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11.2 Energy usage and efficiency in non-conventional micromachining

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Abstract

Energy efficiency is one of the main strategies adopted by companies to reduce their environmental impact. This paper presents some case studies on the energy consumption, both electrical power and compressed air, of abrasive jet and laser drill machines used in the production of printer inkjet cartridges. The study also examines the practical challenges involved in the implementation of energy reduction strategies in an industrial environment, and in particular the technical, economic and practical viability of energy saving solutions for in situ toolsets. The objective of the paper is therefore twofold: 1. To contribute to the understanding of energy use in non-conventional micro-machining, an important element of Life Cycle Inventory analysis and 2. To help researchers understand the difficulties in implementing energy efficiency measures, and in particular the role of risk as a barrier to energy savings.

Keywords:

Energy efficiency, Laser, Abrasive jet, Micromachining, Risk

1 INTRODUCTION

Energy efficiency is one aspect of sustainable manufacturing and is widely pursued by industrial entities as it allows for improvements to both economic and environmental performance. Over the last decade, there have been numerous studies into the energy usage of top level manufacturing plant [1], conventional manufacturing unit processes [2], including micromachining [3] and nanoscale manufacturing [4]. Additionally, based on such energy use studies, a number of papers have investigated and proposed energy efficiency improvements in the general design of machine tools [5], for conventional mechanical cutting machines [6], for laser cutting machines, in particular for sheet metal applications [7] and for manufacturing support systems such as robotics [8], cooling [9], power factor correction [10] and pneumatics [11]. Alternative approaches to the time consuming power measurements required by such energy investigations have also been proposed [12]. Non-conventional micro-machining processes such as abrasive blasting and laser cutting have received less attention. Moreover the focus of research to date has been on changes to future design, while the energy optimisation of machinery already in production is not often considered. This is important given the extended life of many production machines currently in operation.

This paper provides an overview of the energy use in an inkjet manufacturing facility, with a specific focus on Diode Pumped Solid State (DPSS) lasers and high pressure abrasive jet machines for microdrilling applications. Since the abrasive jet and laser drill units are alternative stages in the process chain, an energy usage comparison of both technologies is presented. A number of energy efficiency measures are proposed for the laser drill machine and some of the difficulties in achieving energy savings in an industrial environment are also discussed. A particular emphasis is placed on the role or risk as a barrier to improvement.

2 CASE STUDY: INKJET MANUFACTURING

The case study is based on a large multinational manufacturer of inkjet printer cartridges. The factory produces large volumes of printer cartridges, and in addition to dedicated production buildings the campus also includes other business units such as sales, marketing and also contract manufacturers/component suppliers. The order of magnitude of annual energy consumption is in the double figure GWh scale, with electricity accounting for 67% of usage. The price for electricity is approximately twice the price of natural gas in Ireland at present. The 2011 CO_2 intensity for electricity and gas in Ireland was 0.49 kg-CO_2/kWh, including the additional overhead for processing/transport of fuel, and 0.2 kg-CO_2/kWh (NCV) respectively. Electrical energy is therefore the major driver of energy use, costs and CO_2 emissions on site. An energy management system (Powerlogic, Schneider Electric) and extensive power metering allows for electricity consumption tracking and identification of significant energy consumers.

2.1 Factory energy use

There are a large number of technologies and processes used in the production of a final printer cartridge product. The main process stages located in the factory include 1/ Print Head Manufacture (PHM) and 2/ Final Assembly (FA). Figure 1 shows the breakdown of energy supply and final consumption for the factory. Note, in figure 1 'other electric energy' refers to the electricity usage of other business units located on the campus. Air compressors and production

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machines are the largest electrical energy consumers, accounting for 23% and 21% of usage respectively. Within the production category, print head manufacturing equipment consumes approximately 65% of overall production electricity use. The energy usage due to space heating, ventilation and air conditioning (HVAC) is also large, considering the combined consumption of the air handling units, boilers and chillers accounts for nearly 50% of total site energy usage.

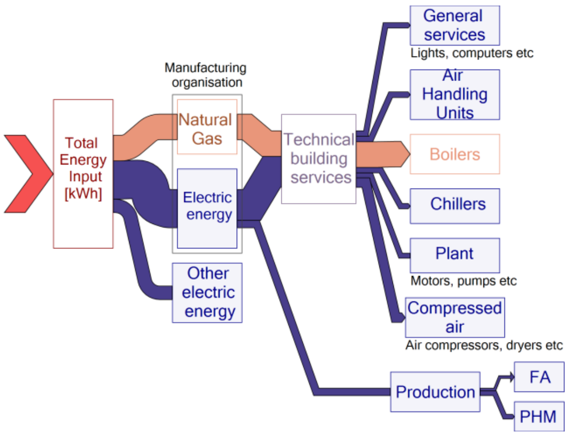

Figure 1: Energy breakdown in inkjet manufacturing facility.

3 PRODUCTION MACHINE ENERGY USE

In order to cut slots of micron spatial scale in a wafer, as part of the print head manufacturing process, two alternative micromachining methods are utilized: abrasive blasting and laser drilling. Laser drilling accounts for a considerable proportion (approx. 20%) of the electrical energy consumed in PHM, and the abrasive jet machines require an additional 110kW dedicated compressor to deliver compressed air at higher pressure than general factory requirements. Therefore both processes are considered significant energy users and were investigated as part of the site energy efficiency program. Note that while the general purpose of both the laser and abrasive jet machines is the same, typically different products, i.e. different slot dimensions, are produced on each.

In terms of the system boundaries for the study, only the electrical power and compressed air demand of the machine tools were measured. The difference in energy usage in post-cut treatment processes and TBS support equipment (e.g. vacuum pumps, dust collectors), required by the sandblast and laser drill machines, was therefore not considered. The energy usage of lighting and ventilation was also outside the scope of the investigation. Unit process level measurements were taken at supply points to the machines e.g. compressed air dropdown pipe or electrical panel. A mobile power meter (HT Italia VEGA78) and two air flowmeters (CS instruments VA420, VP instruments VPF) were used for the measurements. A one second integration period was used for the power meter and the flowmeters were sampled at a rate of 1Hz. The specific power required by the air compressors supplying the machine tool was estimated to be 6 kW/Nm3/min at 7 bar(g) and 7 kW/Nm3/min for 10 bar(g), assuming an overall adiabatic efficiency of 80%.

3.1 Laser drill electrical power demand

A number of laser drill machine tools are shown in figure 2. The main components of the tool include two solid state, diode pumped, Q switched laser heads and associated equipment: controller, galvanometer etc (figure 3). The average output power of a laser in operation is 30W at 120 kHz with material removal via ablation. An air-cooled vapor compression chiller provides cooling for both laser heads and galvanometers. Laser cooling is a critical function as semiconductor devices such as diodes perform better at lower operating temperatures resulting in higher electrical to optical efficiency and extended device lifetime [13]. An XY linear translation stage in each chamber is used for precise positioning of the wafer, and a single robot loads the wafers into each laser head chamber. Other components include: PC's, PLC, cameras, actuators, sensors, cooling fans etc. The nominal energy requirements of the machine are 22A per phase at 400VAC (50 Hz 3 Phase) and 500NL/min at 6 bar(g).

Figure 2: Laser drill machines.

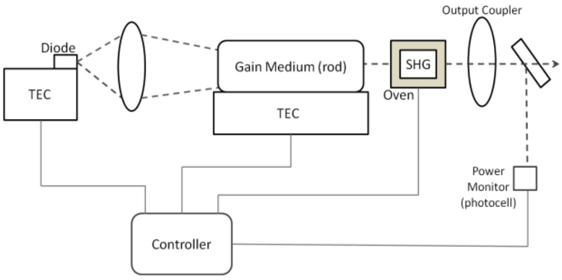

Figure 3: DPSS Laser system subcomponents without Q-switch.

The breakdown of subsystem nominal electrical power requirements for the laser machine tool is shown in figure 4 and is based on data from vendor datasheets. It is clear from figure 4 that the majority (65%) of electrical power demand is due to the laser systems and chiller. A sample power measurement of the machine in operation is shown in figure 5 and demonstrates that the actual proportion of electrical energy usage due to the chiller and lasers will be higher than 65%. This is due to the fact that the robot, whilst nominally having the third largest power rating, only operates for brief loading/unloading periods between wafer processing, and is otherwise in standby mode. A similar energy breakdown was found for the laser cutting of sheet metal [7]. Within each laser head, the Electricity Consuming Units (ECU's) are the Thermo-Electric Coolers (TEC), crystal ovens for Second Harmonic Generation (SHG), diode array and controller (figure 3). The ECU's in the chiller include compressor, pump and fan. The total measured electrical power demand during production and idle mode was 4.9 kW and 3.3 kW respectively. It should be noted that the machine tool is only fully shutdown on rare occasions. The overall wall plug efficiency, ratio of optical output power to total electrical input, of the laser head is estimated to be approximately 3%. This figure is based on the total power demand of the laser system, including TEC's, controller etc, but does not consider the additional energy usage of the chiller. Wall-plug efficiency is often described in terms of the ratio of optical output power to the electrical power delivered to the diodes only [14]. Using this definition, efficiencies of 25% to 28% for solid state lasers, e.g. Nd:YAG, are reported in the literature [14].

The main air consuming units (ACU's) include a venturi vacuum generator for wafer handling, air knifes to prevent water or debris settling on galvonometer lens surfaces, air nozzles to assist the cutting process, and pneumatic cylinders for clamping and actuation. There was a small difference in compressed air demand on the laser tool for the water and air assisted portion of slot ablation process. The equivalent electrical power, due to average measured compressed air demand, was 1.8 kW in production mode and 1.38 kW when idle. Air leakage was found to account for approximately 10% of overall compressed air demand. The power required to supply compressed air is approximately 27% of overall power demand by the laser tool.

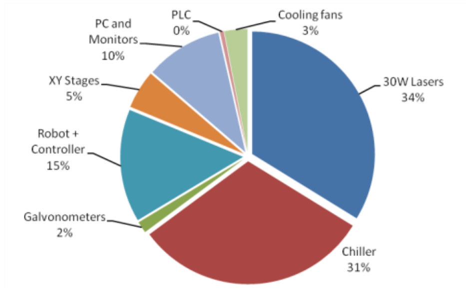

Figure 4: Subsystem nominal power requirements for laser drill.

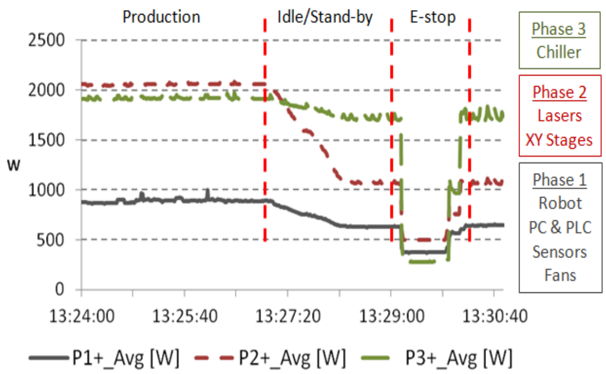

Figure 5: Sample power demand on laser drill.

3.2 Abrasive jet drill electrical power demand

In abrasive jet machining, a stream of very fine abrasive particles, such as aluminium oxide, are propelled by a pressurised gas to impinge a substrate and remove material via erosion. The main components of the sandblast machine tool (figure 6) include two high pressure nozzles in separate blast chambers, positioning tables for each chamber, a robot for loading/unloading wafers, an extraction system, vision inspect system, actuators, PC's, PLC, sensors etc. The nominal electrical energy requirements of the machine are 8A at 230 VAC (50 Hz Single Phase). Two compressed air lines are required to supply air at a lower pressure of 6 bar(g) and a higher pressure of 9 bar(g). Note, the higher air pressure is required from a process point of view, to achieve a defined material removal rate.

In addition to the energy penalty associated with using higher air pressure to increase production throughput, the air quality also affects both energy usage and process output. The compressed air used in the abrasive jet machining process is in direct contact with sensitive electronic components and must therefore be dried, in order to ensure there is no condensation of water vapour on the product with subsequent reduction in production yield. The additional energy usage for dehumidifying the air will depend on the type of air dryer in operation i.e. refrigerant or adsorption. The high pressure compressed air system in the inkjet factory includes heatless desiccant dryers with a relatively low dewpoint of -70°C. The compressed air requirements to purge heatless desiccant dryers accounts for a considerable portion of overall compressed air demand, typically in the range of 15% to 25% of rated capacity [15]. In order to incorporate the additional air demand into the estimate of required air compression power, the measured compressed air flow to the machine was multiplied by a factor of 1.25. Note this purge flow factor will depend on the type of desiccant dryer, inlet air temperature and specified dewpoint. The pressure drop across the air system is also increased with desiccant dryers.

A sample measurement of the high and low pressure compressed air demand is shown in figure 7, with one blast chamber in operation. The equivalent electrical power required to supply the compressed air at both higher and lower pressure levels was estimated to be 5.9 kW in production mode and 2.2 kW in idle. The electrical power demand of the sandblast tool was measured to be 1kW on average during production mode and 0.5 kW when idle. The electric power required to supply compressed air is approximately 85% of overall power demand of the abrasive jet machine.

Figure 6: Abrasive jet machines.

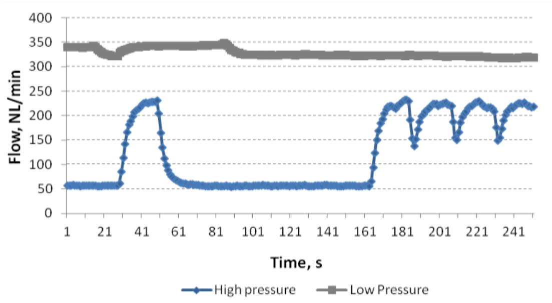

Figure 7: Sample compressed air demand on abrasive jet tool.

3.3 Comparison of energy use for laser and abrasive jet micromachining processes

A comparison of the aggregate power demand, including electrical and compressed air, and specific energy for both machines tools is shown in table 1. Interestingly, the estimated power demand of the abrasive jet machine in production mode is 0.2kW more than that of the laser, but the power draw in idle mode, is considerably (2 kW) less. The power requirements of the sandblast machine in production mode could be reduced through the use of a heat regenerated desiccant dryer. The smaller idle energy requirements of the sandblast unit are due in part, to the ability of pneumatic components to provide a continuous force without needing a continuous feed of energy. This idle energy usage could be reduced further with leak detection and fixing. However considering processing time only, the specific energy required per wafer is less for laser machining than abrasive machining, due to the smaller production mode power demand and shorter cycle time of the laser machine tool. The wafer processing time will vary based on the number of slots required per wafer and slot dimensions, which depend on the product type in production. Therefore for consistency, in table 1 the specific energy per wafer is based on the same product type. It is important to highlight that there is an ongoing migration from the older sandblast to laser drill technology and the process time for the laser drill in table 1 is therefore based on preliminary test data. The main benefits of laser drilling include enhanced production yield and improved product quality, in the form of smoother edges after cutting. The higher quality surface finish ultimately allows for improved functional performance of the inkjet cartridge during the use phase. Therefore the reduction of idle time and idle power demand are keys issues for improved energy efficiency. Note, this analysis does not consider the additional energy related overheads for the laser drills to be located in a cleanroom environment, with associated HVAC requirements, or the dust collection units necessary for abrasive jet machine operation.

	Laser Drill	Sandblast
Production power, kW	6.7	6.9
Idle power, kW	4.7	2.7
Process time, mins/wafer	35*	40
Specific energy, MJ/wafer	14. 1	16.6

Table 1: Power and energy use comparison for micromachining MT's.

4 ENERGY EFFICIENCY IMPROVEMENTS

The laser drill machine tools were the focus of the energy efficiency analysis. The financial viability/return on investment of EEM's can be determined by net present value or internal rate of return methods but the simple payback method is still prevalent in industry.

4.1 Energy saving options - Laser Drill

The energy efficiency improvements discussed for the laser drill are shown in table 2 and are broken into two categories: 1/ No or low cost idle mode optimisation measures and 2/ Design changes, involving the replacement of subsystems or components with newer or more efficient alternative technology. In particular the use of power factor correction [10], kinetic energy recovery methods [6, 8] and alternative coolers using scroll compressor technology [9] look promising in the development of new machine tools. However, given the large capital investment required for laser machine tool components (robot, laser system etc), combined with relatively low energy use and costs, makes the economic case for design changes, such as the replacement of subcomponents, difficult. Additionally, the stringent short term focussed payback requirements of multinational manufacturers also hampers the implementation of energy efficiency measures. Therefore the best potential for efficiency improvements on operational production machinery involves the reduction of idle mode power demand. In the case of the laser drill tool, shutdown of the main energy consumers, laser systems and chiller, over longer time periods, such as weekends, offered significant energy savings. Based on discussions with technical personnel, the shutdown procedure was modified such that problematic older PC's were left on, to avoid software issues on restart. The use of software for the controlled shutdown of the robot for shorter standstill times (e.g. 10mins) [8] also offered considerable savings, given the long idle time of the unit during production mode. Potential savings of around 300,000 kWh per annum were identified for the laser drill production zone with little or no investment costs.

Idle optimisation
Soft shutdown of tool over extended idle periods (>8 h)
PC and monitor shutdown over extended idle periods
Controlled shutdown of robot for idle periods (>10 mins)
Alternative chiller control when idle
Turn off Galvonometer air knives when idle
General optimisation
Regenerative brakes for XY stage and/or robot
Dynamic power factor correction
VSD for chiller pump and/or fans
New IE3 electric motor for chiller
Complete replacement of chiller
Eliminate second PC or replace PC's with newer models
Replace single acting pneumatic cylinders with muscle actuators

Table 2: EEM's for Laser Drill.

5 RISK AND ENERGY EFFICIENCY IN PRODUCTION

In addition to economic and technical efficiency considerations, the risk to product quality and machine availability also require thorough investigation to successfully implement energy saving projects. Risk or perceived risk by operations staff to even relatively simple measures, for example the shutdown of equipment, can prevent the ultimate uptake of EEM's. An early assessment of risk and mitigation plan based on input from technical staff and original equipment manufacturers is therefore essential for the success of energy efficiency projects in production. Some of specific concerns associated with the shutdown of the laser drill over extended periods include:

- Algae growth in the chiller water supply. Risk of increased machine downtime for maintenance.
- Dew condensation in the laser head cavity. Since the laser crystal is hygroscopic, any exposure to moisture can result in crystal degradation and potential failure. There is a subsequent risk of machine downtime and/or product quality issues.
- DPSS lasers are sensitive to temperature, operation outside tight limits can lead to fluctuations in output power, and impaired cutting performance. Risk of reduced yield at start of production run.
- Potential for thermal drift of optical components in laser system leading to slot misalignment and reduced tool yield at start-up.

There is therefore the possibility of significant future expense, due to the extra personnel and time required for machine correction in addition to component replacement costs, should any of the described risks occur. The risk of such occurrences is generally reduced when laser machine tools are situated in temperature and humidity controlled cleanroom environments, as condensation and large temperature fluctuation are unlikely. However, the potential losses are clearly a serious barrier to the implementation of EEM's on operational production machinery.

5.1 Initial risk assessment

Failure Mode and Effect Analysis (FMEA) is qualitative risk evaluation technique that is widely used to identify potential failure modes based on expert experience and knowledge. This approach has been recently applied to a biomedical production machine, in order to address concerns regarding product quality and machine reliability, in relation to planned energy efficiency improvements [16]. The draft ISO14955 standard prescribes that machine tools are to be described in terms of their generalised functions to facilitate analysis and problem solving in relation to energy efficiency [17]. In keeping with this approach, the matrix presented in table 3 allows for the risk of fault, due to implementation of an EEM, to be assigned by the machine tool functions and components. This initial risk assessment can then be followed by comprehensive evaluation of the specific concerns, using Failure Mode and Effect Analysis (FMEA) for example, to assess the severity of EEM induced failure, probability of failure occurrence and likelihood of failure detection.

Generalised MT functions	Component/Sub-System	EEM1	EEM2	...	EEMn
Machine operation (Process, motion, control)	Laser Head	Y/N	Y/N		Y/N
	Galvonometer	Y/N	Y/N		Y/N
	XY stage	Y/N	Y/N		Y/N
	PLC	Y/N	Y/N		Y/N
	PC & monitors	Y/N	Y/N		Y/N
	Vision system, sensors, transformer, UPS etc	Y/N	Y/N		Y/N
Process condition/cooling	Air assist system Water assist system	Y/N Y/N	Y/N Y/N		Y/N Y/N
Workpiece handling	Robot Wafer chuck	Y/N Y/N	Y/N Y/N		Y/N Y/N
Tool handling	Lens purge	Y/N	Y/N		Y/N
Waste handling	Vacuum supply (TBS) Vacuum pump (optional)	Y/N Y/N	Y/N Y/N		Y/N Y/N
Machine cooling/heating	Chiller Fans	Y/N Y/N	Y/N Y/N		Y/N Y/N

Table 3: Example EEM fault risk matrix for Laser Drill.

6 DISCUSSION ON RISK IN ENERGY RELATED INTERNATIONAL STANDARDS

The existing international standard for energy management systems [18] or the draft standard for environmental evaluation of machine tools [17] focus on energy measurement, monitoring and top level management commitments to improve energy efficiency. While such measures are an essential starting point, the risk or perceived risk to industrial key performance indicators such as machine availability and product yield is a critical barrier to the final implementation of energy efficiency measures. At present, a systematic approach for risk assessment and mitigation of energy efficiency measures is not explicitly addressed in the international standards.

Additionally, while a risk centric approaches to energy efficiency has been successfully applied in industry [16], the method is time consuming for two reasons primarily: 1. The necessity of consulting the original machine developers and 2. In overcoming strong organisational resistance to any changes to the status quo, in particular if production personnel are not subject to energy metrics. Therefore, it would be useful for the machine builders to either design for controlled shutdown over extended periods e.g. non 24/7 production, or provide a risk assessment for the end-user to do same.

7 CONCLUSIONS

The energy use in terms of electricity and compressed air, for two micromachining processes, laser and abrasive jet drilling, has been investigated in this paper, and it has been shown that moving product from sandblast to laser drill results in a small decrease in the specific energy for machining a wafer. However, some of the savings in specific energy will be offset by the higher idle electrical energy consumption of the laser tool and the change in overall factory energy use will therefore depend on the production schedule of the machine tool. A number of energy saving opportunities were identified for the laser drills, with a focus on idle mode optimisation for reasons of economic efficiency. The important role of risk in the implementation of energy efficiency measures has also been highlighted and in this context, some specific risk factors involved in the shutdown of laser based production systems as an example, were discussed. Given that machine uptime and product quality are typically prioritised ahead of energy savings, thorough risk assessment of machine or process changes is therefore an essential accompanying task to any industrial energy saving project. Finally it is has been proposed that risk assessment and mitigation should be considered for integration into future international standards regarding manufacturing energy efficiency and energy management.

Future potential work includes a total cost of ownership study of the abrasive jet and laser machine tools, including maintenance, consumables and facility support systems, to provide a more comprehensive insight into overall operational costs. Other environmental impacts, such as the use of sand or other abrasive material, could also be considered. Additionally, from an industrial point of view, holistic methods that prioritise energy efficiency measures for production tools based an assessment of technical/economic efficiency and risk, are required.

8 ACKNOWLEDGEMENTS

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