MICROMILLING ANALYSIS

T.G. Dirkse van Schalkwyk[1]
[1]Department of Industrial Engineering
Stellenbosch University, South Africa
theuns@sun.ac.za

ABSTRACT

This paper reports on a Techno-economic model of micromilling, incorporating major contributors to products' manufacturing cost.

Micromilling is a comparatively new machining technology and is developing rapidly. Many new products are significantly smaller than their legacy counterparts, due to drivers such as increased micro processing, portability advantages and resource scarcity. This allows micro manufacturing in general and micromilling specifically to seize market share at the expense of earlier manufacturing technologies.

The most advantageous areas to consider micromilling were identified as medical implants, micro-moulds, developing and prototyping, small and medium batches of complex 3D shapes and dental accessories.

1. INTRODUCTION

Advantages in capital cost, labour, materials volumes and operating costs all add to the attractiveness of micro manufacturing. The ability to manufacture smaller batches economically promotes local manufacture and has a smaller carbon footprint than traditional approaches. Micromilling also fits well with the concepts of mass customisation and tailor-made fitting products in the medical implants area.

Micromilling is a subclass of Micro manufacturing and more specifically of Micromachining. Micro manufacturing focuses on the emerging global trend toward the miniaturization of manufacturing processes, equipment and systems for micro scale components and products, i.e., "Small Equipment for Small Parts." It encompasses the creation of miniaturized units or hybrid processes integrated with metrology, material handling and assembly to create micro-factories capable of producing micro-precision products in a fully automated manner at low cost. The major international study in this field, the WTEC panel report [1] has investigated both the state-of-the-art as well as emerging technologies from Micro manufacturing. The WTEC report describes various scientific, technological, and commercialization perspectives across key industrial sectors in the U.S., Asia and Europe including medical, electronics, aerospace, and consumer products. The WTEC panel report's main conclusions are that Micro manufacturing will become a disruptive technology and that countries need to support research in Micro manufacturing to ensure future competitiveness in manufacturing.

Micromilling is defined by various authors [1], [2], [3], [4], [5] and [6] related to machine size, tool size, work piece size and feature size. Masuzawa [7], at first related micromilling to the micrometer, meaning the machining of dimensions between 1 and 999 um. However Masuzawa [8] later suggested that a more flexible approach considering factors such as the personal viewpoint, era, machining method and material might be better suited. Dornfeld [9] argued micromachining happens when cutting with tool engagements less than 1 mm. Meanwhile, Chae [10] had an inclusive definition of machining miniature products with features whose size range from micrometres to a few millimetres. Because of the size effect introduced by micromachining, it can be argued that the definition by Simoneau [11] correctly advocates that the difference between conventional and micromachining should embrace factors influencing the cutting mechanisms. In this paper, if size effects impact the cutting mechanism to any extent that makes conventional cutting calculations or assumptions inaccurate, then micromilling is assumed to take place.

Apart from the direct machining of parts, micromilling can form an important part of the manufacturing chain for moulding, stamping and embossing. Since mould-making has a significant contribution to the capital cost of such projects, lower mould cost can play a large role in profitability.

2. EXPERIMENTAL SETUP

2.1 Numerically controlled milling machines used

Three numerically controlled (NC) milling machines are compared in this research. A conventional Leadwell powered by three-phase 380V and utilising a 20KVA spindle motor is used as the legacy machine. Machines similar to this would cost approximately R1000 000 to R2000 000 depending on the vendor. A Denford Micro Mill and a Minitech Micro Mill was used as examples of the newer technology. These types of micromilling machines come in a wide range of cost and quality variations. At the lower end of the spectrum it could be possible to buy a micromilling machine for R30 000 and at the very high end of the spectrum R2000 000. Detailed comparisons were only done for tools that could fit on the micro mill, that is 3.175mm and smaller.

For the capability, accuracy and repeatability required in the current research, the Minitech Micro Mill is sufficient, while the Denford Micro Mill is just used as an additional comparison. The three milling machines are shown in Figure 1 and some comparitive specifications are listed in Table 1. Additional milling were also performed on the micro milling machine only since some of the smaller cutting tools cannot be used on the conventional spindles.

Figure 1: Leadwell VMC 40 Mill Denford Mill Minitech Mill

Specification	Leadwell	Denford	Minitech
Voltage	3 phase 380V	Single phase 240V	Single phase 240V
Maximum power rating(kW)	20kW* (from kVA)	1.7+Accessories 0.36*	2.16+Accessories 0.36*
Spindle power rating(kW)	7kW	1.1kW	0.43kW
Maximum feed mm/min	240 000 mm/min	2000 mm/minute	1654 mm/minute
Maximum spindle speed	6000 rpm	24 000 rpm	60 000 rpm
Expected accuracy	25um	100um	15um
Maximum tool diameter	80 mm	6.35 mm	3.175 mm

*estimated

Table 1: Comparison of selected specifications

2.2 Cutting tools

Accessories All cutting tools are from Performance Micro Tool and are made from carbide. Currently the carbide grain size are limiting these tools to 5um and larger. According to Dave Burton in a personal interview with Dennis Spaeth [12], when materials with a finer grain structure becomes available these cutting tools could become smaller. Comparative experiments used cutting tools of 3mm, since micron sized cutting tools cannot be used on conventional spindles. For other milling on the micromilling machine only, cutting tools ranged from 3mm to 12um.

2.3 Energy measurement

To measure the energy use of a three phase system, the three Wattmeters [13] method is used. This method allows the direct recording of the results into any system and real-time feedback or display. The two Wattmeters method may also be used if preferred. For the single phase measurement a one Wattmeter system is sufficient.

Previous research [14] reported on the average effective utilisation of energy in a milling operation, to be about 15% of total energy used. The energy use of conventional milling is shown in figure 2. The triangular shape of the machining portion indicates that the energy used is variable due to various factors such as cutting tool size, depth of cut, volume removed, cooling, lubrication and material. The total energy used in any milling machine will therefore only vary slightly due to the type of cut, depth of cut, step over and tool size, since a large portion of the energy is utilised for other functions than cutting.

Using the actual energy measurements this can be verified, and the comparative cost as Rand/cm³ of material removed can be calculated and compared for the three milling machines. Material removed is calculated using computer aided design software (CAD).

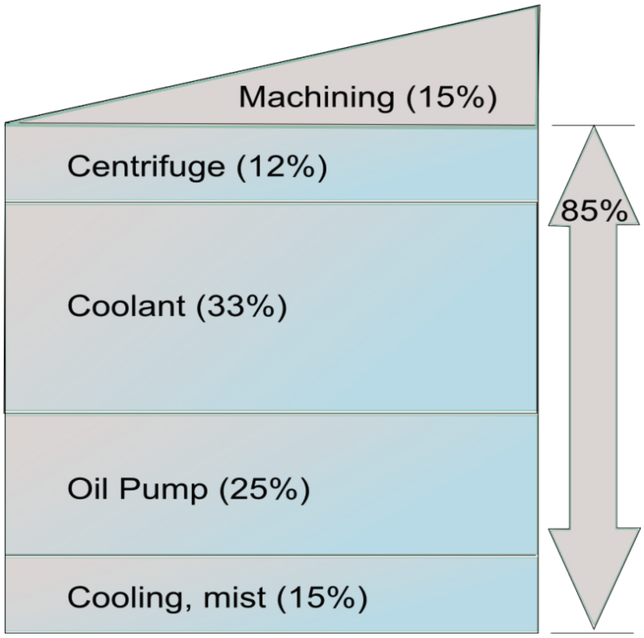

Figure 2: Energy use of conventional milling (Adapted from [15])

3. TECHNO-ECONOMIC MODEL OF MILLING

The basic process flow for a milled product includes the specification or contract for the part, design of the part, software representation, tool path generation, work holding, milling and post processing. Typical resources are machines, software, cutting tools, personnel, energy and work piece material. Other important considerations for the model are number of parts required per time period, volume of material removed, concepts such as batch processing of parts, pallet work holding and other alternative methods of work holding utilising the fundamental forces (or fundamental interactions) of physics, namely gravity, electromagnetism , weak interaction (or weak nuclear force) and strong interaction (or strong nuclear force).

A simple mind map in figure 3 shows the process flow for micromilling with some economic variables linked to the processes.

Since all of the processes shown in figure 3 are required to produce the micro milled parts, it can be argued that all the processes should be included in the techno-economic model. This is however a scope choice and other studies of this type might choose to have a narrower or wider focus. To limit the scope to a purely cutting cost calculation would limit the application of the model severely. To enlarge the scope to include all possible production possibilities (such as stamping and injection moulding as examples) would create complexity beyond a single paper of this type. Ben-Arieh and Qian [16] have proposed an evaluation method to include these activities, which could be included in future research.

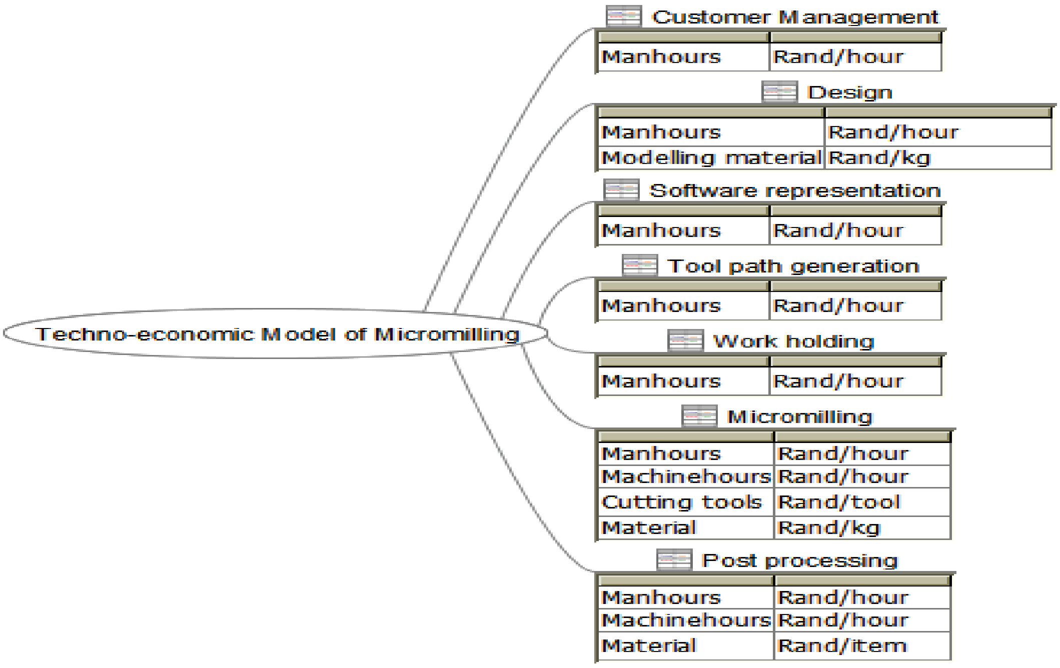

Figure 3: Process flow for micromilling, with selected economic variables.

For convenience and due to different types of data that are available, the techno-economic model will be separated into a high level component and a detailed experimentally based Manufacturing component. The contracting, part design, software representation and tool path generation are grouped as the high level component. The data for the high level comes from secondary research and expert opinion, since the type of products that could be designed and types of software used vary too widely to include these in experimental design for this research. The work holding, milling operations and post-processing are grouped as the Manufacturing component. Data for this component is mostly from primary research and measurements taken during experiments. The product material cost is not reported on in this paper, but it is acknowledged that there will be a big cost difference between machining a gold coin and Perspex coin of the same size and the model does accommodate the material cost.

3.1 The high level component

At a high level of abstraction, any arbitrary company could use this model to determine their capacity requirements. The process starts with an estimation of working hours required on a micro milling machine. This estimation could come from marketing or sales research or from experience in their particular business and lies outside the scope of this article. Next an estimation of the maximum utilisation that can be expected on the micro milling machine(s) is made. For the purposes of this study it was taken as 50% maximum utilisation. The utilisation % for this paper only considers normal working hours, i.e. no shift work or overtime. The following assumptions were also made to populate the model. One machine operator will be able to control four milling machines, each working at up to

50% capacity. A single customer manager will be able to write specifications and sign contracts for up to 10 ten milling machines. A designer will be able to do the required designs, CAD drawings and g-code generation to utilise six milling machines. It was also assumed that a 15% overhead cost is added to the whole design and manufacturing process chain.

The model uses the following formulas to calculate an average cost per hour per milling machine.

First the required number of micromilling machines are calculated:

$$Number\ of\ Micro\ milling\ machines = \frac{Contracted\ working\ hours}{Utilisation\% \times Normal\ working\ hours} \quad ...1$$

The total cost to buy these machines were then discounted by a risk-inclusive interest rate of 30% per annum over 5 years to yield a cost per hour worked. Thereafter the personnel requirements for each position are calculated according to the assumptions made in the model.

$$Number\ of\ personnel\ required = \frac{Number\ of\ Micro\ milling\ machines}{Micro\ milling\ machines\ per\ person} \quad ...2$$

Once the total cost for the above number of personnel and machines were determined, that cost was divided by the number of machines used, utilisation % and working hours.

$$Rand\ per\ hour = \frac{Total\ Rand}{Utilisation\% \times Milling\ machines \times Normal\ working\ hours} \quad ...3$$

For less than four micromilling machines, It is assumed that there will be either a single or in some cases two people who are multi-skilled and that do any of the required functions. The model was used with varying input contract hours, from 500 hours to 7000 hours to generate the expected Rand per hour cost that will cover only costs. It can be seen in figure 4 that a single person operating only one micro milling machine will incur a R642/hour cost. If one person were to operate up to four micro milling machines, the cost will drop to about R215/hour of machine work. The small increments seen at approximately 1000h, 2000h and 2900h are due to the purchase of additional machines required with increasing work volumes. The larger increment seen at 3800h is due to the necessity to appoint an additional person due to increasing work volume.

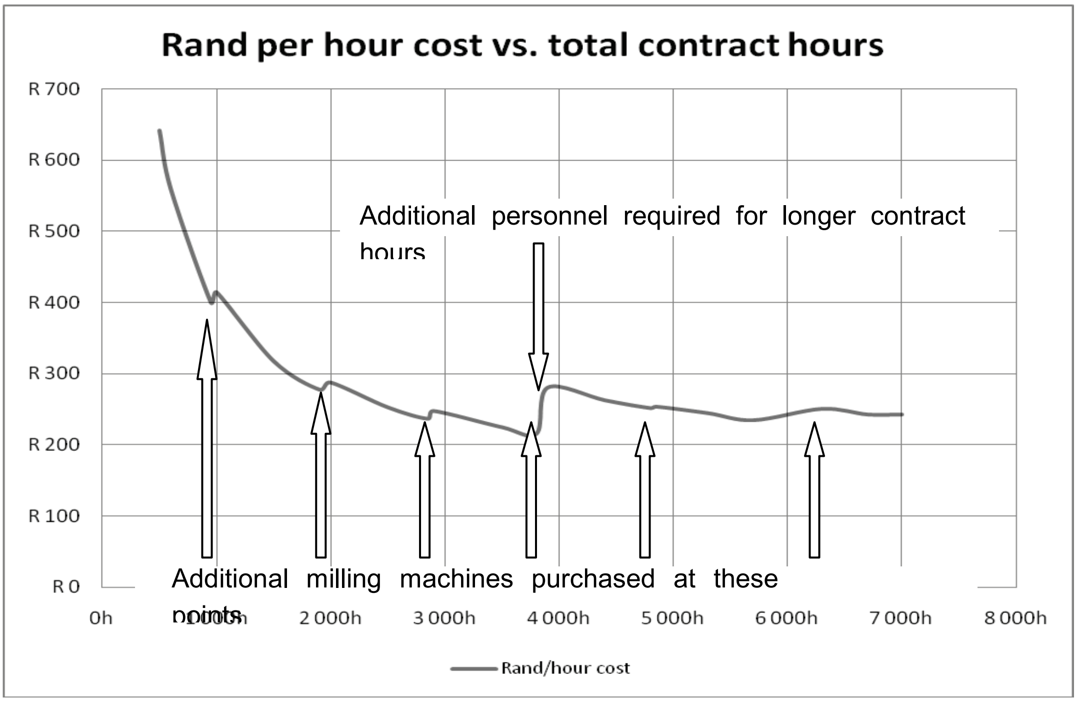

Figure 4: Rand per hour cost are compared at various levels of work volume required

3.2 The Manufacturing component

The following variables were used to calculate total milling cost in Rand per cm^3; the purchase price of the machine and cutting tools, the personnel labour cost, energy cost, setup time, feed speed, cutting tool size, required smoothness and spindle speed. The optimal scenario from the previous section, where one machinist operates four milling machines, was used to do the more detailed manufacturing calculations.

The maximum feed speed is related to the spindle speed, maximum chip thickness, cutting tool diameter, material, cooling and lubrication. For this model the material, cooling and lubrication were kept constant to get the experimental design compact enough. Only one cutter tool type was used for a similar reason.

For roughing operations the specification for a smooth finish is not really a major issue, but for the finishing operation it becomes critical. For milling flat surfaces with an end mill, the smoothness of the surface is mostly dependant on the cutting conditions. For flat surface milling, a milling machine with a larger cutting tool capacity will always win out economically. Micromilling, however comes into its own when small cut-out features and freeform surfaces are required. Small cut-out features requires small tools, and often bal-nose tools to ensure rounded surfaces that do not have stress concentrations. The required smoothness in the model as well as the volume removed is related to bal-nose tools with tool size, feed speed and step-over as the driving parameters as shown in figure 5. For the most part, volume removed is equal to the feed speed multiplied by the cutting area. Variation in the cutting area due to entry or exit from the work piece and non-straight cutting was not considered in this model.

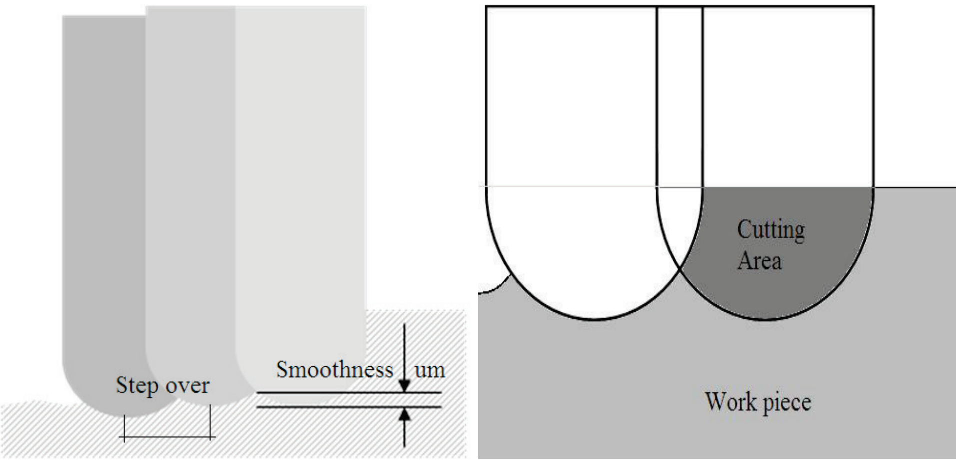

Figure 5: Relating tool size, step over, smoothness, cutting area and volume

Using the volume removal rate, it is straightforward to calculate the total expected machining time, and this is then added to the set-up times. The personnel cost is allocated to the machine time on a percentage basis (with one machinist operating 4 machines, each machine is allocated 25% of his/her time). The energy cost is then estimated, using experimentally measured kW values and expected machine time.

Considering figure 6 it is clear that using a micro mill has distinct financial advantages for smaller cutting tools. The advantages are primarily driven by two parameters, specifically high spindle speeds and lower capital costs. The micro mill has double the material removal rate due to its higher spindle speed, and the material removal rate combined with a lower capital cost produces a ten-fold financial advantage. This is however only true for small diameter cutting tools.

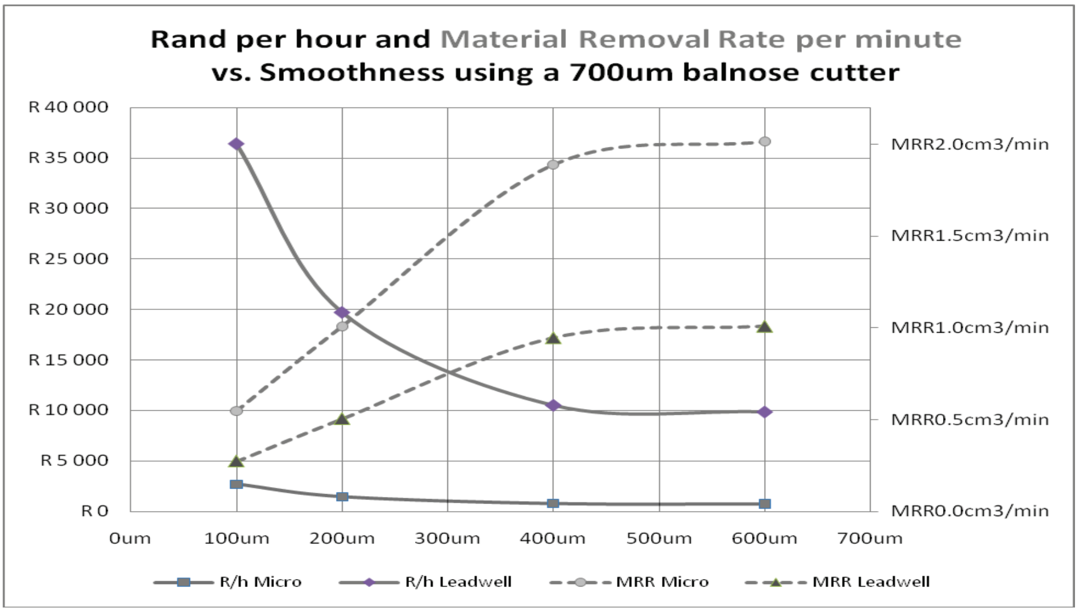

Figure 6: Rand per hour cost comparison between the Leadwell and micromilling machines

Comparing in figure 7 the relative sizes of the cost incurred from energy use, personnel and capital expense of the machine tools, it is clear that the purchase price of a large conventional milling machine contributes the major portion of the cost. It must be stressed however, that the personnel cost was calculated using the assumption that one machinist could operate four milling machines productively, and if only one machine was operated, then the personnel cost would increase to R600/h. Therefore it is imperative that both machine cost and productivity be considered when making such an observation.

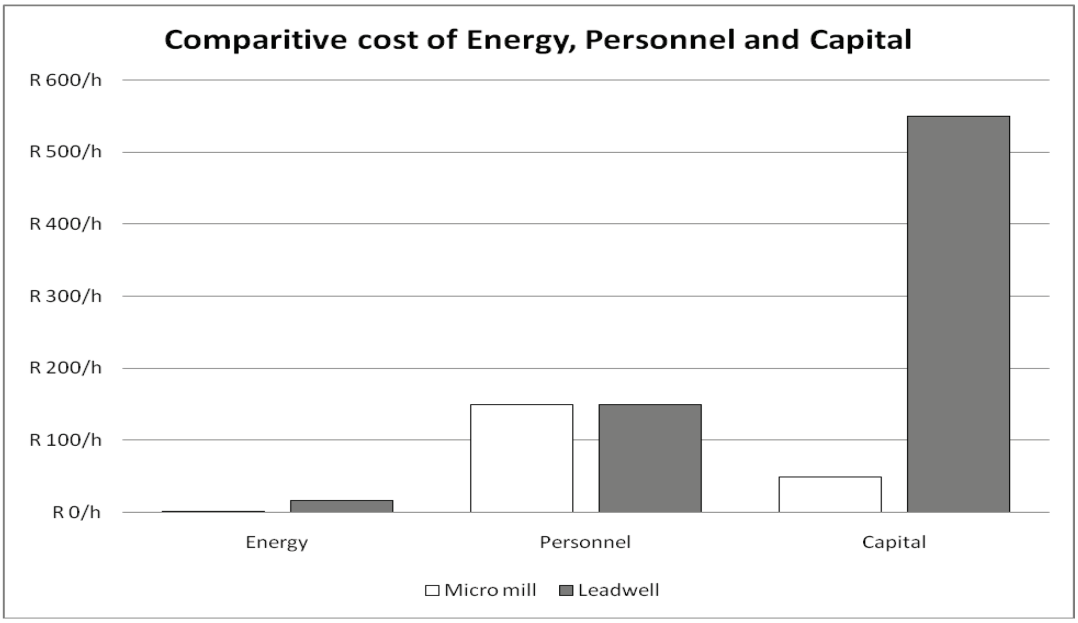

Figure 7: Rand per hour cost comparison between the Leadwell and micromilling machines

4. CONCLUSION

In the introduction it was shown that micromilling has many applications in various areas of industry. These are fast growing and high value areas including energy, medical, electronics, aerospace, and consumer products. Stellenbosch University is involved in micromilling research of medical, electronics and fuel cell components to name some.

Using the Techno-economic model it is clear that it will not be sustainable to compete in these markets while using older technology. It was identified that spindle speed and capital cost are two of the primary drivers for the difference in machining time and cost.

Companies who own older technology milling machines could however transfer their personnel skills fairly easily to the new micromilling machine tools and compete much more effectively in this growing industry sector.

5. REFERENCES

[1] **Ehmann, K. F. Bourell, D. Culpepper, M.L. Hodgson, T.J. Kurfess, T.R. Madou, M. Rajurkar, K. DeVor, R.E.** 2005. WTEC Panel Report on INTERNATIONAL ASSESSMENT OF RESEARCH AND DEVELOPMENT IN Micromanufacturing, pp 1-259.

[2] **Aramcharoen, A Mativenga P.T. Yang S. Cooke K.E. Teer D.G.** 2008. Evaluation and selection of hard coatings for micro milling of hardened tool steel, in International Journal of Machine Tools and Manufacture, 48, pp 1578-1584.

[3] **DeVor, R.E. Ehmann, K. F. Kapoor, S.G.** 2004. Technology Assessment on Current Advanced Research in Micro-Machining and Related Areas by AMT-The Association For Manufacturing Technology.

[4] **Dae Jin Yun, Tae Il Seo, Dong Sam Park** 2008. Fabrication of Biochips with Micro Fluidic Channels by Micro End-milling and Powder Blasting in Sensors ISSN 1424-8220, 8, pp 1308-1320.

[5] **Gafford, J. B.** 2010. Fabrication of High-Quality Microflexures Using Micromilling Techniques in Massachusetts Institute of Technology. Dept. of Mechanical Engineering.

[6] **Heamawatanachai, S. Bamberg, E.** 2010. Cutting force model of orbital single-point micromachining tool in the International Journal of Machine tools & Manufacture, 50, 9, pp 815 – 823.

[7] **Masuzawa, T. Tonshoff H.K.** 1997. Three-dimensional micromachining by machine tools in Annals of the CIRP, 46(2), pp 621-628.

[8] **Masuzawa, T.** 2000. State of the art of micromachining in Annals of the CIRP, 49(2), pp 473**-488.**

[9] **Dornfeld, D. Min, S. Takeuchi, T.** 2006. Recent advances in mechanical micromachining in Annals of the CIRP, 55(2), pp 745-768.

[10] **Chae, J. Park, S.S. Freiheit, T.** 2006. Investigation of micro-cutting operations in the International Journal of Machine Tools and Manufacture, 46(3-4), pp 313-332.

[11] **Simoneau, A. Ng, E. Elbestawi, M.A.** 2006. Chip formation during microscale cutting of a medium carbon steel in the International Journal of Machine Tools and Manufacture, 46, pp 467-481.

[12] **Burton, D.** 2010. Personal interview with Dennis Spaeth at ICOMM/4M reported on www.pmtnow.com.

[13] **Wildi, T.** 2002. *Electrical Machines, Drives and Power Systems*, 5th Edition, Prentice Hall.

[14] **Dirkse van Schalkwyk, T.G. Dimitrov, D.** 2007. Mapping of repeatability, accuracy, and energy use of a micro milling machine in the Proceedings of the 2nd International Conference on Micro-manufacturing, pp314-317.

[15] **Dahmus, J. B. Gutowski, T.G.** An Environmental Analysis of Machining in the Proceedings of the Engineering Congress and RD&D Expo, 2004.

[16] **Ben-Arieh, D Qian, L.** 2002. Activity-based cost management for design and development stage in the International Journal of Production Economics, 83, pp 169–183.