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REVIEW ON MICRO-MILLING OF HARD AND BRITTLE MATERIALS AND EXPERIMENTAL INVESTIGATION ON TCM USING MULTI SENSORS

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ABSTRACT
Miniaturisation of subtractive machining processes has received significant focus in its development of the production of high-precision and high-quality micro-components. There is an ever-pressing demand for micro-components in industries such as aerospace, pharmaceutical and biomedical, industries which require components with high-quality surface finishes and specialist mechanical properties produced by micro-machining processes, where most selected process is micro-milling, where hard and brittle materials are to be machined. Hard and brittle materials are considered difficult-to-machine materials due to their high hardness and tendency to fracture under machining. Tool condition and longevity defines output quality during micro-machining and is very unpredictable. The necessity to carry out Tool Condition Monitoring (TCM) is of paramount importance to high quality procedures. This article will provide an overview of machining requirements and considerations for machining of difficult-to-machine materials and focus work on optimum-process defining areas of micro-milling. It will review the current state of TCM and developments in Industry 4.0 technologies & methodologies and their implementation. Experimental work to support the research done has been performed implementing a TCM system to monitor the machining of glass and silicon using an Acoustic Emission Sensor. A TCM system has been configured from scratch connecting all the necessary hardware, and a program has been written to plot and extract data points individually, to be displayed for analysis. The configured system has produced characteristic results of micro-machining, corresponding with the literature studied and provides a strong platform for future refinement of the system.

INTRODUCTION

Industry and competition

In recent years micro-mechanical machining has received a lot of attention due to the demand for production of micro-scale parts. Performance-critical and high-accuracy micro-scale parts are of paramount importance to industries such as electronics, aerospace, automotive, biomedical, chemical, pharmaceutical and communications [2, 3, 31]. Micro-machining covers a selection of tool-based subtractive manufacturing methods which machine features of a workpiece or part so that its dimensions are in the micrometre range of 1-999μm [17]. These micro-machining processes include micro-milling, micro-electro discharge machining (micro-EDM), photolithography using a synchrotron (LIGA), chemical etching, laser ablation, ELID grinding, micro abrasive jet (AWJ), ultrasonic machining (USM), and hybrid processes which combine various methods to achieve more bespoke and advantageous machining characteristics [2, 4, 6, 31].

Miniaturisation/Macro to Micro adaptation

Micro-machining processes are a result of the downscaling of their conventional Macro-scale inspirations [1]. Miniaturisation of parts to the micro-scale has set the requirement for the miniaturisation of the machining operations that produce their complex 3D geometries, including the tooling to the micro-scale as shown in *Figure 1* [2]. However, this size reduction poses serious complications for tooling, and tool & workpiece interactions. Factors associated with tool instability are emphasised with scale-reduction, and it may not only be detrimental to the tool but also to the workpiece . Small tool sizes, ~ μm are far more susceptible to deflection and are subject to large amounts of vibration under tool and workpiece interaction. This vibration and subsequent deflection can lead to tool failure . Tool failure will occur at maximum deflection [12], and/or crack propagation on the workpiece, ruining the machined part's surface quality, exacerbating the probability of brittle fracture [3]. As feature/workpiece dimensions decrease, the tolerances of these features become tighter [1]. Resulting in an exponential effect on the increase in cost of tooling with respect to volume of material used.

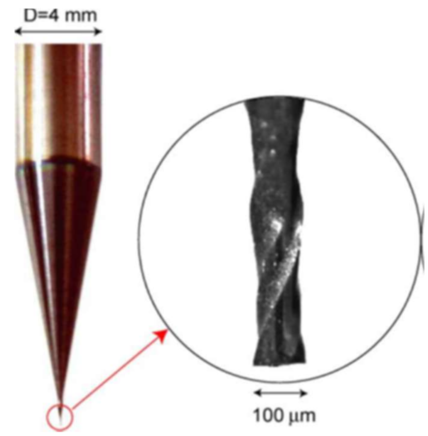


Figure 1. -Tungsten Carbide micro-end mill with 2 flutes [2].

Micro-milling of hard and brittle materials

Across industry applications, micro-machining of-, metals, ceramics, glasses, silicon-based materials, and polymers can be machined using a broad range of subtractive micro-machining processes [2, 8]. Among these materials, glass, and silicon are considered hard-to-machine due to their hard and brittle mechanical nature, making them prone to cracking and fracture under impact and cutting [3, 7]. Glass and silicon both a have comparatively low index of brittleness compared to other brittle and hard-to-machine materials such as ceramics [4]. These characteristics enhance their susceptibility to cracking [4]. The hard and brittle nature of glass is due to its amorphous structure. The formation of atoms in glass is randomised and they are arranged forming long chains. The subsequently formed planes prevent stress relief from occurring since the planes are unable to slip past one another [20]. Should stresses be high enough onsetting formation of cracks under loading, these will propagate causing brittle cleavage-based fracture or chipping. Such cracks and chipping can be seen in slot-milling of glass in *Figure 2* caused by tool deflection.

2.0_Ductile and brittle-mode machining

2.1_Mode of machining's effect on micro-component and crystalline structure process tailoring

Applications of micro components are performance critical, hence machining quality and surface finish are paramount to an optimised machining process [3]. To ensure good surface finish and damage-free machining of hard and brittle materials, material must be removed in the ductile regime or ductile-mode machining rather than brittle-mode machining to prevent surface damage and crack propagation to the workpiece [7]. Muhammad Arif et al. suggested that at a micro-scale, hard and brittle materials such

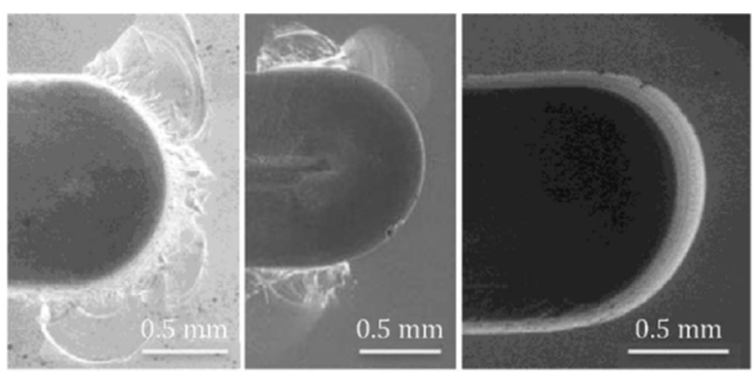


Figure 2. - Example of chipping caused by the tool end deflection (⌀ = 0.8 mm) during exit from the slot at its end (left), after moving the tool backwards (center), with spindle off (right) [4].

as silicon-based materials and ceramics can be machined in ductile-mode machining instead of brittle-mode machining with the use of high-pressure phase transformation mechanism [6]. As a result of industry advances in micro-milling and associated improvements in surface quality, post-processing machining is often not required and can ideally be eradicated. Finishing processes which are commonly used in machining to remove blemishes and burrs, include polishing and grinding, and ensure a machined component is at the designed tolerance as the resolution and accuracy of these processes is very high [7]. The ability of micro-milling to replace slow, abrasive processes such as those stated, is only true for ductile-mode machining [20, 23], as brittle-mode machining causes and propagates cracks resulting in poor surface finish and potential for part failure [3]. However, in some cases as discovered by Hiroaki Tanaka et al. that in the machining of c-SiC with an amorphous layer (silicon carbide (monocrystalline)) under brittle-mode machining, the sub-surface damage didn't extend into c-SiC at the interface between the amorphous layer and the crystalline base material as shown in *Figure 3* . This paper proposed that the modification of surface into an amorphous layer enabled damage-free machining of c-SiC. In the case of the machining of c-SiC it was found that the cutting depth played a critical role in maintaining this damage-free machining [22].

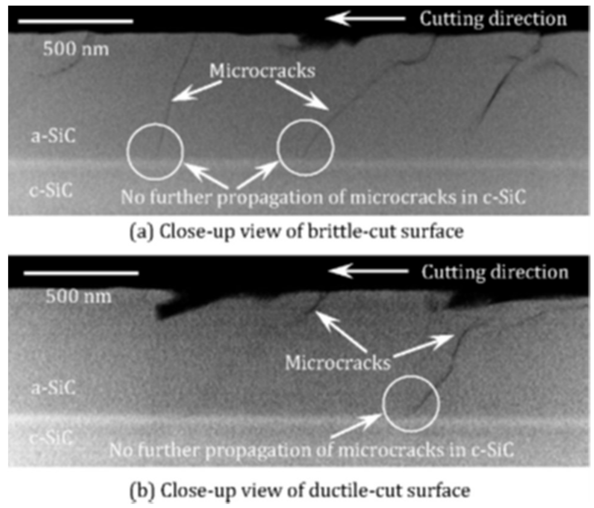


Figure 3. - TEM images of subsurface damage under (a) brittle-mode machining and (b) ductile-mode machining of c-SiC [26].

Cutting parameters in ductile/brittle mode machining

Cutting parameters often play a key role in maintaining ductile-mode machining, as ductile-mode machining relies on the tool's cutting edge initiating the formation of a chip by plastic deformation instead of crack propagation [6]. Understanding of chip formation and its manipulation through parameter adjustment is vital for an operator to adapt brittle-mode into ductile-mode machining to improve micro-component quality [3, 4].

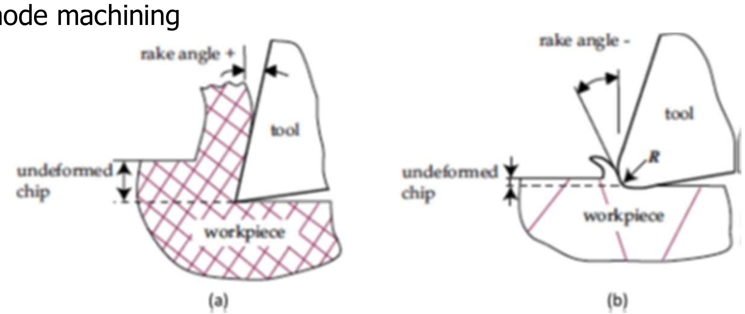


Figure 4. The concept of undeformed chip thickness and effective rake angle in machining process. (a) Macro-cutting process, t > r, (b) micro-cutting process, t < r [3].

2.1.2_Effect of Depth of Cut, Feed Rate, and no. of teeth on Ductile-Mode Machining

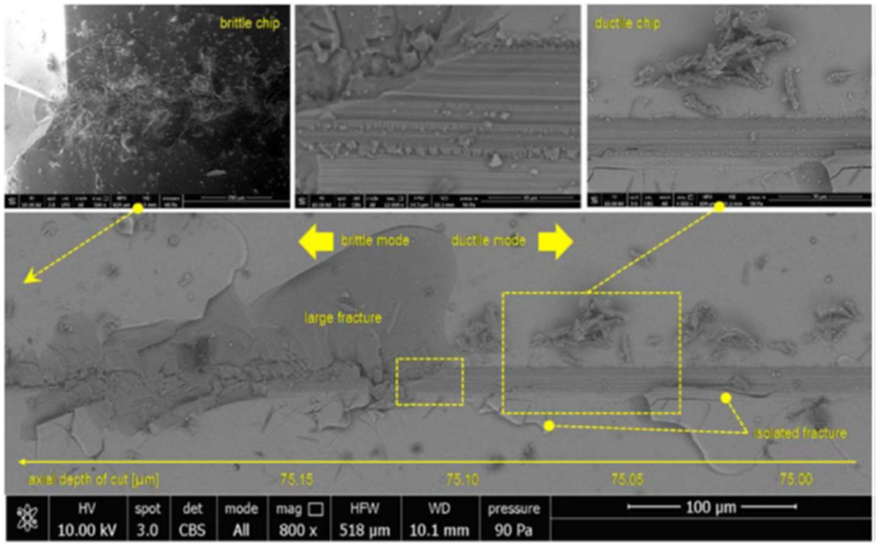


Figure 6. -SEM micrograph displaying the ductile to brittle transition of glass by shaping using a single tool on a straight trajectory at increasing axial depth of cut (right to left) [4].

Depth of cut has been used as a process-defining parameter in many experiments to display the effect of its manipulation on the workpiece. Muhammad Pervej Jahan et al. discussed how the range of transition between ductile-mode and brittle-mode machining depended on the critical depth of cut [3]. In the paper, articles were explored suggesting that, provided a 'sufficiently' small cutting-edge radius, maintenance of ductile regime machining can be carried out if the undeformed chip thickness is less than the cutting-edge radius]. In the transition between brittle-mode and ductile-mode machining, the load subjected on a material that initiates crack propagation is called the critical load, and the depth at which this critical load is subjected is called the critical indentation depth, and these concepts are critical to controlling the loading of brittle materials in machining in the brittle-ductile transition process [8]. Chip thickness ratio, r, is a useful parameter to consider as it defines the mode of cut:

$$r = \frac{t_0}{t_c},$$

Where: t_0-undeformed chip thickness, and t_c-chip thickness [32]. Rusnaldy et al. conducted experiments in which the axial depth-of-cut was varied whilst other machining parameters such as tool-edge radius were kept constant . The effects on surface finish in the micro-milling of silicon were analysed under the variance of axial depth-of-cut. The authors were able to find optimal cutting conditions enabling control of ductile-mode machining. It was discovered that the ratio of thrust to cutting force decreased as the axial depth of cut increased [5], and by refining the depth of cut to match this ratio to the best surface finish, optimal cutting conditions for this set-up were determined.

Cutting forces and tooling

Cutting forces

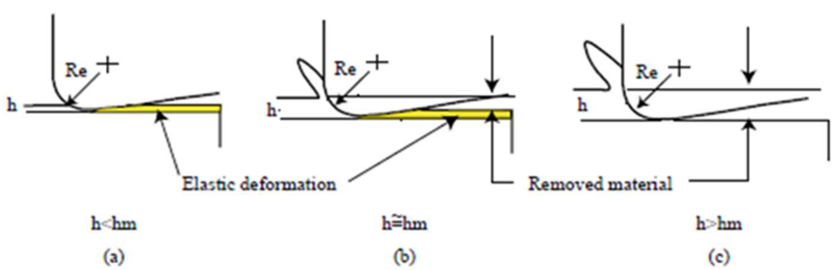


Figure 5. - Schematic of the effect of the minimum chip thickness (Re, radius of cutting tool; h, undeformed chip thickness; hm, minimum chip thickness [2].

The scaling-down from macro to micro-milling has changed the cutting mechanics drastically and hence the cutting forces imposed on tools and workpieces [2]. Cutting force is said to be directly related to chip formation, and its importance is paramount in ensuring the correct mode of machining [2]. The order of scale of micro-tools makes them susceptible to vibrations which cause deflection, as the process is discontinuous, with cutting teeth leaving and re-entering the workpiece during an operation [18], which if escalated may cause tool failure [1]. It is suggested that feed rate may be limited in machining due to bending stresses imposed on a tool as a result of tool deflection. Cutting forces may be categorised as either shearing forces, F_s, or ploughing forces [2]. Considering an orthogonal model of cutting, the following equations can relate different forces present in machining:

$F_S = F_c \cos\varphi - F_t \sin\varphi$, $F_n = F_c \sin\varphi + F_t \cos\varphi$; Then using: $F = R\sin\beta$, $N = R\cos\beta$ $(\tan\beta = \frac{F}{N})$:

$F = F_c \sin\alpha + F_t \cos\alpha$, $N = F_c \cos\alpha - F_t \sin\alpha$,

Where: F-frictional force, N-normal force to friction, β-friction angle, F_s-Shear force, F_n-normal force to shear, F_c-cutting force, F_t-thrust force, φ-shear angle, α-rake angle [32].

3.2_Tool wear

High rotational speeds of the cutter in contact with the workpiece mean the contact sites of cutting generate a lot of heat due to abrasion between tool and workpiece. Adhesion between tool and workpiece may also occur [3]. Adhesion refers to the build-up of workpiece material on the cutting tool, changing the cutter's dimensions and therefore its interaction with the workpiece and, shape of cut of the workpiece, ultimately causing flank wear on the cutting tool [1]. Both modes of wear have drastic effects on workpiece surface quality and surface roughness produced, especially under the rounding of the cutting edge [12].

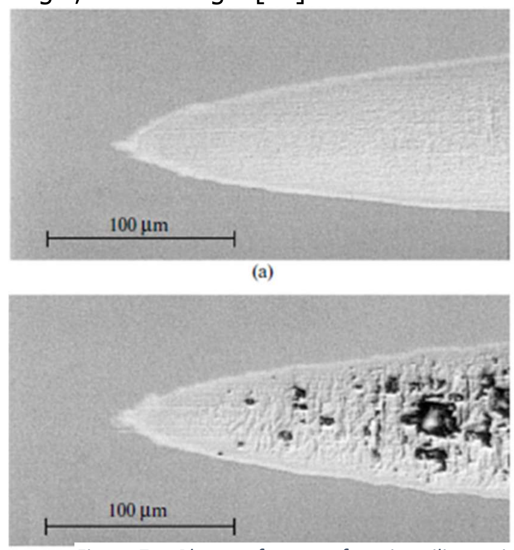


Figure 7. - Photos of traces of cutting silicon with a smooth increase of the depth of cut [99]: (a) cutting in the <100> direction of the crystallographic orientation, spallings are altogether absent; (b) cutting in the <110> direction (increasing silicon spallings are clearly seen with increasing length and depth of cut) [7].

4.0_TCM and its relationship with Industry 4.0 technology and methodologies

4.1_TCM systems

To aid the understanding and control of the unpredictability of tool life, machine monitoring may be implemented, and since tool condition is paramount to process optimisation, tool condition monitoring may be considered most beneficial to process optimisation [31]. The likes of vibration sensors, temperature sensors, acoustic emissions sensors and force sensors can be incorporated into micro-machining processes to allow for real-time monitoring [10, 19, 29]. Process optimisation can then be achieved via adjustments made based on knowledge gained from extracted data. However, such examples of TCM require the sensors to be very close to the workpiece which poses challenge due to the risk of debris damage and local noise interferences due to their sensitivity [1, 3]. Experimental and research-based work that implements TCM will often cut under dry cutting conditions without the use of lubricants or cutting fluids to prevent interference with the target data band-pass width, whether this is due to interference of noise, temperature, or vibration. All experiments conducted by Zhenyu Shi et al. were conducted under dry conditions when monitoring using an Acoustic Emission (AE) sensor.

4.2_TCM assisting and predictive software- Modelling, Industry 4.0, Digital Twins

Most TCM set-ups can be complemented by the integration of predictive modelling software and/or digital twins (DT) alongside already implemented hardware such as sensors, as performed by Yi Cai et al. where sensor data is used directly and fed to a DT to help improve real-time machining and, looking forward, it can be used as "one of the major building blocks for the development of a cyber-physic manufacturing."- [31, page 1032]. In some cases, it is possible to replace a hardware system, especially as we adopt Industry 4.0 methodologies [21, 24, 25]. Emiliano Traini et al. suggested that "Artificial intelligence enables manufacturers to reduce equipment downtime, spot production defects, improve the supply chain, and shorten design times by using machine learning technologies which learn from experiences" [20, page 177].

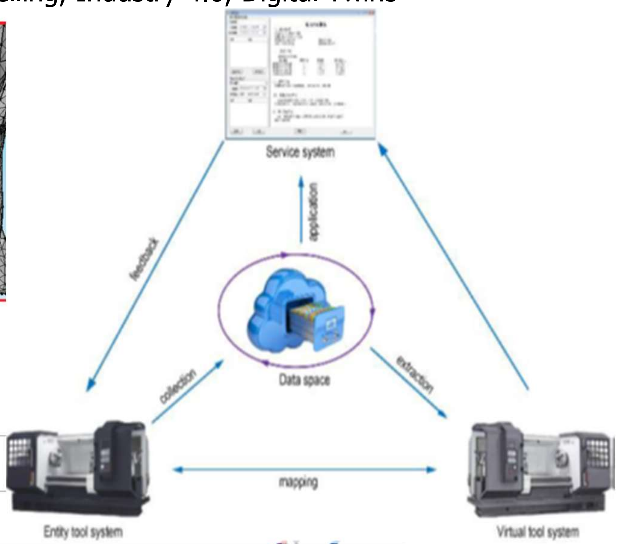
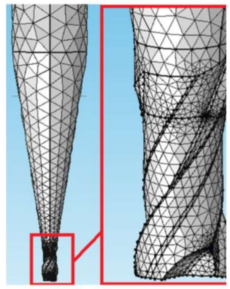


Figure 9. -Five-dimensional Digital Twin model of tool system [30].



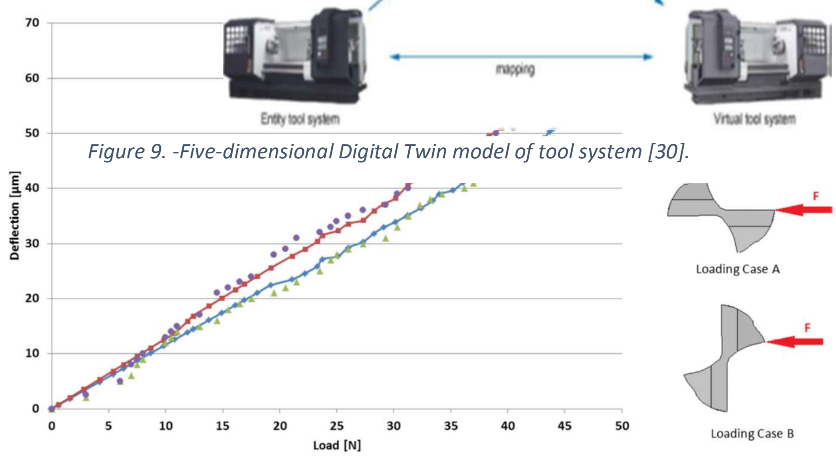


Figure 8. – a) Finite element model of an end mill and b) comparison between measured and simulated tool deflections [13].

Cutting dynamics can be modelled in CAD using finite-element software to aid the prediction of tool deflection under calculated or known cutting forces, therefore, helping select appropriate cutting conditions that will ensure optimum tool condition maintenance in a non-destructive manner, as was utilised in by Samad Nadimi Bavil Oliaei et al. *Figure 8* shows a modelled micro-tool and a comparison of its accuracy to that obtained in experimental work. The finite-element software was able to predict tool failure to a very high accuracy and its predictions agreed with experimental findings of failure point with a difference in length of broken micro-tool of only $\sim 14\mu m$ [12]. Some authors have also been able to model entire machining set-ups to gain an even better understanding of the process [22]. Such configurations will follow a form like that in *Figure 9* [26].

4.3_AE Signals and processing

AE sensors are piezoelectric transducers, and they are mounted to either the surface of the workpiece or as close to the workpiece as possible to receive the cleanest possible signal, and they measure transient elastic waves in a material [16]. These elastic stress waves are released due to rapid variation in strain energy in the material during machining. The strain energy is released in the material due to either plastic deformation or fracture [13]. The generated elastic waves or AE signals can be categorised as either burst or continuous signals [18]. Burst signals can be defined as those generated by tool chipping within the material and chip fracture and the wave characteristics have both high-amplitude and frequency [17]. Continuous signals are categorically generated by the three deformation zones: primary, secondary, and tertiary, and are associated with the elastic waves of both low frequency and amplitude. These propagated waves are in the frequency range of $\sim 20 - 2000kHz$ [27]. Since this frequency range is so broad it is necessary to narrow the band-pass width to within the target frequency range produced by solely tool and workpiece interaction to help eliminate unwanted noise interference, allowing for easier data interpretation [16]. The determination of appropriate High-pass and Low-pass filters is dependent on cutting parameters such as spindle speed and feed rate, and the magnitude of the time constant used in the Root Mean Square (RMS) calculation. This RMS calculation is normally done after the raw signal has been acquired and filtered [27]. The RMS provides the digitisation of the signal, so that there are fewer points to work with over large sampling intervals, hence aiding analysis [13]. The RMS signals are said to show a very strong correlation between signal generation in micro-scale machining and cutting conditions [30].

Experimental Work

5.1_Introduction/experimental aim

With the objective of supporting the current literature as surveyed above, experimental work has been conducted on the TCM of the micro-milling of glass and silicon. The work set out to monitor the real-time elastic stress waves generated by tool and workpiece interaction during micro-milling of glass and silicon via an acoustic emission sensor. Acoustic Emission signals can be generated because of many factors, but namely can be categorised by either plastic deformation or fracture [13]. Waves due to plastic deformation would be of lower amplitude of generated frequency than those generated by fracture [17]. An AE sensor also picks up elastic signals in machining, i.e., ploughing. Most AE signals due to cutting are generated due to the tool flank face’s contact with the micro-structural features of the workpiece [30].

The signal must first be extracted by an AE sensor. It is then converted into an RMS value/signal by the coupler. This converted RMS signal is then sampled by a fast Data Acquisition system (DAQ) and fed to a computer where a program processes the data and plots it for analysis.

5.2_Experimental set-up and method development

Prior to commencement of experimental work, the instruments had to be unified into one system. This included the programming of the LabVIEW software and real-time machining data display interface; the wiring configuration of sensor and coupler to one another; and finally, the cohesive integration of all instruments together for the entire TCM arrangement.

5.2.3_AE Sensor Validation

Validation of the sensor required exposure to frequencies high enough to surpass the Highpass filter of the coupler. It was set out to validate the sensor in a non-destructive manner, i.e., without performing a milling operation and wasting expensive material and tooling. DC motors and ultrasonic baths were used as the frequency source at first but were not able to generate high enough frequencies. A Piezo-Stack-Actuator was used with the capability of generating up to 1MHz. The AE sensor was placed in extremely close proximity to the piezo-stack, and the coupler RMS output cables wired directly to an oscilloscope. The frequency was moved through a range of amplitudes, 50kHz-80kHz. Voltage readings observed on the oscilloscope agreed with the frequency magnitude selected to be generated by the piezo-stack. This validation testing is conclusive of an AE sensor that can detect high frequency elastic waves to good accuracy, and, therefore, the sensor was ready for mounting to a workpiece to monitor frequencies generated by cutting.

LabVIEW and DAQ validation

Before real-time TCM could be carried out, the DAQ and LabVIEW cohesion also had to be validated. To do so, the coupler RMS output was un-wired from the DAQ Analogue input channels and grounding, and replaced by a variable power supply to act as the voltage feed to the DAQ to be processed by LabVIEW. Again, this permitted validation in a non-destructive, manner eliminating wastage of material and tooling. The voltage was varied by ~0-6V, and this was displayed in real-time on the LabVIEW interface. The generated plot agreed with the corresponding manner in which voltage was varied with minimal noise disturbance present as shown by *Figure 10*. Consequently, the software interface and DAQ could be deemed validated.

Set-up and Specifications

Experiments were carried out using a CNC Mini-Mill/GX from MINITECH with an NSK NR-3060S ceramic bearing spindle powered by a NSK EM-3060 350W brushless motor. The allowable motor speed which the spindle could reach was 5,000-60,000rpm with an accuracy within 1μ for the spindle. The milling-machine has an X-Y table resolution of 0.0001mm.

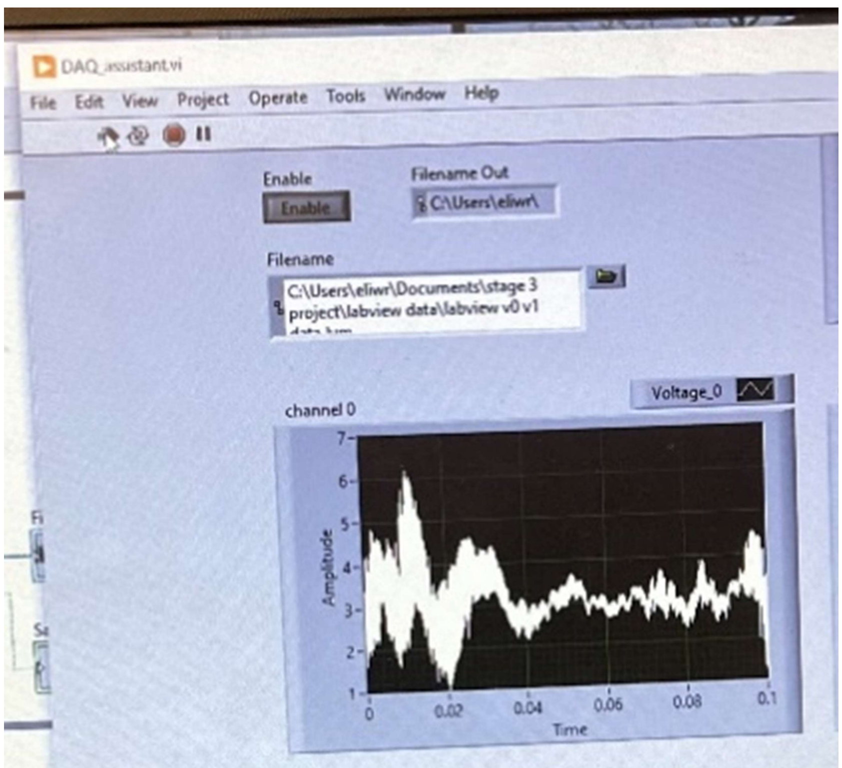


Figure 10. – Voltage against Time plot when DAQ wired to Variable power supply for DAQ and LabVIEW Validatioin.

The glass and silicon were waxed onto an aluminium plate which had clearance material either side of the brittle materials and M6 holes for fixing the workpiece to the mini-mill table. Dimensions of the silicon and glass were 16mm x 19mm x 0.8mm thick and 18mm x 25mm x 1mm thick respectively. The cutting tool used was a KYOCERA 1610-0394.118 0.5 diameter endmill (2 flute) made from solid carbide with a 30° Helix angle. The cutting was carried out under dry-cutting conditions with each cut lasting approximately 40s. The experimental set up and workpiece clamping is shown adjacent:

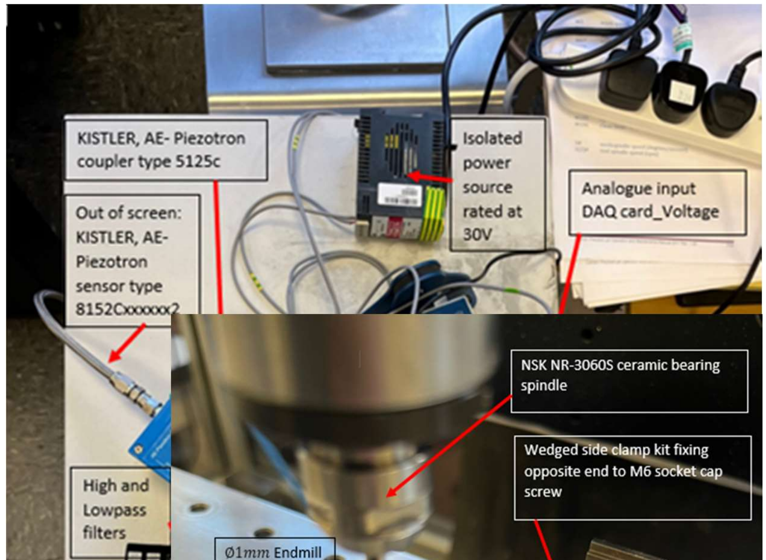


Figure 11. - TCM hardware configuration for the experimental work carried out in this paper

The cutting signals were measured using a KISTLER AE- Piezotron sensor type 8152Cxxxxxx2 and connected with the DAQ and computer as shown in *Figure 11*. The sensor was mounted onto the workpiece base plate and fixed to the machine table with an M6 socket cap screw. The sensor was wired into a coupler to convert the signal to a more workable RMS signal using a KISTLER AE- Piezotron coupler type 5125c powered by an isolated power source rated at 30V from which the coupler would only draw 24V. The coupler fed the RMS signal to DAQ for sampling using a Compact DAQ, NI (National Instruments) cDAQ-9184. The sampled data was connected to the computer via an ethernet cable then processed in the computer software to give a visual representation of real-time AE signal generation graphically, plotting voltage against time for the user to monitor, namely NI LabVIEW 2021. *Figure 12* shows the experimental set up on the CNC Mini-Mill.

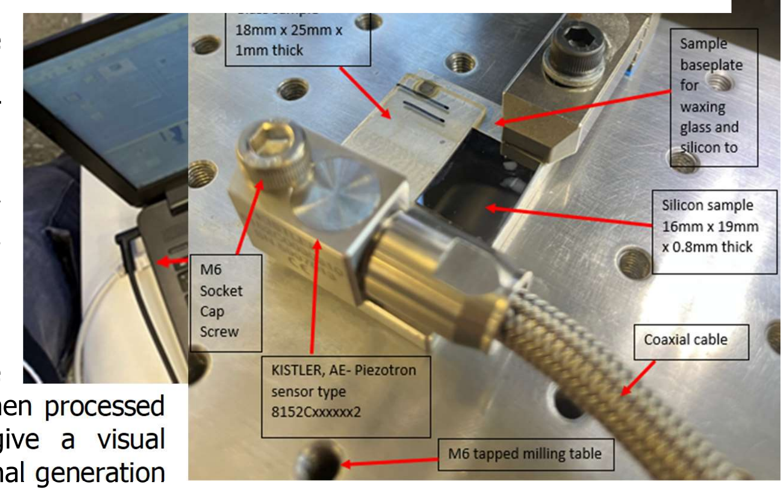


Figure 12. – Experimental setup for TCM machining mounted to Base plate of CNC Mini-Mill.

Table 1. Cutting parameters for cut 1 using $\emptyset 1mm$ endmill (2 flute)

Parameter	**Value**
S (rotational cutting speed), [rpm]	10,000
F_z (Feed per tooth), [μm]	0.05
V_c (cutting velocity), [m/min]	31
F (feed rate), [mm/min]	1

5.4_Results and Discussion

A trench was slot milled into the glass, with the tool lowered to cutting depth of $0.05\mu m$ adjacent to the workpiece and tool entry from the side. From tool entry to exit, the slot was milled for ~40s. The operation was monitored using the TCM system detailed above. Once the system was connected it was apparent background noise dominated the plot from channel Ai0 even with no frequency generation from the AE sensor at the instance where no machining was taking place. Despite interference, machining was carried out to assess impact of generated cutting signal on the signal

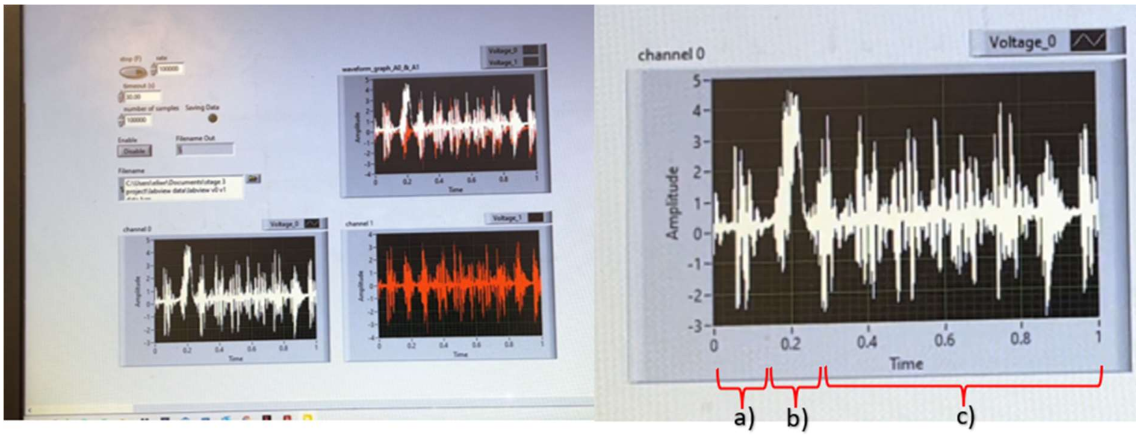


Figure 13. – Real-time machining data from LabVIEW interface demonstrating noise interference, whilst no High frequency signal is being fed to LabVIEW and channel 1 remains unconnected also with noise interference present.

plot. The first cut was carried out using the $\emptyset 1mm$ endmill at the cutting conditions stated in *Table 1*. The Bandpass width used was 50kHz-1MHz and the gain and time constant remained at factory settings of x10 and 1.2ms respectively. Once the tool was lowered to cutting depth and was adjacent to the workpiece the LabVIEW program was run in preparation for tool and workpiece contact. With no signal generation from cutting as shown by the average voltage reading of 0 in zone a) of ***Error! Reference source not found.,*** there is evident noise interference on the plot with both negative and positive components of signal, which in theory should not be visible as RMS signal should only generate positive values. At tool contact after 0.2s There is an evident spike in AE signal displayed on the Channel_0 plot in Zone b). This spike is instantaneous and of the order of milliseconds, as would be predicted for initial tool contact, and is in agreement with findings by I. Tansel et al. and K. Jemielniak et al. [13, 15]. After Zone b) the signal decreases rapidly and begins to stabilise to an average reading of about 1V. This timeframe in zone c) is representative of tool performing consistent slot milling and therefore, would not expect any drastic spikes in AE signal unless tool breakage occurred or cutting conditions were altered [13]. The plotted voltage reading read an average of around 1V up until the tool began to exit the workpiece. At this point average voltage graphed reading drops immediately to 0V as tool and workpiece contact diminishes. Prior to this immediate drop of voltage, it was expected to observe a varying signal on the plot due to tool vibrations as it exits the workpiece [15]. However, due to the background noise dominating the plot, it is difficult to distinguish between cutting signal and noise interference.

CONCLUSIONS

The literature collectively demonstrates how challenging the interfacing of micro-milling to the macro-domain has proved. Current technology, research and academia has facilitated the capability to produce and meet the demand for high-precision micro-components, with developments allowing machining of hard and brittle materials to reach standards adequate and paramount to highly bespoke applications in industry such as aerospace and pharmaceutical. The current state of this field of technology, micro-machining of hard and brittle materials, favours the importance of certain process quality-defining methodologies over others; namely ensuring micro-machining is carried out in the ductile-mode of machining is paramount to process optimisation. Since tool condition attributes greatly to the maintenance of ductile-mode machining, it is most beneficial to implement a TCM system to experimental, academic, or industry-based work as a mode of establishing the highest quality micro-component possible. Industry 4.0's gain in momentum has provided the opportunity for any TCM system to either be improved or replaced by the implementation of TCM modelling or digital twins. These non-destructive and predictive software developments have assisted the elimination of machining issues and aided the development of physical machining and TCM systems without said issues becoming apparent post-production.

5.6_Experimental and Literature-Based Recommendations

Following issues faced in the experimental work, there is a requirement for more literature and research into solely de-noising of micro-machining TCM set-ups. This would allow for a more accessible and easier to implement opportunity to incorporate TCM into machining systems from scratch. Later research should also further develop the integration of multiple sensors into a TCM configuration using data fusion algorithms, creating a more robust outlook on behaviour of tool and workpiece in real-time machining. An ideal TCM system would incorporate industry 4.0 methodologies, with modelling software or the use of digital twins alongside a conventional multi-sensor configuration, offering potential for removing issues faced during machining prior to their exposure.

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