Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 35 (2019) 361–366

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Materials Processing and Manufacturing

(SMPM 2019)

Process Mechanisms and their Relevance for Sustainable Machining Processes

Vincent A. Balogun[a]*, Isuamfon F. Edem[b], Paul T. Mativenga[c]

[a]*Faculty of Engineering, Department of Mechanical Engineering, Edo University Iyamho, Edo State, Nigeria*
[b]*Faculty of Engineering, Department of Mechanical Engineering, Akwa Ibom State University, MkpatEnin, Akwa Ibom State, Nigeria.*
[c]*School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, United Kingdom*

Abstract

The optimization of electrical energy demand is an important objective function in machining science. This ensue minimum cost and specific energy demand of manufacturing processes. Mechanical machining as one of the major manufacturing processes consumed on average 38 TWh of electrical energy. This generated on average 16 million tones of CO2 emitted to the environment in the UK in 2012. Since carbon dioxide emission is attributable to electrical energy consumption, urgent action is required at all levels of machining processes in order to curtail the impact of electrical energy consumption on the environment through the optimization of process mechanisms. In this work, the specific cutting energy and process mechanisms were correlated in order to determine the efficiency of machining processes and to evaluate the specific energy optimization criterion for sustainable machining. The results show that for minimum energy demand and sustainable process mechanism, it is important that the ratio of the undeformed chip thickness to the cutting edge radius be equal or greater than 1. This ratio encourages shearing dominated mechanism and eliminates ploughing and rubbing at the tool-workpiece interface. This work could aid energy management for resource efficiency and sustainable manufacture of products at the production and process planning stages.

Peer-review under responsibility of the organizing committee of SMPM 2019.

Keywords: machining, process mechanism, cutting energy

* Corresponding author. Tel.: +2348036434484.
E-mail address: vincent.balogun@edouniversity.edu.ng

2351-9789
Peer-review under responsibility of the organizing committee of SMPM 2019.
10.1016/j.promfg.2019.05.053

1. Introduction

The United Nations World Commission on Environment and Development described sustainable development as a procedure of meeting the basic needs of all and giving all the opportunity to satisfy their aspirations for a better and prosperous life [1]. Sustainable developments can be grouped into three pillars [2] as economy, social responsibility and the environment. This implies that economic and social needs should all be met with an environmental sustainability framework hence, manufacturing industries should have comprehensive plans in place to reducing the negative impact of their production or services on the environment.

Manufacturing is energy intensive, and they have high environmental impact tendencies [3]. It is reported that manufacturing industries consumed 37% of world total electrical energy generated in 2006 [4], and 42.6% of the world total electrical energy was consumed by the industries in 2011 [5]. Also, the industries consumed on average 17.9% (292 TWh) of the total energy consumption in the UK in 2012 [6]. Machine tools and their 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 [6]. This generated on average 16 million tones of CO2 emitted to the environment in the UK in 2012. Therefore, a reduction of electrical energy usage in this domain (machining) would reduce the CO2 emission globally and in the UK.

1.1. Specific energy demand and process mechanisms in machining processes

Energy efficiency of machine tools is generally less than 30% [7] and to improve the machine tools efficiencies, a frame work was proposed by the European Union (EU) in the Eco-Design directive [8]. The electrical energy input during machining processes can be evaluated by considering the material shearing, ploughing, friction, new surface generation, chip momentum change [9, 10] and machine tool energy losses and process upkeep.

For adequate modeling of the total electrical energy demand [11, 12], the specific energy in machining which relates to the tip energy [13-16] (energy required for actual material removal) must be properly accounted for. The surface energy and the momentum energy are not considered in this work since they do not contribute to chip removal processes [17]. Hence, the total specific cutting energy K_e in Jmm^{-3} can be evaluated as shown in Equation 1.

$$K_e = k_f + k_p + k_s \tag{1}$$

where K_e represents the total specific cutting energy, k_f is the specific friction energy in Jmm^{-3}; k_p is the specific ploughing energy in Jmm^{-3} and k_s is the specific shearing energy in Jmm^{-3}.

1.2. Process mechanisms in mechanical machining operations

Machinability index of any materials can be determined through its chip formation characteristics. Chip formation does not only depend on material characteristic and cutting tool geometry, but also on the ratio of feed per tooth to cutting edge radius. This ratio is between 5% and 35% of the tool edge radius [18]. If this ratio falls below the minimum chip thickness, no chip is formed and the process mechanism will be dominated by rubbing and ploughing. At this mechanisms, high frictional force ensued as a result of high temperature [19, 20].

Process mechanisms are dominated by rubbing, ploughing and shearing depending on the ratio of the feed per tooth to cutting edge radius [19, 21, 22] as shown in Figure 1.

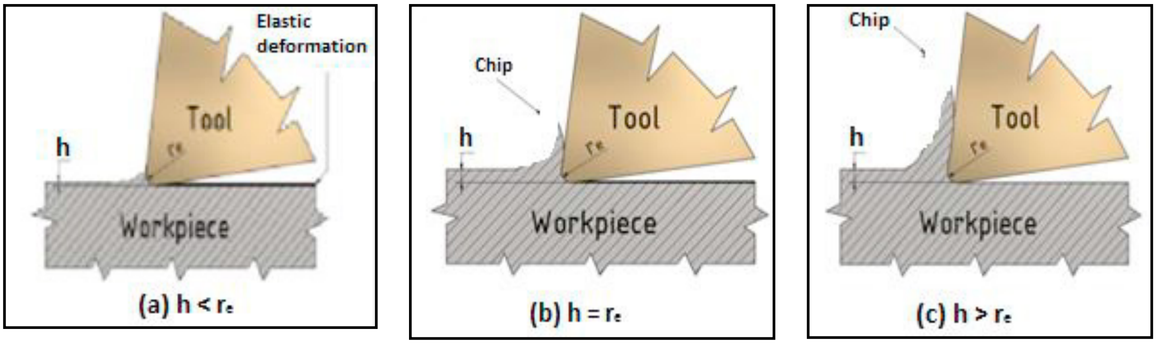

Fig. 1. Effect of un-deformed chip thickness ratio to the cutting edge radius in orthogonal cutting adapted from [9, 10] [22].

The first scenario occurs when the ratio h/re is less than the minimum chip thickness. Rubbing and ploughing mechanisms are established and pronounced. In the second scenario (Figure 1b) h/re is approximately equal to 1, ploughing and shearing dominates the process mechanism. Figure 1c shows the ratio h/re greater than 1. The process mechanism tends to move from a ploughing dominated area to a shearing dominated mechanism. The elastic deformation of the workpiece decreases rapidly and an improved chip is formed. Hence, a value adding machining efficiency is established and giving rise to a lower specific cutting energy demand which is an indication of the efficiency of the machining process. In the case where rubbing and ploughing are said to be dominant, the process is within the 'Waste' dominated zone since no chips are removed from the workpiece. Therefore, for a process to be energy centric, efficient and sustainable, it should be within the value adding zone.

1.3. Research aim and Objective

The aim of this work is to correlate the specific cutting energy and process mechanisms in order to determine the efficiency of machining processes and to evaluate the specific energy optimization criterion for sustainable machining. This was to enable the identification of process parameters and evaluate process efficiency at which the mechanisms of rubbing, ploughing and shearing effect are dominant.

2. Research and experimental strategy

In order to correlate the specific cutting energy and process mechanisms to determine machining efficiency through the process mechanisms, cutting test was conducted on AISI 1045 steel alloy on the Mikron HSM 400 machining centre under a dry cutting environment. The x-, y-, and z-axes accelerate at 10 *m/s* with rated power requirements of 11 kW for the x-axis, and 14.8 *kW* for the y- and z-axes respectively. The spindle motor has a rated power of 13 kW [23].The cutting tool insert of diameter 8 *mm* (general purpose TiAlN coated carbide single insert SOMT-060204-HQ) was used for the side milling test. The cutting test mimics the orthogonal milling methods. This is to ensure that the effect of the nose radius is avoided during cutting so as not to create induced mechanisms within the cutting zone [24-26]. The electrical current consumption was measured with a FLUKE 345 power clamp meter.

The machine table feeds are varied between 0.01 and 0.55 *mm/rev*. This is to ensure that variable specific cutting energy is deduced. The cutting velocity and the depth of cut were kept constant at 156 *m/min* and 3.5 *mm* respectively in order that they do not over shadow the impact of the chip load on the specific energy at the tool tip. The radial width of cut is also varied between 0.25 and 1.00 *mm* for each of the machining test. This is so because it is important to have variable values of radial width of cut to evaluate the swept angle and the material removal rate. Material removal rate is a major determinant of the values of the specific energy demand [25, 27]. The cutting test incorporates the optimum value of the radial width of cut model deduced from Equations 2 and 3 proposed by Balogun and Mativenga [25].

$$a_e = 0.23r \quad (2)$$

$$h_{max} = 0.64 f_z = \textit{Optimised maximum undeformed chip thickness} \quad (3)$$

Where, h_{max} is the maximum undeformed chip thickness in mm, f_z is the chip load in mm/tooth and a_e is the step over or the radial depth of cut in *mm*.

Therefore, the radial width of cut was set at 0.92 *mm* since the insert diameter is 8 *mm* and the undeformed chip thickness estimated with values to overlap the ranges of feed per tooth.

3. Result and Discussion

From Table 1, the specific energy demand at 0.01 *mm/tooth* was 5.382 J/mm^3. This value correlates with the rubbing/ploughing zone of the process mechanisms when compared with the specific energy demand for AISI 1045 steel alloy as reported by Balogun et al. [10].

Table 1. Machining efficiency and effects

AISI 1045 Steel alloy							
Vc (m/min)	156	156	156	156	156	156	156
N (rpm)	6206	6206	6206	6206	6206	6206	6206
f_z (mm/tooth)	0.010	0.100	0.190	0.280	0.370	0.460	0.55
havg (mm)	0.003	0.035	0.066	0.097	0.128	0.159	0.190
Feed (mm/min)	62	621	1179	1738	2296	2855	3413
a_p (mm)	3.50	3.50	3.50	3.50	3.50	3.50	3.50
a_e (mm)	0.92	0.92	0.92	0.92	0.92	0.92	0.92
MRR (mm^3/s)	3.33	33.31	63.28	93.26	123.24	153.21	183.16
h/r_e	0.050	0.583	1.100	1.617	2.133	2.650	3.167
Specific energy demand, k (J/mm^3)	5.382	3.725	2.075	1.972	1.652	1.547	1.471

The energy demand at the rubbing and ploughing mechanisms is about 39% more than when h/r_e is approximately equal to 1 (i.e. corresponds to 0.19 *mm/tooth*) as shown in Figure 2. As the cutting progresses, the process mechanisms transit towards a more shearing dominated zone. At this point, the specific energy is at 1.471 J/mm^3 the lowest range, the process mechanism tends to show a degree of energy saving characteristics. Cutting can be encouraged at these mechanisms. However, depending on the parameters being considered (machining efficiency or cost) for machining efficiency that deals with minimum energy demand, shearing dominated mechanisms are considered. However for aesthetics of finished products, other variables have to be considered. For example, It has been reported that surface integrity renders this zone non-efficient and the surface finish is rather poor [28]. Irrespective of the parameters and variables considered, this zone could be exclusively used for rough machining. The result is tabulated in Table 1 and Fig 2.

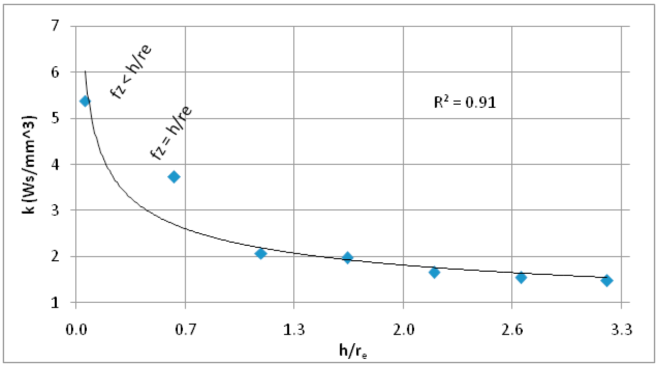

Fig. 2. Relationship between specific energy and h/r_e for AISI 1045 steel alloy.

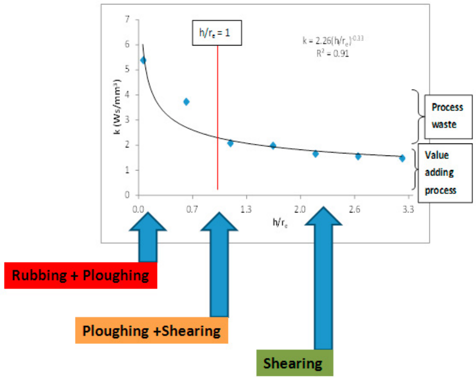

Fig. 3. Process mechanisms and specific cutting energy relationship

From Figures 2 and 3, it can be deduced that specific energy is indirectly proportional to the chip load. As the material removal rate increases, the specific energy decreases. This is due to the fact that the cutting activity is now within the shearing dominated regime having transited from the ploughing and rubbing dominated regime to a more sustainable machining regime. At this regime therefore, electrical energy demand for machining is much lower than at the rubbing regime where the feed is much less than 0.10 *mm/tooth*.

It can be observed from Figure 3 that as the process mechanisms moved from rubbing and ploughing to shearing dominated mechanism, the energy efficiency which is a measure of the specific cutting energy, decreases to below 2 J/mm^3. This is a clear indication that energy efficiency has a direct relationship to the process mechanism. Hence, for optimized energy efficiency, the machining parameters must be selected in such a way that it favors shearing dominated mechanisms, a mechanism whereby the specific energy tends towards its minimum values. This strategy also promotes and favors the circular economy [29].

4. Conclusion

This work has investigated the process mechanisms and correlated it with the machining efficiency when machining AISI 1045 steel alloy material. From the observed and the analyzed data and machining efficiency of machining point of view, the following conclusions can be drawn:

- It is found that during machining of AISI 1045 steel alloy, the specific energy decreases as the material removal rate increases. This is an evidence of the transition of the process mechanisms from the ploughing dominated regime to the shearing dominated regime. This machining strategy reveals that shearing dominated machining should be promoted for sustainable machining.

- It is proposed that machining AISI 1045 steel alloy should be conducted at range of feed f_z between 0.19 *mm/tooth* and 0.55 *mm/tooth*. This is true because electrical energy demand is at its lowest range of values

- The electrical energy demand at the rubbing and ploughing mechanisms is about 39% more than when h/re is approximately equal to 1 (i.e. f_z corresponds to 0.19 *mm/tooth*). Hence, machining AISI 1045 steel alloy should be conducted at a range of values where h/r_e is approximately equal to 1 in order to improve the machining efficiency.

- In order to improve the process efficiency in mechanical machining, shearing dominated machining should be encouraged. Machining efficiency can be improved by over 50% by controlling the process mechanisms to reduce the electrical energy wasted due to rubbing and ploughing mechanisms.

References

[1] Brundtland, G.H., Report of the World Commission on environment and development:" our common future.". 1987: United Nations.
[2] Pusavec, F., P. Krajnik, and J. Kopac, Transitioning to sustainable production - Part I: application on machining technologies. Journal of Cleaner Production, 2010. 18(2): p. 174-184.
[3] Park, C.W., et al., Energy consumption reduction technology in manufacturing - A selective review of policies, standards, and research. International Journal of Precision Engineering and Manufacturing, 2009. 10(5): p. 151-173.
[4] Dang H., T.J., Wilkinson D., New Zealand: Energy in Brief. 2007, New Zealand Ministry of Economic Development, Wellington, New Zealand
[5] IEA, Key World Energy Statistics 2013. 2013.
[6] MacLeay, I., Digest of United Kingdom energy statistics 2010. 2010: The Stationery Office/Tso.
[7] He, Y., et al., A modeling method of task-oriented energy consumption for machining manufacturing system. Journal of Cleaner Production, 2012. 23(1): p. 167-174.
[8] EPTA. Study for preparing the first Working Plan of the EcoDesign Directive. Report for tender No.: ENTR/06/026 2007 [cited 2012 30 March]; Available from: http://ec.europa.eu/enterprise/policies/sustainable-business/files/workingplan_finalreport_en.pdf.
[9] Kalpakjian, S. and S.R. and Schmid, Manufacturing Processes for Engineering Materials, 4, New Jersey, the United States of America: Prentice Hall,. 2003.
[10] Balogun, V.A., et al., Specific energy based evaluation of machining efficiency. Journal of Cleaner Production, 2016. 116: p. 187-197.
[11] Edem, I.F. and P.T. Mativenga, Modelling of energy demand from computer numerical control (CNC) toolpaths. Journal of Cleaner Production, 2017. 157: p. 310 - 321.
[12] Edem, I.F. and P.T. Mativenga, Impact of feed axis on electrical energy demand in mechanical machining processes. Journal of Cleaner Production 137 (2016) 230-240, 2016.
[13] Li, W. and S. Kara, An empirical model for predicting energy consumption of manufacturing processes: a case of turning process. Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, 2011. 225(B9): p. 1636-1646.
[14] Anderberg, S.E., S. Kara, and T. Beno, Impact of energy efficiency on computer numerically controlled machining. Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, 2010. 224(B4): p. 531-541.
[15] Diaz, N., E. Redelsheimer, and D. Dornfeld, Energy consumption characterization and reduction strategies for milling machine tool use. Glocalized Solutions for Sustainability in Manufacturing, 2011: p. 263-267.
[16] Balogun, V.A. and P.T. Mativenga, Modelling of direct energy requirements in mechanical machining processes. Journal of Cleaner Production, 2013. 41(0): p. 179-186.
[17] Arsecularatne, J., On tool-chip interface stress distributions, ploughing force and size effect in machining. International Journal of Machine Tools and Manufacture, 1997. 37(7): p. 885-899.
[18] Chae, J., S. Park, and T. Freiheit, Investigation of micro-cutting operations. International Journal of Machine Tools and Manufacture, 2006. 46(3): p. 313-332.
[19] Ducobu, F., E. Filippi, and E. Rivière-Lorphèvre. Chip Formation and Minimum Chip Thickness in Micro-milling. in Proceedings of the CIRP conference on modelling of machining operations. 2009.
[20] Kim, C.-J., J.R. Mayor, and J. Ni, A static model of chip formation in microscale milling. Transactions of the ASME-B-Journal of Manufacturing Science and Engineering, 2004. 126(4): p. 710-718.
[21]Chae, J., S.S. Park, and T. Freiheit, Investigation of micro-cutting operations. International Journal of Machine Tools and Manufacture, 2006. 46(3-4): p. 313-332.
[22] Aramcharoen, A. and P.T. Mativenga, Size effect and tool geometry in micromilling of tool steel. Precision Engineering, 2009. 33(4): p. 402-407.
[23] Edem, I.F., V.A. Balogun, and P.T. Mativenga, An investigation on the impact of toolpath strategies and machine tool axes configurations on electrical energy demand in mechanical machining. International Journal of Advanced Manufacturing Technology, 2017. 92(5-8): p. 2503 - 2509.
[24] Balogun, V.A., H. Gu, and P.T. Mativenga, Improving the integrity of specific cutting energy coefficients for energy demand modelling. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2014: p. 0954405414546145.
[25] Balogun, V.A. and P.T. Mativenga, Impact of un-deformed chip thickness on specific energy in mechanical machining processes. Journal of Cleaner Production, 2014. 69(0): p. 260-268.
[26] Mulyadi, I.H., V.A. Balogun, and P.T. Mativenga, Environmental performance evaluation of different cutting environments when milling H13 tool steel. Journal of Cleaner Production, 2015.
[27] Edem, I.F. and V.A. Balogun, Sustainability analyses of cutting edge radius on specific cutting energy and surface finish in side milling processes. International Journal of Advanced Manufacturing Technology, 2017.
[28] Balogun, V.A. and P.T.J.P.M. Mativenga, Specific Energy Based Characterization of Surface Integrity in Mechanical Machining. 2017. 7: p. 290-296.
[29] Liu, C., et al., Emergy based sustainability evaluation of remanufacturing machining systems. 2018. 150: p. 670-680.