power models of each machine tool of Therblig and obtained the total energy demand for the machining process through summation of each power of Therblig (i.e. standby operation, lighting, axis feeding cutting etc.). Seow and Rahimifard [25] categorised energy consumption in the manufacturing sector into direct and indirect energies. Mativenga and Rajemi [26, 27] analysed the energy footprint in machining a given product. They considered the direct energy demand and the energy embodied in tooling. Other researchers also classified energy demand estimation into the specific energy models. For example, Sarwar et al. [28], in their analysis with three different workpiece materials showed the relationships that existed between specific cutting energy and process variables. Li and Kara [29] proposed an energy model that showed a strong correlation between the specific cutting energy and material removal rate. Diaz et al. [30] also modelled energy consumption using the specific cutting energy approach. Their analysis involves the variations of process parameters that determine the material removal rate (Q). The specific cutting energy is process dependent and thus has a correlation with the machinability of materials. Its values have been assumed constant in the models found in literature [5, 12]. These approaches do not incorporate the NC codes.

Few other researchers also measured energy demand in a real-time event through the use of sensor devices or software applications commonly used for online measurement. For example Teti et al. [31] and Shi and Gindy [32] developed a PXI-based online machining process monitoring system. This system was developed in LabVIEW environment and was used to acquire, present and analyse sensory signals automatically through the use of advanced queue and triggering technique. Vijayaraghavan and Dornfeld [33] investigated the energy requirement of machine tools and their effect on the overall life cycle and power consumption through system monitoring and data analysis software. The authors proposed a software-based approach for automated energy reasoning which can support decision making at all levels. The software utilises 'Complex Event Processing (CEP)' which handle data reasoning and information processing. 'MTConnect' interface was used to link data from the machine tool and/or other manufacturing equipment to the 'Event Cloud' for information processing and strategic decision making. MTConnect is based on 'eXtensible Markup Language (XML)', which provides semi-structured and machine readable data for exchange [34], process planning and process optimization during the manufacturing operations. Hu et al, [23] proposed an online approach to monitor the energy efficiency of machine tools and developed an architecture for the online energy monitoring system (OEEM system).

In a similar work, He et al. [10] presented a task-oriented modelling method for machining using simulated event graph on Matlab software. They reported that, in estimating the energy demand of a machining process, the operations within the process can be categorised into event blocks. These three event blocks (i.e. start machining; end machining and idle/waiting) forms the basis for the machining system tasks model. The authors proposed that a task-based simulation can present alternative machining strategy that could lead to energy saving potentials and sustainable manufacture. In 2015, Guo et al. [35] proposed an operation-based energy demand model. The model was based on NC codes which incorporate the simulation of machining processes (i.e. turning and drilling) for energy demand prediction. The model was validated by performing face turning, external turning and grooving operations.

A number of researchers have considered the process control level to reduce the energy consumption in machining by improvement in tool-chip contact mechanics. Zolgharni et al. [36], for example investigated the improvements in energy efficiency of machine tools by using diamond-like carbon (DLC)-deposited tools, which were shown to be able to reduce the cutting power machine consumption by as much as 36 %. In a related research, Fysikopoulos et al. [37] also proposed a strategy to increase the energy efficiency of an already balanced production line, using machine tool stand-by or shut-down modes, during the idle phase. The critical review of energy efficiency of manufacturing processes are well documented [38]. Vijayaraghavan and Dornfeld [33] introduced an event stream processing-based framework to analyse energy consumption. Their work was based on a framework which identified five different levels of manufacturing analysis scales from the supply chain to machine process control, each with its own temporal decision scale, energy consumption characteristic and affecting parameters. He et al. [10] investigated energy demand of NC codes by disaggregating energy consumers into NC codes that control them. For example, Table 1 presents the detailed NC codes and their corresponding operation which are in common use during machining operations.

From the literature, it can be observed that few electrical energy models were proposed and reported to date. Among the machining energy models proposed, only a few reported the important contribution of G codes for e-smart machining. The proposed electrical energy models however, do not inculcate numerical codes (i.e. G codes) of machining toolpath into the energy-estimation method. In general, knowledge gaps exist in this regard to understudy the contribution of G codes to electrical energy demand during the machining processes and to propose a machining strategy that would enhance e-smart machining for sustainable manufacture of products. These are presented in this work.

Table 1 NC codes and their functions

NC codes	Functions
G00	Rapid movement for location
G01	Linear interpolation
G02	Circular interpolation
G03	Counter clockwise circular interpolation
S	Spindle speed
F	Table feed
M02	Coolant on
M03	Coolant off

2 Aim and objectives

The aim of this work is to develop a deeper understanding and to propose a new framework and e-smart software to evaluate the electrical energy demand in mechanical machining processes of CNC toolpath. The toolpath and G codes generated from the geometrical modelling of the component from any of the commercially available CAD/CAM software could be adopted for the energy estimation. In this method, the correlation between the NC code and energy-consuming units of the machine tools were analysed in order to simplify and disaggregate energy demand into various axes transition of the machine tool. The driver was to support energy centric product and process planning for resource efficiency and sustainable manufacture and to compare energy consumption using the toolpath (X, Y and Z) to the direct electricity consumption.

3 Research methods

3.1 Proposed electrical energy consumption estimation model and software

In developing an energy-estimation model (shown in Eq. 1) for CNC toolpath machining, a framework as in Fig. 2 was developed. The electrical energy model for the development of the e-smart software was adopted from Balogun and Mativenga [8, 14] and shown in Eq. 1.

$$E_{\mathrm{Tot}} = P_{\mathrm{b}}(t_{\mathrm{b}} + t_{\mathrm{r}} + t_{\mathrm{c}}) + P_{\mathrm{r}}t_{\mathrm{r}} + P_{\mathrm{tc}}t_{\mathrm{tc}}\left[\mathrm{INT}\left(\frac{t_{\mathrm{c}}}{T}\right) + 1\right] + P_{\mathrm{air}}t_{\mathrm{air}} + (mN + C + P_{\mathrm{cool}} + k\dot{v})t_{\mathrm{c}} \quad (1)$$

Where, P_{b} and P_{r} are the basic and ready-state power required by the machine tool in *W*. P_{tc}, P_{air} and P_{cool} represent tool change, air cutting and coolant power demand in watts, respectively. t_{b}, t_{r}, t_{tc}, t_{air} and T represent setup time, ready time, tool change time, air cutting time and tool life in seconds, respectively, and $mN+C$ is the spindle-speed characteristic model in watts.

In developing the model of Eq. 1, the authors improved on the proposed electrical energy demand model by Gutowski et al. [12], which specifies that the basic energy requirement of machine tools dominates the direct energy requirement in machining. This shows that machine tools have a 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 and hence adopted for this work.

The machining electrical energy demand framework, shown in Fig. 2, grouped into production planning, process planning, strategic decisions and output stages, incorporate energy analysis into various stages for pre-process evaluation of electrical energy resource in order to meet the economic objective. In the production-planning stages, the CAD model is designed. Through the CAD models, the geometrical representations of the part are translated into ISO G codes through the CAM software as shown in Table 2. In order to generate the G codes, references are made to the databases i.e. machine tool, cutting tool and materials databases and adequate selections are made based on the material characteristics to be machined. The machine tool database stores the parameters

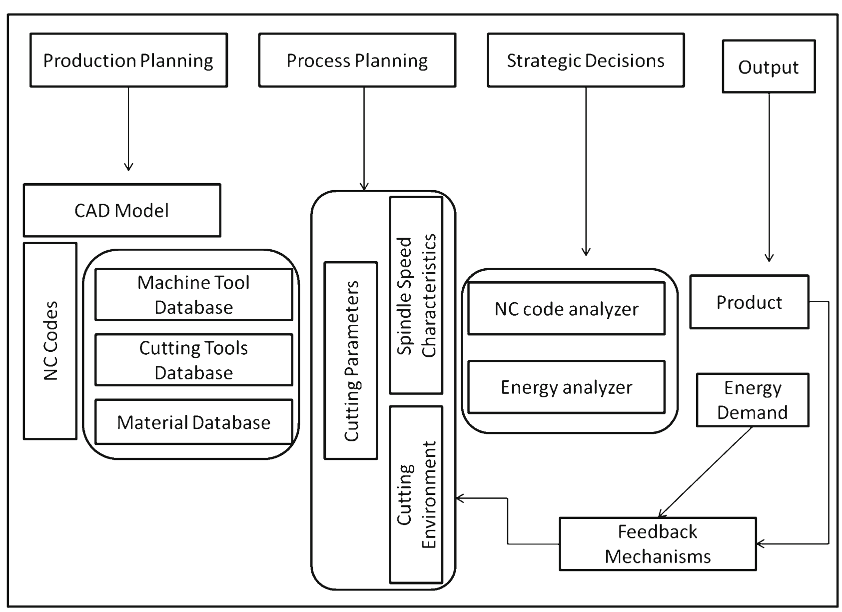
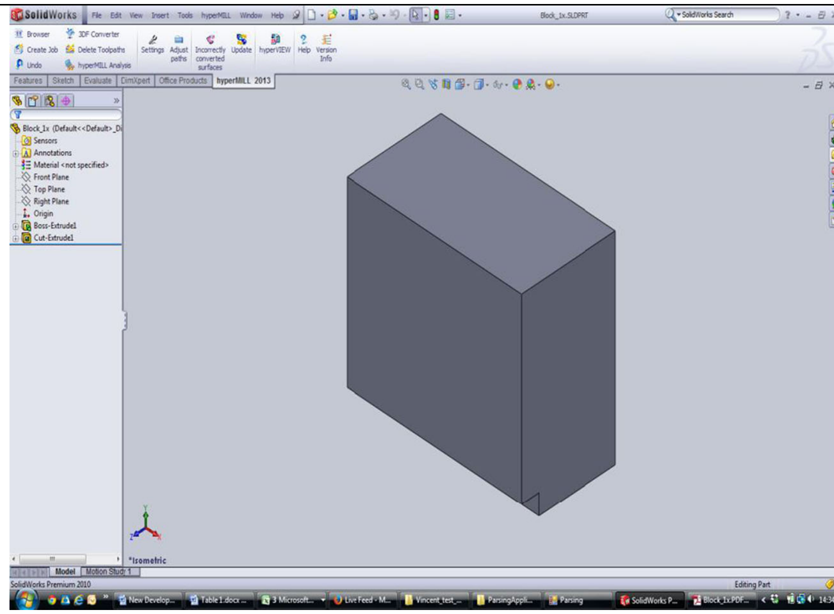


Fig. 2 Proposed comprehensive NC energy model

Table 2 NC code generated with the HYPERMILL CAM software

G codes generated from Sample Block	**CAD Drawing**
G21 G90 G40 G17 G80 H00 G59 (OPERATION 1)(ENDMILL) M01 M09 T1M6 G90E01 G0X56.292Y2.058S2000M03 M8 G43H1Z33. Z29. G1Z24.F50. X54.923Y2.797F200. X54.636Y2.768 X54.35Y2.535 X53.36Y1.297 X52.028Y0.43 X51.277Y0.166 X49.695Y0. X0.095 X-1.479Y0.224 X-2.219Y0.519 X-3.145Y1.113 X-3.723Y1.662 X-4.35Y2.541 X-4.564Y2.755 X-4.852Y2.837 X-5.228Y2.716 X-6.074Y1.528 G0Z33. T0M6 M09 G28 M30 %	

related to the specific machine tool and their basic and ready states [8, 39] energy consumption.

In the process-planning stages, cutting parameters, i.e. depth of cut, width of cut, cutting speed and table feed are selected based on the optimum values proposed by the tool manufacturers. In some cases, consideration is given to the workpiece material. The selected parameters are based on the operators or the process planner experiences. The spindle-speed characteristics are machine tool dependent and could vary with different machine tools. For example the Takisawa milling machine exhibited three different characteristics of power demand at three ranges of spindle speeds [8]. The selection of the cutting environment is also a choice based on workpiece material and cutting tools. However, for sustainable machining, and resource efficiency, dry and MQL environments are promoted in recent times [40]. The power demand of the fluid pump is well documented [8, 20] and can be incorporated into the comprehensive NC code energy estimation of toolpaths. The adopted values are imputed into the NC energy analyser for evaluation and strategic decisions. The energy analyser compute the energy required in fabricating the CAD model through the toolpath and G codes generated and send report to the feedback mechanisms for benchmarking with the geometrical coordinates. The virtual cutting simulator also sends feedback in terms of the geometry of the output with reference to the CAD model. The feedback is analysed at the process planning stage and imputed parameters can be optimised by changing cutting parameters and cutting strategy through alternative toolpath strategy to reduce electrical energy demand.

3.2 Model validation and machining test

In order to validate the model, G codes were generated with the Depocam CAM software integrated with the Solidworks CAD software. The G codes generated are as stated in Table 2. The codes were fed into the developed e-smart software and with the rule vectors; the total electrical energy required for the *x*-axis, *y*-axis and *z*-axis moves were evaluated before the actual cutting tests. The code generated was again adopted and sent to the Takisawa CNC milling machine. The electrical energy demand during the machining tests was recorded with a Fluke 345 power clamp metre, and the area under the power-time curve was evaluated as the total energy demand to manufacture the test piece. The area under the graph was estimated and compared with the values estimated using the software.

4 Results and discussions

4.1 Benchmarking e-smart software and total direct machining energy

The graphical user interface (GUI) of the developed e-smart is as shown in Fig. 3. The GUI is user friendly and an expert system that requires the input of the machine operator (user) [41] in order to compute and display the total electrical energy required to manufacture the component. User's input such as machine tool home position (*x*-axis, *y*-axis and *z*-axis), type of machine tool, cutting parameters and environment, workpiece material and the generated NC code (G code) from the CAM software are required for the internal processing in order to evaluate the total electrical energy required.

The electrical energy evaluated with the e-smart software for machining the NC code in Table 2 is displayed in excel format as shown in Table 3.

In order to validate the e-smart software, the NC code generated (Table 2) from the DepoCAM software is then fed into

Fig. 3 E-smart user interface

Table 3 E-smart output result in excel format

Variable	Total demand	Units
G0	10,000	mm/min
P_basic	2760	W
P_ready	2860	W
Kv	12,000	W
P_cool	288	W
P_air	0	W
p_tool_change	0	W
P_spindle	679.500	W
Cycle time	0.0529	h
Total energy	243.4134	Wh

the Takisawa milling machine to mill out a simple slot shown in Table 2. The electrical energy demand milling the slot was recorded with the Fluke 345 power clamp metre. The power-time curve is as shown in Fig. 4.

The total electrical energy estimated with the e-smart software to mill the slot was 243.4 Wh while the area under the graph (Fig. 4) from the Fluke 345 power clamp metre was 276.30 Wh. The area under the graph is calculated based on the average of the recorded power demand and corresponding total process time. From this analysis, it can be deduced that the direct electrical energy measurement using the Fluke 345 power clamp metre is approximately 12 % higher than that evaluated with the e-smart software. This could be attributable to the various energy losses due to friction, heat, sound etc. (that are beyond the scope of this research) and other model assumptions, which were adopted in the course of developing the electrical energy model [8, 14]. It can be inferred that the e-smart software can be adopted to estimate the electrical energy demand pre-process for process planning and sustainable manufacture.

5 Conclusion

The e-smart energy analysis software solution provides efficient methods for small- and medium-scale manufacturing industries to critically evaluate the electrical energy requirement of machining components pre-process for process planning. The e-smart software can be adopted and incorporated into any of the commercially available CAD and CAM software. It is user friendly with ease of use and better interpretations of specific energy-based evaluations. The calculation is based on tool path strategy and geometric dimensions of the model. The generated G code and M code, feed rate, tooling and other spindle-related operations are used in the electrical energy calculations. The e-smart energy software solution will assists companies towards developing products with minimum electrical energy resource to support the global energy labelling and resource efficiency agenda. This is archived since the electrical energy demand to manufacture (in this case machining) machined component can be estimated from the generated G codes from any of the commercially available CAD/CAM software. The proposed e-smart energy solutions could be adopted by several machining-based industries such as the automotive, aerospace, industrial machinery, electrical and electronics, consumer durables, shipbuilding, healthcare and woodworking industries for process planning. From the cutting tests, the e-smart software compared well with the actual cutting tests analysis done through the event streaming evaluation with the Fluke 435 power clamp metre.

The e-smart technology provides a platform for product and process planner to manage the energy resource requirement to manufacture a part at the design stages. Hence, the CO_2 emission and carbon footprint can be evaluated without going through the rigorous LCA methods. However, it is important in the future research to collate appropriate and adequate data in order to populate the databases (i.e. machine tools, cutting tools and workpiece materials) and at the same

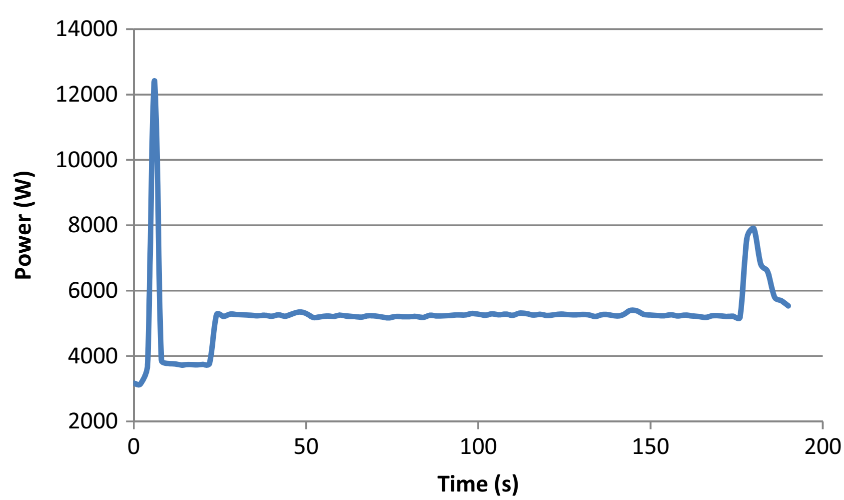


Fig. 4 Power-time profile when machining stainless steel 316L

time determine the specific cutting energy for different workpiece materials and the spindle speed characteristics of commercially available machine tools for the e-smart software. This could contribute towards achieving the sustainability objectives of the manufacturing processes.

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