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machinability, energy footprint

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MACHINABILITY ANALYSIS FROM ENERGY FOOTPRINT CONSIDERATIONS

Recent global developments have heightened the need to choose the best sustainable manufacturing methods in order to mitigate the effects of industrial processes on the environment. Energy consumption is seen as one of the key performance indices for assessment of the environmental credentials of an enterprise. It is through energy consumption that the carbon emission penalty (amount of carbon emitted in generating the energy) can be estimated. Machining remains one of the key discrete-parts manufacturing processes and its mechanics has received considerable attention in research and development. However, energy analysis for machining processes is a relatively new area. In this paper the environmental impacts of machine utilisation are assessed through energy consumption. The paper considers the energy requirements in machining of a number of alloys according to recommended cutting conditions. The energy is accessed through electrical power requirements of the machining process. The results illustrate the impact that high speed machining could have on energy consumption and hence a more sustainable machining industry.

1. INTRODUCTION

Scientific evidence points to increasing risks of serious, irreversible impact from climate change associated with business as usual paths for emissions (Stern, 2006). There is a strong view that the level of greenhouses gases in the atmosphere such as carbon dioxide, methane, nitrous oxide and a number of gases that arises from industrial processes is rising, as a result of human activity. In the year 2000, sources of CO_2 emissions were evaluated as shown in Fig. 1.

The data presented in Fig. 1, revealed that energy derived emissions contributed about 65% of world CO_2 emissions. More specifically, 24% and 14% of world CO_2 emissions by then were attributable to power generation and industrial activity respectively. It is thus clear that technologies are required to develop cleaner energy sources as well as sustainable low energy and carbon footprint industries.

Gutowski (Gutowski 2007) disaggregated carbon emissions in terms of four components as shown in equation 1

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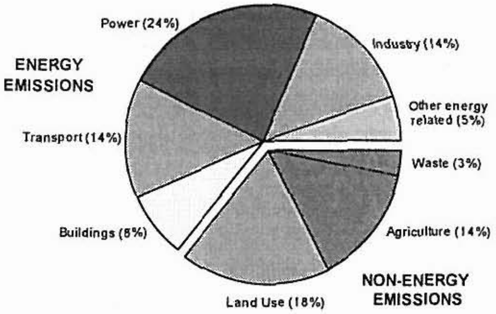
$$Carbon = Pop \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{Carbon}{Energy} \qquad (1)$$



Total emissions in 2000: 42 GtCO2e

Energy emissions are mostly CO2 (some non-CO2 in industry and other energy related). Non-energy emissions are CO2 (land use) and non-CO2 (agriculture and waste)

Fig. 1. Sources of world CO2 emissions by the year 2000 (Sreejith and Ngoi 2000; Stern, 2006)

According to equation 1 the carbon footprint can be seen in terms of three factors the population factor, energy factor and emissions penalty. It is generally agreed that reducing the world population to cut carbon emissions is a very unlikely strategy. However in terms of production engineering promoting a higher GDP while reducing energy consumption/footprint and the carbon intensity of energy are more viable options. Despite the world attention on the urgent and growing problems of climate change, very little research has been undertaken on the technological solutions for reducing energy and ultimately carbon footprints. In industry the amount of energy consumed is an indirect source of carbon footprints, since the CO_2 emissions can be traced to energy generation. The CO_2 emissions per energy use depend on the balance between renewable and non renewable energy sources supplying the electrical grid. Thus, sustainable manufacturing can be partly addressed by a goal to reduce the energy footprint of the manufacturing processes. Among industrial processes, mechanical machining is one of the most widely used technology for the fabrication of discrete components. The technology enables closer dimensional accuracies, a wider product size range and can be economic for both small and large sizes.

Moreover, recent trends in high speed machining have largely promoted dry cutting which helps mitigate the effects of cutting fluids on the environment. Elimination of the use of cutting fluids can help create a cleaner environment and also reduce process cost (Sreejith and Ngoi 2000). In addition when dry machining the power that would otherwise be needed to pump the coolant is eliminated thus reducing the energy footprint of the machining process. Energy utilisation of machines as viewed from an environmental perspective as a focus area for sustainable manufacturing. From literature it was suggested that energy required for the material removal processes can be quite small compared with the total energy for the machine tool operation (Gutowski et al., 2006). It was further suggested that the energy footprint for primary processes involved in material fabrication is usually higher than that for secondary shaping processes (Gutowski 2007). This emphasis the need for life cycle analysis in the evaluating energy footprint of products. Notwithstanding this factor, for manufacturing companies the raw material inputs are usually defined by the customer and sustainable innovations thus relate to improvements in the specific and available production processes.

The energy requirement for the machining process is dependant on the specific energy in cutting operations. Representative specific energies for machining a range of materials are reported in literature (Kalpakjian and Schimd 2006). The values to adapt depend on the combination of tooling and workpiece material/grades used. Following on earlier work by Gutowski (Gutowski et al. 2006), the electrical power requirement, P, for machining can be calculated from equation 2.

$$P = P_0 + k\dot{v} \tag{2}$$

Where, P_0 is the idle power (or power consumption for a running that is not cutting) in *kW, k* is the specific energy requirements in cutting operations, in Ws/mm^3 *and* $\dot{v}$ is the material removal rate (MRR), in mm^3/s. From equation 2 the total power for machining can be identified as the idle power (P_0) and the machining power$(k\dot{v})$. The idle power is the power needed or required for equipment features that support the machine. For example power to start up and run the computer and fans, the motor and the coolant pump. The machining power, *P*, for a lathe machine using a three phase motor is calculated using equation 3:

$$P = V \cdot I \cdot \sqrt{3} \tag{3}$$

Where *V*, is the voltage and *I* is the Current. In turning the MRR is calculated from the cut cross sectional area and the feed velocity. The energy required for machining process, ***E***, can be deduced by converting the power equation 2 into an energy equation 4.

$$E = (P_0 + k\dot{v})t \tag{4}$$

Where, P_0 is the idle power in *kW, k* is the specific energy requirements in cutting operations, in $Ws/mm^3, \dot{v}$ is the material removal rate (MRR), in mm^3/s and t is the time taken for machining, in *seconds*.

2. RESEARCH METHOD

The research was inspired by previous research done by Gutowski et al who studied energy utilisation for a milling machines (Gutowski et al., 2006). However unlike their study, the work reported in this paper is based on CNC lathe operations and focuses on energy consumption for machining different types of workpiece material. An 1988, MHP lathe machining centre was used to study the power consumption for a machine in standby mode (idle power) and also while cutting selected industrial alloys. Five types of workpiece materials were used in this research, namely an EN8 steel, aluminium alloy, cast iron, titanium 6-4 alloy and brass. To standardised the cutting tests and enable comparison between materials a general purpose TiN coated CNMG 120408 carbide insert was used. This was mounted on Sandvik tool holder type PCLNL2020K12. In evaluating the specific cutting power coefficient, unified depths of cut of 1.2 mm and feedrates of 0.15 mm/rev were used within the range of cutting speeds recommended by Sandvik Corromat for the workpiece materials (Sandvik, 2002). The final comparison of the power and hence energy requirements was done at the recommended/optimum cutting condition for each workpiece material.

The electrical power consumption was measured using a DT-266 digital clamp meter (Refer Fig. 1). The meter was clamped on one of the three live wires supply to the MHP lathe machine. The clamp meter rely on the Hall Effect to measure current flow (Kardonowy and David, 2002). The clamp meter creates a magnetic field around the live wire causing a resulting force which can be measured as current by the clamp meter. The measurement is taken without physically touching the life electrical supply wire and hence reduces the risk of an electric shock.

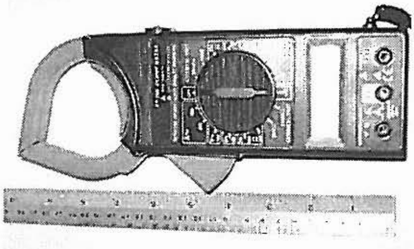


Fig. 1. DT-266 Digital Clamp Meter

Firstly the total current flow through the live wire was measured when the machine is idle i.e. that when the machine and control computer has been turned on and no cutting is taking place. The current drawn was measured for actions such as machine jog, positioning the tool and running the coolant. Current consumption was also studying for the machine running at various spindle speeds but in non cutting modes. The current was then recorded for the cutting tests. The experimental design enabled a reverse calculation of the current drawn for each of the machine operations/functions. All current measurements were converted into power using the electrical power equation 3 and into energy using equation 4.

3. RESULTS AND DISCUSSIONS

From the cutting tests the power required for machining was plotted against the material removal rates for the different cutting speeds used. Fig. 2 shows such results for

EN8 steel. From such analysis, the specific energy for each material was evaluated and as shown in Tab. 1. These values reflect the relative machinability of the workpiece materials.

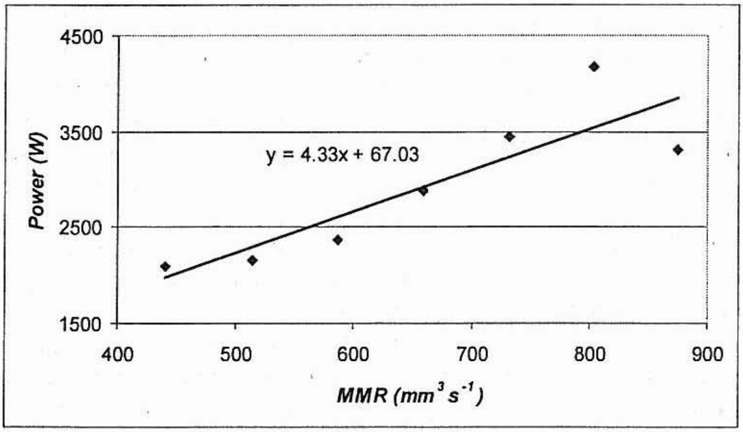


Fig. 2. Machining power vs MRR for EN8 steel

Table 1. Specific power requirements evaluated from cutting tests

Workpiece Material	Specific cutting energy k $\left(Ws/mm^3\right)$
Steel	4.3
Aluminium	1.0
Cast Iron	1.2
Titanium alloy	3.2
Brass	2.2

The values in Tab. 1 are in the range of the specific energy requirements for cutting reported in literature (Kalpakjian and Schimd, 2006). This adds credibility to the methodology adapted here for evaluating the specific energy.

The second set of analysis examined power and energy requirements for machining each of the materials at cutting conditions adapted from recommendations by the tool supplier (Sandvik, 2002). In practice a number of machine shops follow recommendations from their tool supplier. Hence the analysis throws light into the relative energy requirements in industrial machining operations. Variations from the results reported here may emanate from use of different cutting tools and tool geometry. However carbide cutting tools are the most versatile in terms of a wide application over a range of cutting speeds and hence present the best option for a comparative study. Additionally, most of these tools are now coated.

Fig. 3 shows the relative percent of power consumption in a machining EN8 steel. Only 36% of the total power drawn is used for actual machining. The bulk 64% of power was spent for the non-cutting operations. Running the spindle and the control computer and cooling fans consumes most of the idle power. Thus machine tool design should be one of the engineering challenges in order to reduce the impact of machining on the environment. This conclusion support work by Gunter and Gunther (Gunter and Gunther, 2007). In this machine running the coolant uses 4% of the power requirement and hence a move to dry machining can save this power/energy. This share is comparable to a 2% coolant pump energy reported by Gutowski (Gutowski et al., 2006) for a 1998 Bridgeport automated milling machine. The power required for machining aluminium, cast iron, titanium and brass alloys were 31%, 28%, 15% and 13% respectively. The results from all the workpiece materials show that the machine power or idle power dominates the machining process. Yet power/energy footprint is seldom considered as an optimisation priority in the design of machine tools.

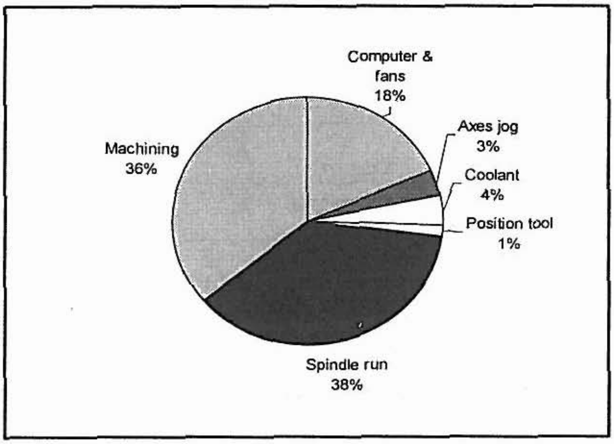


Fig. 3. The power distribution for the MHP lathe while turning EN8 steel

An evaluation was then made of the energy required to remove 1m^3 of material. Using the material removal rate the time taken to machine this quantity was evaluated and then multiplied with the power consumed to get the energy requirement. The results obtained for typical finishing operations (Tab. 2) with the recommended cutting conditions are shown in Fig. 4.

Table 2. Finish turning cutting parameters adapted from Sandvik (Sandvik 2002)

	Steel	*Aluminium*	*Cast Iron*	*Titanium Alloy*	*Brass*
Feedrate (mm/rev)	0.25	0.30	0.30	0.15	0.15
Depth of cut (mm)	1.00	1.50	1.00	0.40	1.20
Cutting speed (m/min)	395	654	240	85	140

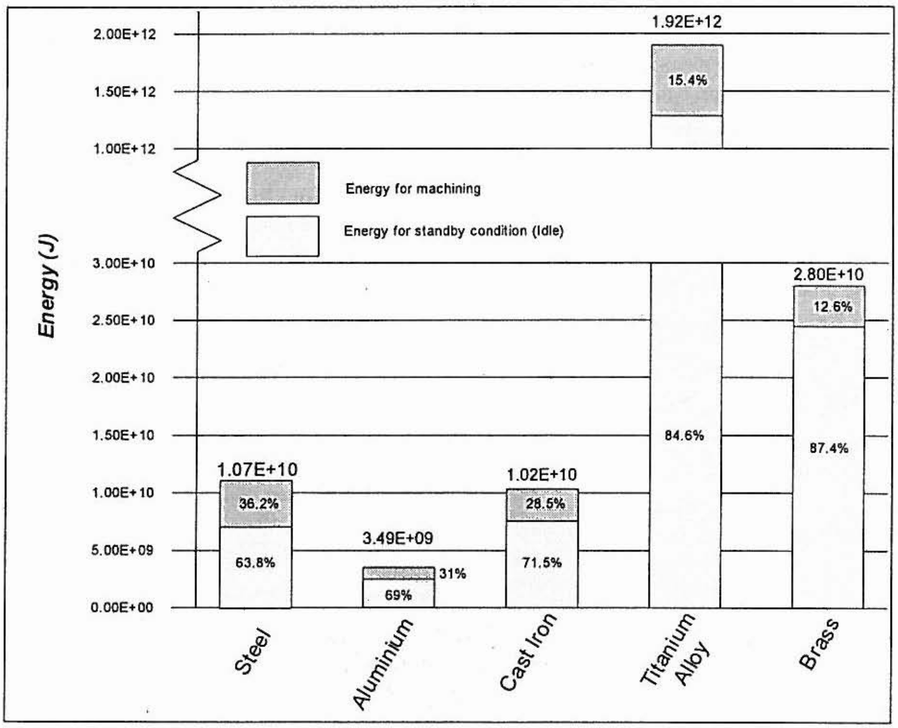


Fig. 4. Total industrial energy requirements to remove 1 m^3 of material

It can be seen in Fig. 4 that the total energy to remove 1 m^3 of titanium alloy is significantly higher than that for other materials. Aluminium alloy machined at the highest cutting speed has the lowest energy footprint. Brass is shown here to have a high energy footprint because of the lower feedrate compared to steel, aluminium and cast iron. Among these alloys titanium is machined at the lowest cutting speed and material removal rate. Thus in low volumetric rate machining processes, a longer cutting time is needed to remove a specified amount of material and this is done at a penalty of a higher energy footprint. It can thus be seen that one benefit of high speed machining or rapid machining would be to significantly reduce the energy footprint for a machined product.

4. CONCLUSIONS

The energy consumed in the machining can be used as an indirect measure of the energy derived carbon footprint for a process. This is because in generating the power that is then used to drive machines carbon emissions are produced. Thus in the interest of energy availability and reducing carbon footprints it is essential to run production operations at the lowest energy footprint (consumption). Analysis of power/energy consumed on a CNC lathe shows that non cutting operations consume the bulk of the energy. In particular the energy required by the lathe spindle was found to be the dominant consumer. Implementing dry cutting instead of using coolants can reduce the power/energy consumption by 4%. This is an additional sustainability benefit to the elimination of the contaminating fluids. Design of low energy footprint machines should be targeted as a strategy to improve sustainability of machining operations.

Comparing the energy required for different engineering alloys it was found that machining at higher volumetric removal rates or high speed machining results in lower energy consumption for an identified removal volume for product. In addition, the type of material machined affects energy consumption. If the origin of power supply to a machine shop is known then this work could be extended to calculate the associated carbon footprint. The energy mix differs from one country to another, thus energy footprint provides a better basis for comparative analysis. Thus one strategy to reduce industrial activity related carbon emissions is to reduce the energy consumptions in production processes.

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