

ULTRASONIC IMPACT GRINDING MACHINE TOOL AND PROCESS DEVELOPMENT



BY

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DECLARATION

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ABSTRACT

Ultrasonic Impact Grinding (UIG) is a mechanical material removal process used to erode holes and cavities in hard and brittle materials such as glass, ceramics, silicon carbide, quartz and titanium as examples by using shaped tools, high frequency mechanical motion and an abrasive slurry. An old but relatively unknown technique in the micromechanical systems community, the process is effective whether the workpiece material is conducting or not. The machined workpiece has little or no subsurface damage and does not suffer thermal damage. The process has numerous advantages such as the ability to machine high tolerance through holes, to carry out micromachining, and to carry out cutting at high aspect ratios. Ultrasonic impact grinding is often preferred over conventional machining approaches as it can machine intricate features in advanced materials with hardness values of greater than 40 Rockwell Hardness (HRC). The use of CNC control to generate motion profiles for ultrasonic impact grinding is emerging as a new area of interest. The objective of the work presented in this thesis was to design, develop and commission a bench-top computer numerically controlled (CNC) ultrasonic impact machine tool.

The development of the ultrasonic impact grinding machine tool was based on the adaption of a traditional 3 axes machining platform and the integration of a CNC control system. An ultrasonic system to include an ultrasonic generator and ultrasonic stack – converter, booster and sonotrode were integrated into the machine tool. An abrasive slurry delivery system and workpiece clamping system was also designed and developed in the project work. The developed ultrasonic impact grinding machine tool has been shown to successfully machine brittle materials and detailed process characterisation investigations were undertaken.

A number of process measurement systems have been integrated into the ultrasonic impact grinding machine tool and the process has been characterised and a process parameter window for successful machining operations have been identified. In-process measurements of process forces were undertaken and demonstrated significant insight into the ultrasonic impact grinding process, as well as insight into pre and post engagement conditions.

Investigations based around the machine feed levels, amplitudes of displacement of the vibrating tool, process force levels and machining distances has allowed detailed process analysis to be carried out. A machine vision based wear measurement system was integrated in order to have in-situ measurement of tool wear .It has been shown that a CNC ultrasonic impact grinding machine with the associated in- process force and toll wear

measurement systems provides significant insight into the ultrasonic impact grinding process. The platform developed within the research will provide a platform for future research in ultrasonic impact grinding.

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NOMENCLATURE

<u>Abbreviation</u>	<u>Description</u>	<u>Unit</u>
2D	Two-dimensional	-
3D	Three-dimensional	-
AC	Alternating current	-
AISI	American Iron and Steel Institute	-
Al ₂ O ₃	Aluminium oxide	-
ASTM	American Society for Testing and Materials	-
ATC	Automatic tool changer	-
B ₄ C	Boron carbide	-
CNC	Computer numerical control	-
Cr	Chrome	-
DC	Direct current	-
E	Youngs modulus	N/m ²
ECM	Electro-chemical machining	-
EDM	Electro-discharge machining	-
G and M codes	Operational codes used in CNC control	-
H	Hardness on Mohs scale	
H13	Grade of Tool steel	
HCS	High carbon steel	
HPSN	Hot pressed silicon nitride	-
HRC	Hardness measured on the Rockwell scale	-
HSS	High speed steel	-
IC	Integrated circuit	-
ID	Inside diameter	-
M/C	Machine	-
MEMS	Microelectromechanical systems	-

MRR	Material removal rate	
Ø	Diameter	m
OD	Outside diameter	m
PVC	Polyvinly chloride	-
PZT	Piezoelectric lead zirconate titanate crystals	-
Ra	Average surface roughness,	µm
R _{max}	Peak to peak surface roughness	µm
R _t	Peak to peak surface roughness	µm
Rz	Ten – point mean roughness	µm
SiC	Silicon Carbide	-
SS	Stainless steel	-
Ti	Titanium	-
TiO ₂	Titanium dioxide	-
TITAN15	ASTM Grade 2 Titanium	-
TITAN31	ASTM Grade 5 Titanium	-
TWR	Tool wear rate	-
UIG	Ultrasonic impact grinding	-
Vs	versus	-
WC	Tungsten carbide	
ZrO ₂	Zirconia	-

Chapter 1: Introduction to Micromachining

1.1 Introduction to Ultrasonic Impact Grinding

Ultrasonic Impact Grinding is an old but relatively unknown technique in the microelectromechanical systems community which can be used to fabricate small, even ornate patterns in brittle materials [1]. It is an abrasive machining process by which hard and brittle materials such as semiconductors, glass, quartz, ceramic, Silicon, germanium, ferrites can be machined whether conducting or not, and the workpiece experiences no thermal damage [1, 2].

1.2 History and Background of Ultrasonic Impact Grinding

The history of Ultrasonic Impact Grinding began with a paper by R.W. Wood and A.L. Loomis in 1927 [3] of the Loomis Laboratory, Tuxedo, New York and the first patent was granted to American engineer Lewis Balamuth in 1945 [4, 5]. Ultrasonic Impact Grinding has been variously termed ultrasonic drilling; ultrasonic abrasive machining; ultrasonic cutting; ultrasonic dimensional machining and slurry drilling. However, from early 1950s it was commonly known either as Ultrasonic Machining or Ultrasonic Impact Grinding. It was during the 1950s that Ultrasonic Impact Grinding was further developed for 2 and 3 dimensional machining of hard and brittle materials. The interest in the method increased during the 1980s, because of the more widespread use of advanced materials such as ceramics, optical glasses, semi-conductors and Titanium in industry.

As mentioned these recent developments in materials technology have given rise to high strength and very-hard materials that are difficult to machine using conventional chip-removal methods with hard tools. The need for machining these materials has led to the widespread use of several unconventional machining methods, one of which is Ultrasonic Impact Grinding or Ultrasonic Machining [6, 7]. The process is able to effectively machine all materials harder than 40 Rockwell hardness (HRC), whether or not the material is an electrical conductor or an insulator [8]. Today, it is becoming one of the most common methods, after grinding, for the machining of brittle materials [9].

1.3 Application of the Ultrasonic Impact Grinding Process

Ultrasonic impact grinding is a valuable method for the precision machining of hard, brittle materials because of many of its unique characteristics. The ultrasonic impact grinding process is non-thermal, non-chemical, and non-electrical and does not produce any changes in the metallurgical, chemical or physical properties of the material machined. This

characteristic distinguishes itself from electro-discharge machining (EDM), wire-EDM or electro-chemical machining (ECM), which are all suited only for machining electrically conductive materials and inevitably can cause thermal or chemical alterations in the subsurface characteristics of the machined material. As a consequence, ultrasonic impact grinding offers virtually stress free machined surfaces [10-12].

Ultrasonic Impact Grinding is widely used to drill holes or machine cavities in ceramic materials. Other applications include cutting of semiconductor materials and diamonds, machining of small diameter laser rods from blocks, manufacture and redressing of EDM electrodes, the machining of hard materials, e.g. Tungsten and Titanium Carbides and the machining of die and tool steels. It is also used to cut and engrave glass, hardened steel and sintered Carbides and although suited primarily for brittle materials, ultrasonic impact grinding has been used to prepare metallic foils and metal composites successfully [1, 13].

An overall improvement in the ultrasonic impact grinding process performance (i.e. higher machining rate and better surface quality) is the main goal of ultrasonic impact grinding manufacturers and users. During the 1990s the ultrasonic impact grinding process was applied to the machining of Titanium and its alloys. This proved successful and although the material removal rate achieved while machining with ultrasonic impact grinding was found to be lower than other non-traditional machining methods the surface quality generated by the ultrasonic impact grinding process is far better than both conventional and non-conventional processes. In most ultrasonic impact grinding practices, an average workpiece surface finish R_a value of $0.50\mu\text{m}$ can be obtained. With appropriate measures, a surface finish of $0.25\mu\text{m}$ R_a can also be achieved [11, 14, 15]. Holes as small as $76\mu\text{m}$ min diameter can be machined with the depth to diameter ratio limited to about 3:1 [16]. Nevertheless since its invention, ultrasonic impact grinding has developed into a process that is relied upon to solve some of the manufacturing community's toughest problems.

1.4 Project Objectives

The primary objective of the research was to design, develop and commission a bench top CNC Ultrasonic Impact Grinding machine tool. A particular focus was to explore the machining strategies for positional hole making including consideration of plunge and pecking strategies that can be enabled with CNC control.

The objectives of the project include:

- Adaptation of a 3 axes Cartesian bench-top CNC machine tool for the purpose of Ultrasonic Impact Grinding, integration of a sonotrode, CNC motion control, slurry delivery, workpiece clamping and in-process measurement of forces.
- Characterisation of the Ultrasonic Impact Grinding process on brittle materials such as glass in position hole making using plunge and pecking strategies.
- Quantification and analysis of tool wear issues in UIG of brittle materials such as glass.

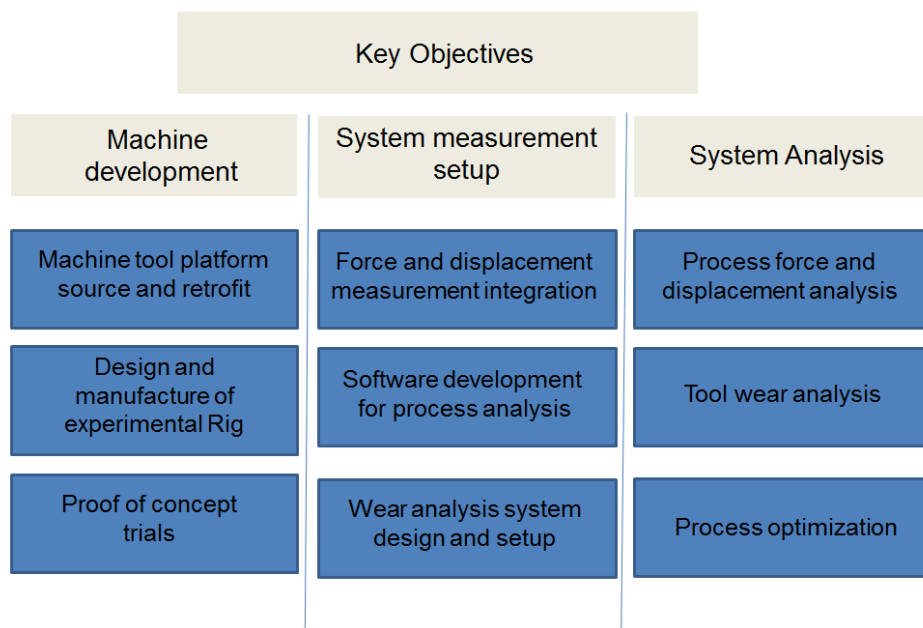


Figure 1-1: Project overview

Chapter 2: Literature Review

2.1 The Ultrasonic Impact Grinding process

The ultrasonic impact grinding process begins with the conversion of low frequency electrical energy to a high-frequency electrical signal. The high frequency electrical energy is then fed to a transducer. The transducer is typically Magnetostrictive (Figure 2-1) or Piezoelectric (Figure 2-2) and converts the high frequency electrical energy into mechanical vibrations.

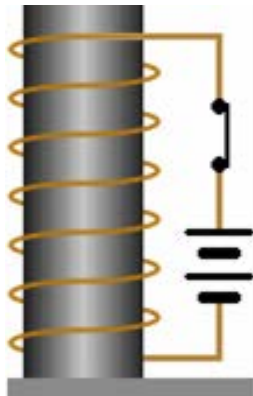


Figure 2-1: Magnetostrictive actuator [17]

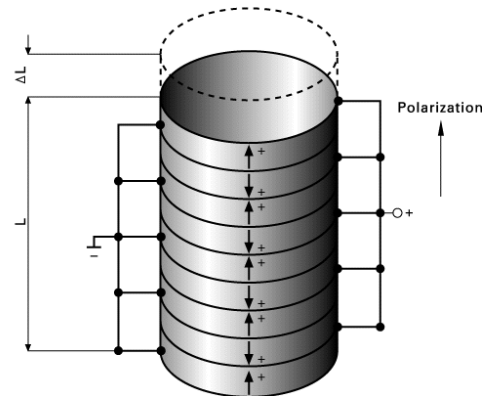


Figure 2-2: Piezoelectric stack [18]

These mechanical vibrations are in turn transmitted through a booster to an energy focussing device known as the horn or sonotrode on which the form tool is attached. This causes the tool to vibrate along its longitudinal axis at high frequency; usually 20 kHz with amplitude of 5 -50 μm [19, 20]. Typical power ratings from 50-3000 W and can reach 4 kW in some machines.

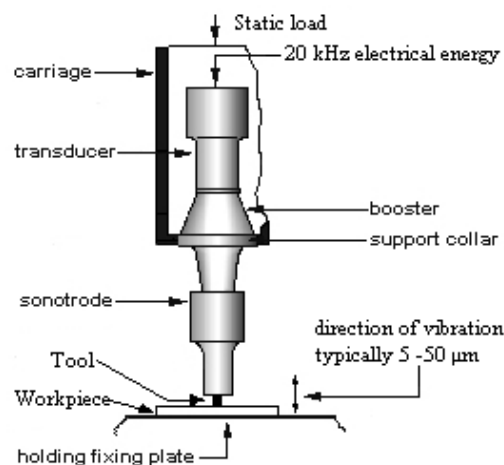


Figure 2-3: Ultrasonic stack assembly [21]

The workpiece is mounted on a table and an appropriate static load is applied [22]. An abrasive slurry comprising a mixture of abrasive material e.g. Silicon Carbide, Boron Carbide or Aluminium Oxide suspended in water or oil is continuously pumped across the gap between the tool and the workpiece [19]. The vibration of the tool causes the abrasive particles held in the slurry between tool and the work piece to impact the workpiece surface causing material removal by micro-chipping. The work material is not stressed, distorted or heated in any way because the grinding force is seldom over 10 Newtons and there is never any tool to work contact [23].

As material is removed a cavity is formed in the workpiece which has the inverse profile of the form tool. During the machining operation the sharpness of the abrasive particles is progressively eroded requiring a fresh supply of abrasive slurry which is fed regularly into the machining zone and at the same time the machined chips of the workpiece are flushed out of the machining zone [7]. The presence of cool slurry makes this a cold cutting process. A schematic representation of the ultrasonic impact grinding set-up is shown in Figure 2-4 [24].

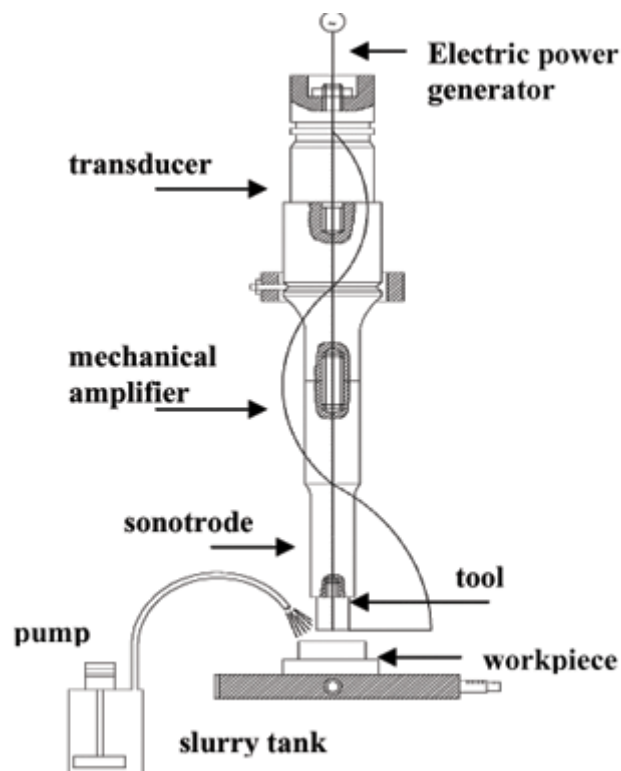


Figure 2-4: Schematic representation of the ultrasonic impact grinding apparatus [24]

For maximum amplitude of vibration at the tool and for maximum material removal rate, the resonance of the sonotrode and the tool need to be within the adjustable frequency range of the ultrasonic impact grinding machine. Resonance is attained when the transducer

generates a standing acoustic wave of one half wavelength along the tool-toolholder assembly with the antinode at the tool as shown in Figure 2-5 [7]. More specifically, in order for machining to be effective, the ultrasonic machine tool must provide for vibration of the tool at anti-nodal maximum amplitude and at a given frequency range of the ultrasonic impact grinding machine [25]. Another important aspect of the sonotrode/tool assembly is that it should provide a nodal point or a point of zero amplitude of vibration which facilitates the attachment of the whole unit to the machine base, minimizing the vibration energy loss to the machine base. Usually this will be achieved by designing both the transducer and the remainder of the sections to have the same natural frequency. Thus by tuning the ultrasonic unit to produce an electrical signal with the same natural frequency, the maximum vibration results in resonance at the tool tip [1].

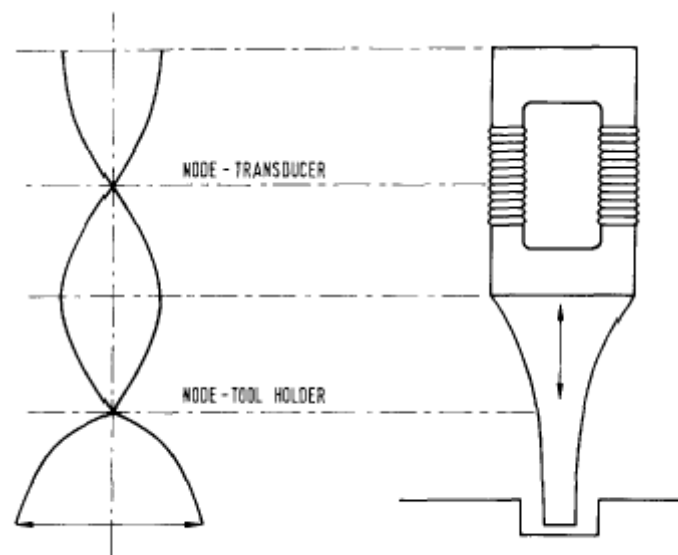


Fig. 2. Nodal and maximum amplitude locations in USM.

Figure 2-5: Nodal and maximum amplitude locations in ultrasonic impact grinding [7]

2.1.1 Mechanisms of material removal

The main mechanisms responsible for the material removal in ultrasonic impact grinding have been characterised as follows [13, 26, 27];

- The direct hammering of the abrasive particles on the workpiece by the tool, resulting in material removal and particle crushing. As Figure 2-6(a) shows, only the largest particles take part in this material removal mechanism, either because they rest on the work and receive a blow from the tool face, or because they descend in contact with the tool face to hammer the work.

- Micro-chipping by free impact of particles which fly across the working gap and strike the work surface at random locations. This is possible when the abrasive particle sizes are smaller than the working gap, as in Figure 2-6(b).
- Erosion of the work surface due to cavitation effects of the abrasive slurry.

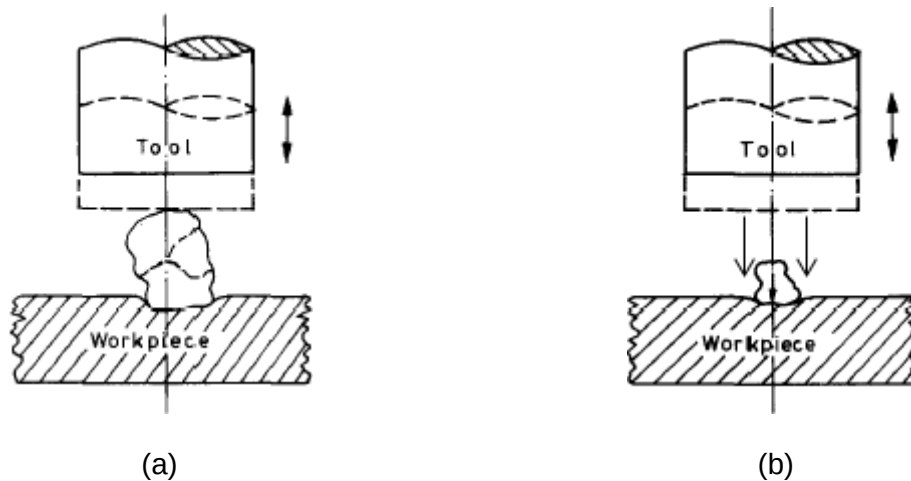


Figure 2-6: Material removal by (a) hammering and (b) impact [28]

It has been reported that among the above mentioned mechanisms, the first two are primarily responsible for major stock removal [27, 29]. The part played by erosion has been reported as insignificant for normal materials machined by this process. However in the machining of porous materials such as graphite, it has been observed that erosion by cavitation is a significant contributor to material removal [26]. The mechanisms involved in ultrasonic impact grinding are shown schematically in Figure 2-7.

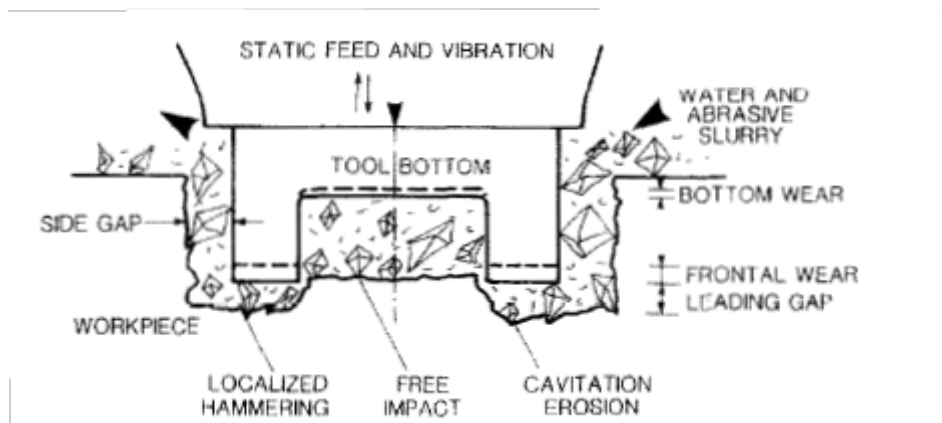


Figure 2-7: The 3 mechanisms of material removal in ultrasonic impact grinding [30]

2.2 Process capabilities

Ultrasonic impact grinding can be used to generate a wide range of intricate features in advanced materials. It is a mechanical material removal process that can be used for

machining both conductive and non-metallic materials with hardness's of greater than 40 HRC. All materials below this such as lead, copper, brass and hardened steels exhibit plastic deformation and do not suffer fracture from impulsive grain impact and their ultrasonic impact grinding rate is negligible. The best machining rates can be obtained on materials harder than 60 HRC. Ultrasonic impact grinding is used in the production of high-quality components for the semiconductor, MEMS, transportation, defence and aerospace, medical, and life sciences industries.

The ultrasonic impact grinding process can be used to machine precision micro-features, round and odd-shaped holes, blind cavities, and OD/ID features. Multiple features can be drilled simultaneously, often reducing the total machining time significantly Figure 2-8 [31].

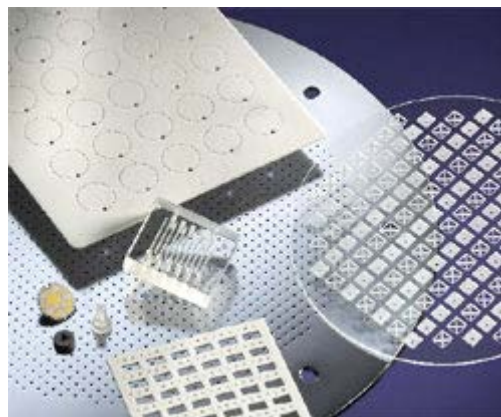


Figure 2-8: Square, round and odd-shaped thru-cuts in alumina [31]

Amongst the hard and brittle materials ultrasonic impact grinding is used to machine include ceramics, glass, sapphire, Silicon Carbide, quartz and fused silica, zirconia, industrial diamonds, ferrite, germanium, graphite, alumina nitride and Titanium. Figure 2-9 illustrates a variety of materials which can be machined using ultrasonic impact grinding [32].

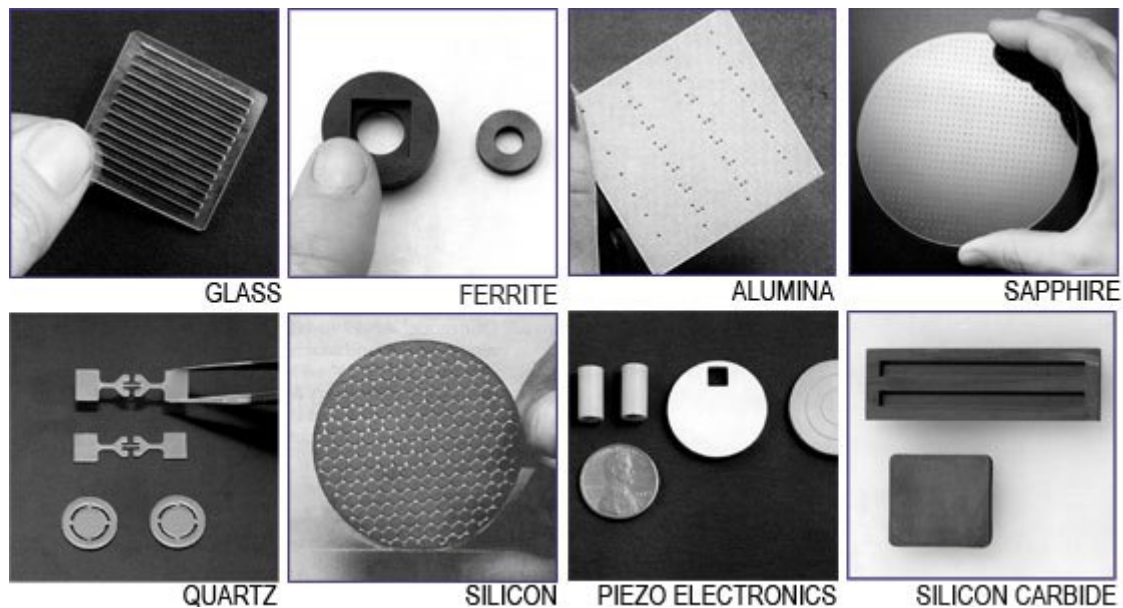


Figure 2-9: Common materials machined using ultrasonic impact grinding [32]

2.2.1 Process applications and benefits

Ultrasonic impact grinding offers a unique blend of capabilities, quality and material compatibility for the machining of engineered ceramics and advanced technical materials. The process is versatile, offering flexibility to meet a wide range of design requirements, and yields high-quality parts with little or no subsurface damage and no heat-affected zone. These benefits make it a valuable resource for the scientists, engineers and designers who are developing tomorrow's advanced technologies [31].

Applications for ultrasonic impact grinding include:

- Tight-tolerance round thru-holes for semiconductor processing equipment components.
- Micro-machined and micro-structured glass wafers for Micro-electromechanical systems (MEMS) applications.
- High-Aspect ratio thru-vias; 25:1 aspect ratios are possible in glass and advanced material.
- The drilling of IC (Integrated circuit) substrates where the through port created is used for pressure/vacuum transfer to a Silicon IC.
- The drilling of ceramic substrates for the incorporation of electronic circuit connector pins.
- Removing of broken tooling where EDM or lasers pose too great of a risk of damage to a high value part [33].
- Machining of both natural and synthetic quartz used in the manufacture of resonators used in pressure sensors and frequency control devices [34].

- Additional applications include machining of phased array radar components, cutting tool inserts, superconductors, wire draw dies and extrusion dies.

2.3 Workpiece materials

2.3.1 Ultrasonic impact grinding of ceramics

Properties such as high hardness, high thermal resistance, chemical stability, and good insulating aspects make engineering ceramics suitable for applications in many fields [10]. Currently there is a major effort to develop new and enhanced ceramics for components requiring higher accuracy, better surface finish, lower degrees of surface degradation and more complex geometry than ever before. The automobile industry, which already incorporates 30kg of ceramics in a car, is looking to ceramics to provide improved motion sensors and light-weight, high-strength and high-temperature components for engines [10]. In the conservation of energy and environment protection, ceramics seem to be a viable possibility in fuel cells, batteries, photovoltaic cells, and fibre optic transmission of energy [35, 36]. Advanced ceramics are playing an important role in improving aerospace engines, as aerospace manufacturers look for high-temperature materials that increase performance, improve fuel efficiency and satisfy safety standards, while lowering manufacturing costs [37]. Listed below are some common types of ceramics which are machined using the ultrasonic impact grinding process and some applications of their uses [37]:

- Aluminium Oxide (Al_2O_3) – Seal rings, medical prostheses, electrical insulators, ballistic armour.
- Silicon Carbide (SiC) – Ideal for processing chambers, gas distribution plates, edge rings, electrostatic chucks, heating elements and susceptors.
- Macor – Welding nozzles, Insulators and supports for vacuum Environment feed-throughs, sample holders for microscopes.
- Hot pressed Silicon Nitride (HPSN) – Fixed and moving turbine components, seals, bearings, pump vanes, ball valve parts.
- Titanium Dioxide (TiO_2) – Thread-guides
- Zirconia (ZrO_2) – Precision ball valve both balls and seats, pump seals, valves and impellers, medical prostheses, metrology components.



Figure 2-10: Ceramic components [37]

In contrast to metallic or polymer materials, the machinability of ceramics is very limited. Characteristic ceramic properties, such as high hardness, lack of ductility, and low resistance to thermal shock, often result in low material removal rate, relatively poor surface quality and subsurface damage, which may grow into a spontaneous fracture during machining [38].

Aluminium Oxide (Al_2O_3) is the most mature high technology ceramic. It is noted for its high hardness and wear resistance, its chemical resistance, and its smooth surface properties. Aluminium Oxide or Alumina is used extensively for the manufacture of medical components, sealing rings and electrical insulators. Alumina can be considered as the cheapest high-performance ceramic. However, machining of alumina and all ceramics by conventional manufacturing processes is extremely difficult and usually uneconomical [11, 39, 40].

The ultrasonic impact grinding process for advanced ceramics is preferred due to its ability to refine materials efficiently and inexpensively, its high reliability and productivity [41]. Ultrasonic impact grinding of ceramics has a number of important benefits in carrying out this process. As mentioned previously, ultrasonic impact grinding is non-thermal, non-chemical, and non-electrical, and does not produce any changes in the metallurgical, chemical, or physical properties of the material being machined [20, 42, 43]. Also, although the small ultrasonic impacts impart a shallow, compressive residual stress to the surface of the ceramic it has been reported that this residual stress actually promotes an increase in the high cycle fatigue strength of the work material after ultrasonic impact grinding [44, 45]. The process is commonly used for drilling holes, slots and irregular configurations in ceramics.

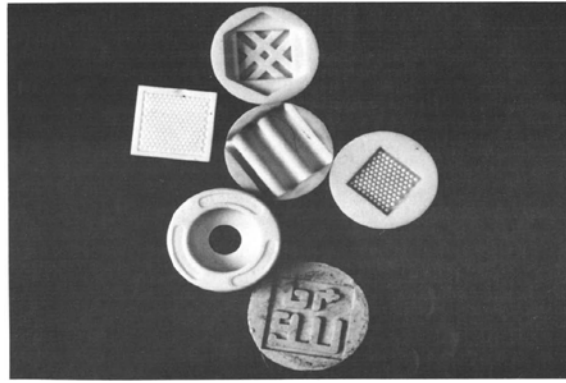


Figure 2-11: Ultrasonic techniques can be used to machine a wide variety of ceramic components [45]

In the ultrasonic impact grinding of ceramics, the abrasive particles within the slurry impact the ceramic surface at high frequency under the movement of the tool. The material removal by particle impact is thought to occur primarily by surface chipping when lateral cracks curve up and intersect the surface [38]. Other tests have shown that brittle materials such as ceramics are known to have subsurface flaws, such as voids, micro-cracks, and inclusions. Observations of the effect of the stress distribution pattern in the subsurface showed a distinct tendency of the stresses to migrate more rapidly toward the region of the void, thereby initiating premature material failure from this zone in the material [13].

Zirconia (ZrO_2) is another typical example of a hard and brittle ceramic material, while its fracture toughness is several times higher than that of alumina. As stated it is used in the manufacture of precision ball valves both balls and seats, pump seals, valves and impellers, medical prostheses and metrology components. Studies carried out by Hocheng et al [46] to investigate the machinability of zirconia ceramics using the ultrasonic impact grinding process conclude:

- That material removal rate tends to increase with amplitude of the tool, as illustrated in Figure 2-12.
- An intermediate static load yields the maximum removal rate.
- A larger static load is advantageous for a finer surface, while mid-range amplitudes should be adopted to avoid a rough surface.
- An increase in static load decreases tool wear. Larger amplitude results in larger tool wear.

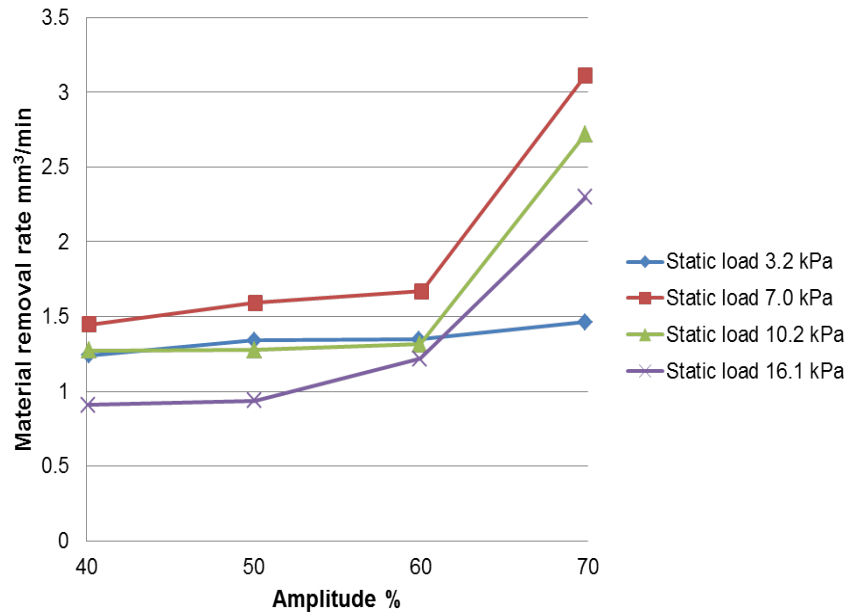


Figure 2-12: Influence of amplitude on material removal rate during the machining of Zirconia ceramics [46]

2.3.2 Ultrasonic impact grinding of Titanium

Titanium is a relatively lightweight metal whose density is approximately 60% of steel and 50% of nickel and copper alloys [47]. Commercially pure Titanium that is American Society for Testing and Materials - Grade 2 and Titanium alloy Ti-6%Al-4%V that is American Society for Testing and Materials - Grade 5 are considered the workhorses of the Titanium family. Most of the applications of commercially pure Titanium ASTM - Gr. 2 and Ti-6%Al-4%V ASTM - Gr. 5 are common and are summarised as follows [47]:

- Surgical implants i.e. biomedical implants and dental prosthesis
- Jet engines, airframe components, aircraft ducting, hydraulics, tubing, etc.
- Automotive components
- Consumer goods
- Hydrometallurgical extraction
- Chemical processing plants
- Marine applications

Titanium and its alloys are alternatives for many engineering applications due to their superior properties such as chemical inertness, high strength and stiffness at elevated temperatures, high specific strength, corrosion resistance, and oxidation resistance. However, these distinguishing properties of Titanium and its alloys also pose numerous

difficulties in their machining, and as a result, their widespread applications have been hindered by the high cost of machining with current technology [16, 48].

Ultrasonic impact grinding has recently been successfully applied for machining of Titanium and its alloys, but the material removal rate achieved while machining with ultrasonic impact grinding was found to be lower than other non-traditional machining method [20, 39]. However, the surface quality generated by the ultrasonic impact grinding process is far better than both conventional and non-conventional machining processes such as electro-discharge machining (EDM) or laser beam machining (LBM) [15, 47]. Electro-discharge machining has the inherent advantage of being able to machine work pieces of intricate shape, regardless of material strength or hardness but the electro-discharge machining process creates a recast layer with micro-pits and cracks, caused by rapid cooling giving both worse surface accuracy and shorter tool life than ultrasonic impact grinding. Laser beam machining being a thermal process produces thermal stress and a heat affected zone in the material. Also, laser beam machining usually result in holes with a funnel or pear-like shape: holes with straight profiles are difficult to obtain [49].

The machining characteristics for Titanium and its alloys with conventional machining processes are summarized below [50]:

- Titanium and its alloys are poor thermal conductors. As a result, the heat generated when machining Titanium cannot dissipate quickly and, as a result, most of the heat is concentrated on the cutting edge and tool face.
- During machining, Titanium alloys exhibit thermal plastic instability that leads to unique characteristics of chip formation. The shear strains in the chip are not uniform; rather, they are localized in a narrow band that forms serrated chips.
- The contact length between the chip and the tool is extremely short at less than one-third the contact length of steel with the same feed rate and depth of cut. This implies that the high cutting temperature and the high stress are simultaneously concentrated to within 0.5 mm of the cutting edge.
- Serrated chips create fluctuations in the cutting force. The vibrational force, together with the high temperature, exerts a micro-fatigue loading on the cutting tool, which is believed to be partially responsible for severe flank wear [51].
- The surface finish achieved by a single machining process (no finishing operations) is very poor.

Consequently, ultrasonic impact grinding can be suitable for machining of Titanium and its alloys due to following characteristics [49]:

- Titanium and its alloys have low thermal conductivity and in ultrasonic impact grinding there is a thinner zone affected by machining, generous quantity of cutting fluid is used resulting in better heat dissipation, efficient slurry flow can be maintained, depth of cut can be maintained due to rigidity of tool fixed in tool holder, and chemically active medium can be used to transfer heat efficiently and reduce cutting forces between the tool and workpiece.
- Titanium and its alloys have a tendency to react with cutting tools, which contributes to seizing, galling, abrasion, and pick up on cutting edges and faces and in ultrasonic impact grinding there is no tool work contact preventing all the above-mentioned side effects.
- Ultrasonic impact grinding is superior to hybrid processes in terms of simplicity, economic and provides a better control.

Research carried out has suggested that the optimum material removal rate in the ultrasonic impact grinding of Titanium can be achieved by using a tool material of high hardness such as cemented Carbide along with a high power rating of 400W using a coarse grit size of 220 mesh of hard abrasive such as Boron Carbide material [52]. Furthermore as ultrasonic impact grinding is a very random process, minor fluctuations in the process variables such as slurry concentration can cause significant alteration in the results; hence, it is very important to maintain the fixed parameters as constant with the highest possible accuracy.

2.3.3 Ultrasonic impact grinding of Graphite

Graphite is a very soft and brittle material. Its favourable attributes such as its ability to conduct electricity, its chemically inertness and its thermal conductivity qualities lead to its use as electrodes in electro-discharge machining. ultrasonic impact grinding is widely used in the manufacture and repair of graphite electrodes. During this process machining speeds vary according to the vibration amplitude, abrasive grain size and workpiece material. Typical ultrasonic impact grinding feeds in graphite range from 0.4 to 1.3 cm³ per minute. Surface finishes for the ultrasonic process range from 0.2 to 1.5 μm R_a. Accuracies of +/-10 microns are typical; tolerances of +/- 5 microns can be obtained for specialized applications. Low machining forces permit the manufacture of fragile electrodes. The electrode shown in Figure 2-13 has five ribs measuring 0.19, 0.31, 0.44, 0.57 and 0.70 mm which were formed ultrasonically to a depth of 9 mm demonstrating a width-to-depth ratio of approximately 47:1 [45].

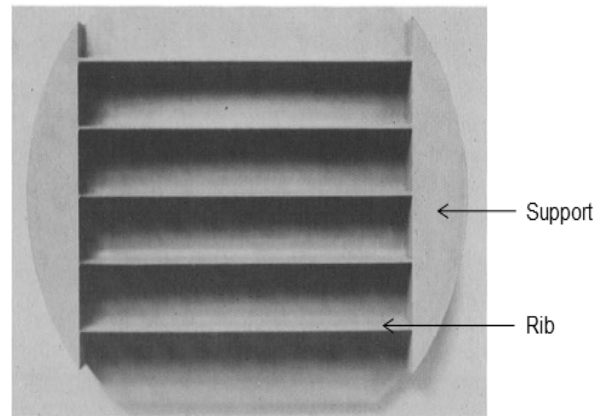


Figure 2-13: Graphite electrode formed using ultrasonic impact grinding [45]

Complex electrodes often comprise the most expensive part of an electro-discharge machining manufacturing system. The ultrasonic impact grinding process offers significant improvements in the manufacture of graphite electrodes over conventional techniques. Ultrasonic impact grinding of graphite electrodes have considerably reduced the time required to machine the same electrodes using the conventional milling process [53-55].

The main advantage of ultrasonically forming graphite electrodes lies in the ability to quickly and conveniently redress worn electrodes, restoring the original detail for re-machining. Additional benefits include graphite dust elimination, consistent accuracy of duplicate electrodes, the need for fewer electrodes and lower graphite costs. The problem with using tools of complex form, however, is that they are not subject to same machining rate over the whole of their working surface and experience differential wear rate, both of which affect the product shape. In addition, there are also greater problems in tuning a complex tool to achieve maximum performance compared to more basic tool [20]. The convenience of electrode forming and redressing makes electrode wear less important, permitting higher machining rates and less EDM time [45].

2.3.4 Ultrasonic impact grinding of glass and Silicon

Monocrystalline Silicon is a commonly used substrate material for the production of microelectronic components worldwide. The machining of this material is critical to high quality standards [56]. The need for fabricated glass has also been increasing to generate diversified functionalities on optical devices and bio-fluidics devices. In recent years, beside silicon, glass materials have important applications in micro-fluidics and micro-electromechanical systems (MEMS) as it can provide advantages such as optical transparency, good fluorescence properties, dielectric properties, good chemical resistance, high thermal stability and high mechanical strength [57]. However, most machining methods have difficulties in machining hard and brittle materials such as glass and Silicon. Ultrasonic

impact grinding is a unique method from this point of view because it easily machines these materials [58]. Research investigations carried out in the University of Cincinnati by Medis et al [1] into the ultrasonic impact grinding of glass and Silicon suggests that virtually any shape such as shallow or deep reservoirs and channels can be machined by this technique. The pattern dimensions are limited by one's ability to machine the master pattern in the metal for the tool head, and the size of the particles in the slurry [1].

The structure shown in Figure 2-14 is a ~2 mm deep 9.95 mm × 9.95 mm square cavity, machined into a wafer of borosilicate glass using a solid square tool giving a vertical wall. It has a stepped/tapered 1.33mm ID inlet/outlet hole at the centre, formed from the back surface. The average machining rate for this particular cavity was 25µm per minute. The left bottom insert shows a corner of the reservoir from a different angle.

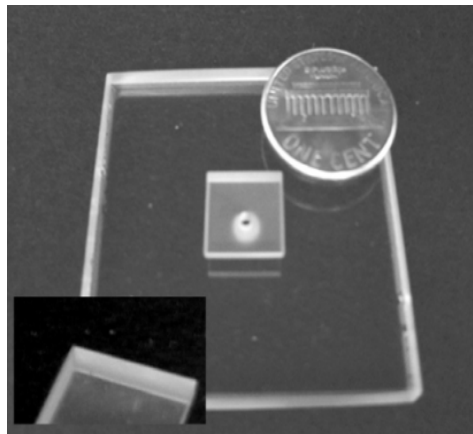


Figure 2-14: Ultrasonically machined borosilicate glass [1]

Side A of the machined part shown in Figure 2-15 illustrates half of a circular hole machined in Silicon using ultrasonic impact grinding while side B illustrates a similar hole machined using a diamond impregnated drill bit. Clearly the smoothness of the walls shows far less damage using ultrasonic impact grinding. The importance of the illustrations in Figure 2-14 and Figure 2-15 is that in as much as there is no anisotropic wet etchant available for glass to achieve a vertical wall, one otherwise must resort to using an expensive directed plasma or laser machining to achieve relatively straight and vertical walls in glass. While techniques such as photolithography and wet or dry etching derived from semi-conductor industry are also sometimes used to fabricate both glass and Silicon substrates they need special processes to be developed for each material in order to adapt to its chemical reactivity. Moreover, in the case of wet etching, the geometry of the crystalline workpiece may be limited by the anisotropy of the etching process vs. the crystallography of the materials. Such processes, once developed, may be interesting for mass production but not efficient for prototyping or small series [59]. In contrast to other anisotropic chemical etching schemes,

one can in this case form any type of channel with any depth or orientation without concern for the crystallographic orientation.

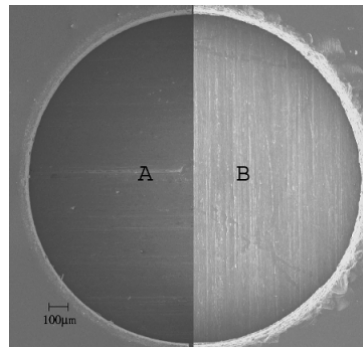


Figure 2-15: Comparison of Silicon machining modes [1]

An example of this is shown in Figure 2-16. The serpentine pattern shown was machined into (100) Silicon with vertical walls and flat bottom using ultrasonic impact grinding. Another advantage of this technique for micro-fluidics is, for example, that one can sequentially or simultaneously render a channel to connect to previously fabricated reservoirs very easily because no lithographic, high temperature or chemical processes are necessary [1].

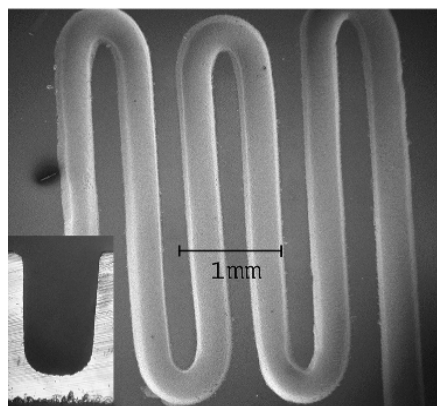


Figure 2-16: Machined serpentine channel in Silicon [1]

Figure 2-17 represents a $\varnothing 420 \mu\text{m}$ through-hole in a 5 mm thick Pyrex 7740 substrate machined with $15 \mu\text{m}$ abrasive grains. The granular aspect of the sidewalls is characteristic of material removal through the erosion of the workpiece due to abrasive grains. Nevertheless, the sidewalls of the hole are almost vertical on most of the height (conicity of about $10 \mu\text{m} / \text{mm}$) except close to the bottom where edges become rounded due to the inhomogeneous wear of the tool. The dimensions of abrasive particles influence the erosion rate and the quality of the surfaces and by using a variety of abrasive sizes, one should be able to achieve much smaller dimensions and dimensional control for the required profiles as well as the desired smoothness of the surface of the final product. It is clear that a higher quality surface finish results in a compromise with material removal rate [1, 60, 61].

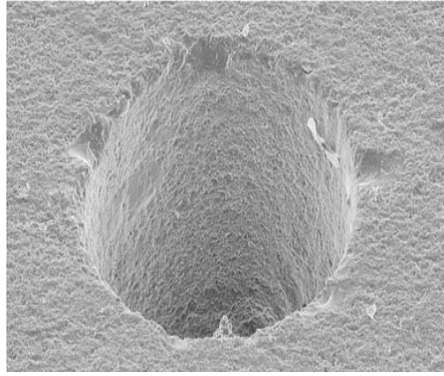
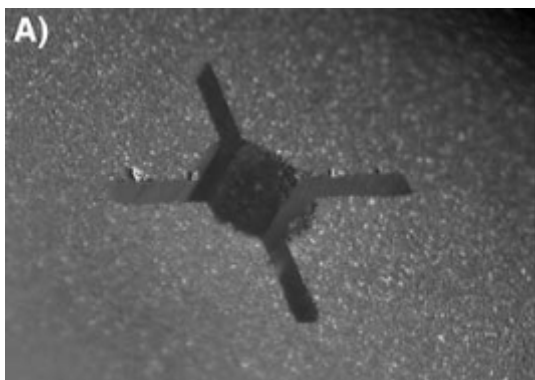
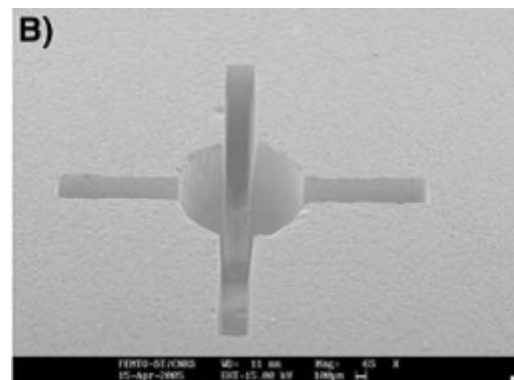


Figure 2-17: Ø420µm hole in 5mm thick Pyrex substrate [60]

As can be seen in Figure 2-18, using an abrasive with a diameter comprised between 3 and 5 µm, and applying a low static load, microstructures with much smoother sidewalls can be obtained. In this case the erosion rate is very low but the quality of the machining is improved [60].



(a)



(b)

Figure 2-18: (a) 3D optical picture and (b) SEM picture of channels formed into Pyrex 7740 glass by micro-ultrasonic impact grinding: depth 1,900 µm, width of the trench 300 µm, aspect ratio > 6, tool material steel, abrasive grain size 5 µm [60]

The coarser the abrasive grains, the higher the surface roughness and the higher the erosion rate. As can be seen from Figure 2-19 and Figure 2-20, a surface roughness of 1µm R_a can be achieved with a peak-to-peak value less than 7µm R_t which is comparable to values obtained with wet chemically etched surfaces [59].

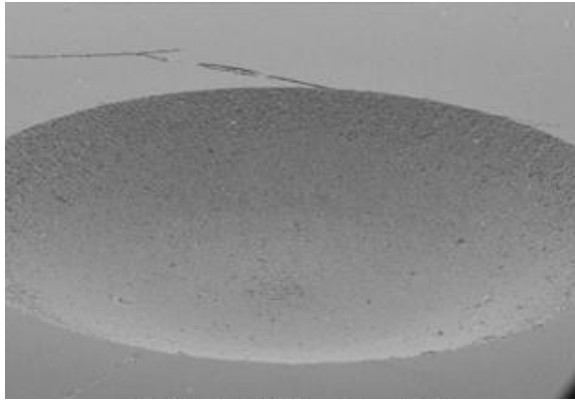


Figure 2-19: Semi-spherical structure machined in soda lime glass with a steel tool and 5 μ m abrasive grains

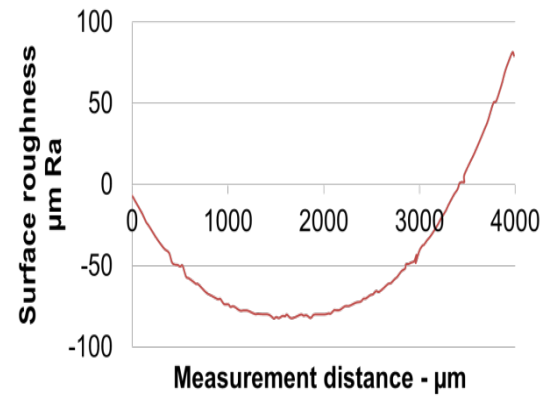


Figure 2-20: Roughness measurement at the bottom of the hemisphere

One issue arising with ultrasonic impact grinding is that the walls of the machined cavity tend to be slightly tapered instead of vertical as illustrated in in exaggerated form in Figure 2-21. The degree of the taper and the clearance will primarily depend on the size of the abrasive grit used.

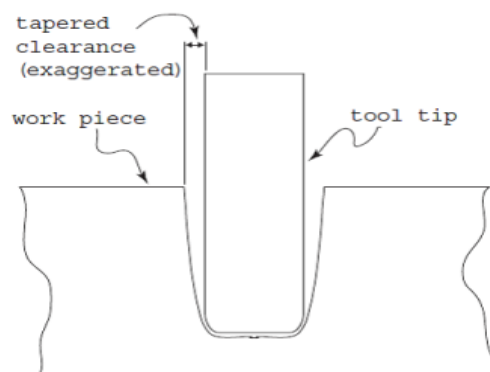


Figure 2-21: Cross-section of a typical machined hole [1]

As with the existence of the optimum material removal rate of the workpiece at a given static load, we need also to establish the optimum tool wear rate when machining both glass and Silicon. As will be seen later in Section 2.5.2 the flat at the bottom of a non-through hole is not so flat due to the inhomogeneous slurry distribution across the machining face, resulting in fewer active grits at the tool centre, inducing also in-homogeneity in the tool wear [20].

If the wear affects mainly the length of the tool, it is also possible that the abrasive grain modifies its shape introducing a certain amount of conicity in the hole specifically with holes of large aspect ratio. Fortunately with glass, conicity can be reduced down to become negligible, by the use of Carbide or stainless steel as the tool material [59, 62].

Measurements of tool wear as a function of static load were performed on Pyrex glass using a circular steel tool with a diameter of 6 mm. The realisation of 200- μm -deep non-through holes induces a wear of approximately:

- 1 μm /hole when using a static load of 6 N and 9 μm abrasive grains (mesh 600)
- 2 μm /hole when using a static load of 6 N and 17 μm abrasive grains (mesh 400)
- 0.3 μm /hole when using a static load of 3 N and 17 μm abrasive grains (mesh 400)

The lower the static load, the smaller is the wear, down to a value for which the erosion becomes negligible [59]. The dimension of abrasive grains, though less influential, also contributes to the wear, with an increase of erosion rate with bigger grain sizes. Figure 2-22 presents erosion rates for three different grain sizes [61].

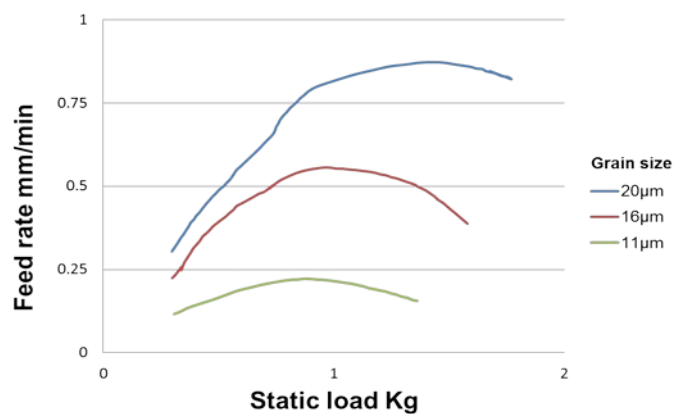


Figure 2-22: Machining of Glass: erosion rate as a function of static load – modified from [61]

2.4 Influence of process parameters

The parameters which influence the ultrasonic impact grinding process can be named as follows:

- Workpiece properties
- Tool material properties and geometry
- Abrasive slurry characteristics
- Machine related factors

2.4.1 Workpiece properties

In ultrasonic impact grinding, the properties of work material such as hardness, toughness, and impact strength play a significant role in the variation of machining characteristics (Material removal rate, tool wear rate, and surface roughness) [52].

It has been concluded that productivity by ultrasonic impact grinding in terms of machining rate is primarily determined by the brittleness of the work material [43, 63]. High plasticity of work materials leads to low productivity. The lower the impact hardness of a work material has been found to have an adverse effect on machining rate. However, while machining annealed steel, the machining rates observed have been found to be significantly better than steel which has been normalized or quenched [64]. Guzzo and Shinohara [24] outlined the ultrasonic abrasion of different hard and brittle materials using stationary ultrasonic impact grinding. Results show that the rate of material removal abruptly decreased for workpiece materials where the hardness of the workpiece is at the same order of magnitude as the hardness of the abrasive grit. Komaraiah and Reddy [22] also reported that the fracture toughness and hardness of the workpiece material play an important role with respect to material removal rate in ultrasonic impact grinding stating that as the fracture toughness and hardness increase, there is reduction in the material removal rate. Choi et al [65] reported on the chemically assisted machining of glass that it is the bonding forces of the Silica (Si) molecules on the surface of the glass which make the initial penetration of the glass difficult. After the tool penetrates the smooth hard surface of the glass, the machining forces decrease dramatically.

2.4.2 Tool material properties and geometry

The tool material used affects the material removal rate significantly. Tool materials should have high wear resistance, good elastic and fatigue strength properties, and have optimum values of toughness and hardness based upon the specific application [16].

According to studies carried out by Kumar and Khamba [52] in the ultrasonic impact grinding of Titanium the different tool materials used in ultrasonic impact grinding can be ranked in the order of increasing material removal rate as; Titanium alloy, high speed steel, Titanium, high Carbon steel, and cemented Carbide. The highest material removal rate has been recorded with cemented Carbide as the tool material. This can be attributed to its very high hardness (92 HRC) as compared to the other tool materials.

In ultrasonic impact grinding, the indentation of abrasive grains in the workpiece and the tool is inversely proportional to the hardness ratio of tool and workpiece materials. Hence, the use of a harder tool results in more indentation in the workpiece and therefore allows the material removal rate to be increased [22, 29, 66]. The use of tougher and more ductile tools such as Titanium or Titanium alloy tends to lower the material removal rate as it encourages the plastic deformation of the tool as well as work material. High carbon steel, being harder than high speed steel and Titanium, has also been found to perform better than these tools in terms of material removal rate. In fact, the difference in the performance of high Carbon

steel and cemented Carbide tools is marginal, the latter being on the higher side. It can also be concluded that the material removal rate increases with the increase in relative hardness of the tool-work combination, which has also been suggested by other previous research [43, 67].

It has been reported that the machining rate is directly proportional to the tool form [20, 43] and shape factor. A tool's shape factor is the ratio of tool perimeter to tool area. The tool form defines the resistance to slurry circulation: a tool of narrow rectangular cross-section yielding a better machining rate than one with a square cross-section of the same area [20, 39, 43]. The use of hollow tools has been reported to result in higher rates of material removal than tools of solid geometry for the same area of the cross-section [20].

Komaraiah and Reddy[67] investigated the influence of tool material properties, i.e., tool hardness on the material removal rate in ultrasonic impact grinding of glass. The different tool materials were arranged in the increasing order of superiority as mild steel < Titanium<stainless steel< silver steel< niomonic-80 A< thoriated Tungsten. Also, the material removal rate has been found to vary in a linear proportion to the hardness of the tool being used [29, 67].

2.4.3 Abrasive and slurry characteristics

The three main types of abrasive materials used in ultrasonic impact grinding are Silicon Carbide, Aluminium Oxide, and Boron Carbide. The type of abrasive used has been found significantly affect the material removal rate. Boron Carbide is favoured over Silicon Carbide and Aluminium Oxide as it results in faster erosion of work surface and thereby improving the material removal rate [52, 68, 69].

Various investigators [24, 29, 42, 63, 66, 68, 70] have reported results indicating that the material removal rate for a certain abrasive is a function of its concentration, grain size, and hardness as well as the feed system [52]. In general the hardness of abrasive should be more than the work piece [16].

The abrasive particle size strongly influences the material removal rate and surface finish [71]. On increasing the abrasive grit size or slurry concentration, an optimum value of material removal rate is reached but any further increase in either aspect, results in difficulty in the larger grains reaching the cutting zone [68, 70] leading to a subsequent decrease in material removal rate. The surface finish is governed by the abrasive particle size [16, 20, 39]. The analysis of various raw data indicates that it is the grit size and the slurry concentration which have the most effect on surface roughness over all other parameters. In

theory, smaller grains chip off smaller microscopic flakes, resulting in a smoother surface. As the particle size increases the material removal rate increases proportionally and surface finish is decreased [20, 39]. Surface finish also decreases with an increase in abrasive slurry concentration from 25% to 35% [47].

The material removal rate increases as slurry concentration increases from 25% to 30%, but decreases with further increase of concentration to 35%. As the concentration is increased further, several layers of abrasive are present in the working zone and the machining becomes less effective because more energy is expended in pulverizing the abrasive particles rather than removing material [10, 63, 70, 72].

The transport medium for the abrasive should possess low viscosity with a density approaching that of the abrasive, good wetting properties and, preferably, high thermal conductivity and specific heat for efficient cooling. Water is one of best option as regard to transport media for slurry [16]. It has been claimed that forced delivery of the slurry increases the output of ultrasonic impact grinding five-fold without the need to increase grit size or machine power [71, 73].

The temperature of slurry also affects the surface finish of the work piece obtained [35]. Figure 2-23 shows the photomicrographs of ultrasonically machined surface of Titanium at various slurry temperatures. The results shows that more uniform distribution of surface texture (non-directional) at low temperature 10°C, followed by high temperature 60°C and then at room temperature 27°C leading to better strength and improved mechanical properties.

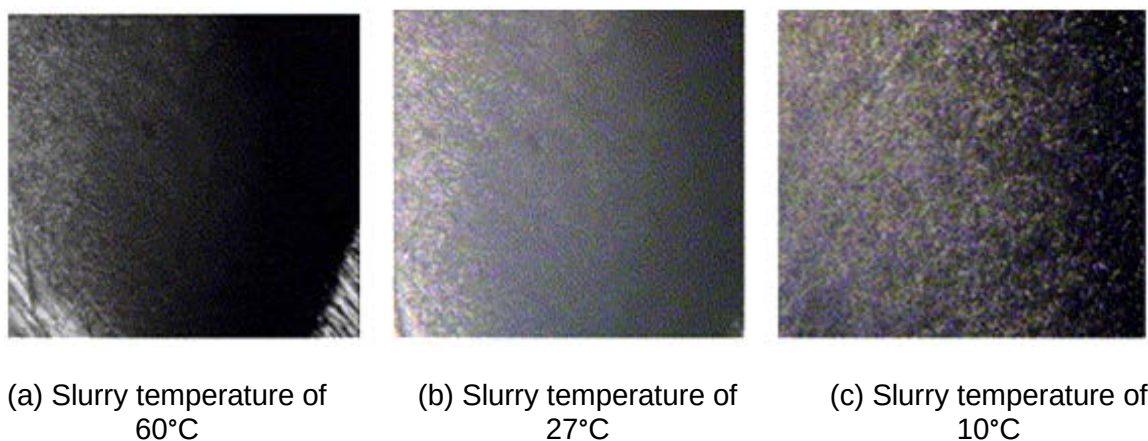


Figure 2-23: Photomicrographs of ultrasonically machined surface of Titanium at various slurry temperatures, power rating: 150W, magnification: 100× [16]

It is illustrated that at a better surface finish is attained at the low temperature of 10°C than at room temperature 27°C [16]. This can be explained by studies carried out involving

refrigerating the abrasive slurry. This has the effect of causing the embrittlement of the work material. In one study it was found that AISI 4140 steel could be ultrasonically machined 20% to 30% faster when the slurry was refrigerated to 0 °C. Another study carried out shows that by raising the abrasive slurry temperature to 50°C cavitation in the water is optimized and as high an increase as 70% in metal removal rate can be achieved [35].

2.4.4 Machine related factors

The power supply for an ultrasonic impact grinding machine is more accurately characterised as a high powered sine-wave generator that offers the user control over both the frequency and power of the generated signal. It converts low-frequency 50 Hz electrical power to a high-frequency signal of approximately 20 kHz which in turn is supplied to the transducer for conversion into mechanical motion [20, 39].

The power of this ultrasonic generator determines the mass of the tool–tool holder combination used in the ultrasonic impact grinding application. This means the more power available in a ultrasonic impact grinding machine, the larger the tool that can be supported [39]. An increase in power produces a substantial increase in the rate of machining as the momentum with which the abrasive particles strike the work surface increases uniformly with a corresponding increment in power. These particles with higher momentum and kinetic energy remove larger chunks of material from the work surface, promoting the increase in material removal rate [23, 52, 64]. Figure 2.24 shows the direct relationship between the ultrasonic power and the material removal rate of Ti15/Ti31 using alumina slurry of 320 grit size with a high speed steel tool [74].

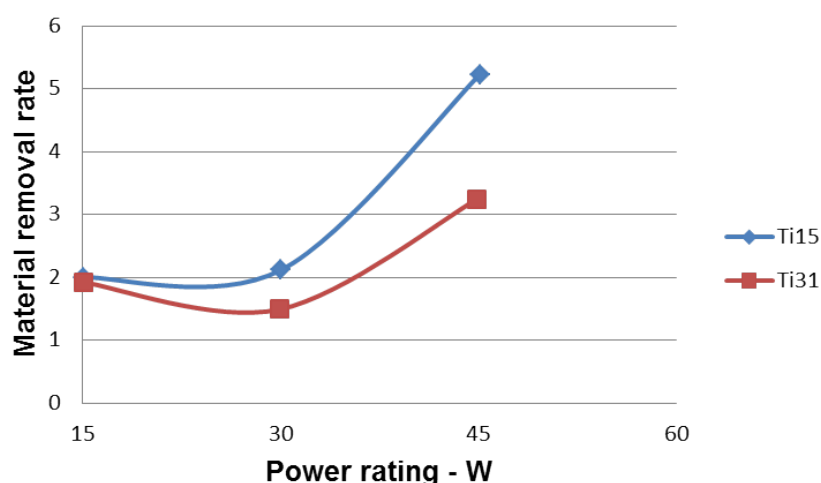


Figure 2-24: Effect of ultrasonic power on material removal rate on Ti15/Ti31 using alumina slurry of 320 grit size and high speed steel tool – modified from [74]

It has been reported that increasing the power of the ultrasonic machine increases the tool wear. Increasing the power increases the momentum at which the abrasive particles strike with the workpiece surface as well as the tool surface. The particles striking with more energy cause rapid fracturing of the tool surface thus promoting the tool wear rate [15].

While drilling large size holes, the machine power requirements can be reduced by trepanning the shape with a hollow tool rather than by using a solid tool [75]. With regard to the average response, the power rating factor has emerged as the most significant factor (42% contribution) followed by abrasive type (21.3%) and slurry grit size (17.2%). Tool material factor can be termed as the least significant for material removal rate (13.7%) [52].

The amplitude of vibration has been found to affect the machining performance of ultrasonic impact grinding [39]. Higher amplitude is obtained by using a tool with a larger transformation ratio, i.e., the ratio of transducer/tool diameter [20]. The amplitude of the tool motion affects the removal rate and determines the maximum size of the abrasive particles that can be used [20, 39]. Ideally the amplitude should be equal to the mean diameter of the abrasive grit used in order to optimize cutting rate [28, 45].

The optimum static load for maximum machining rate has been found to be dependent on the tool configuration (e.g. cross-sectional area and shape), the amplitude and mean grit size [16]. Excess static load can compact the grit and slow the penetration rate [44].

2.5 Process performance

The performance of the ultrasonic impact grinding process can be analysed and monitored by observing the following variables:

- Material Removal Rate
- Tool Wear Rate
- Accuracy
- Surface Finish

2.5.1 Material removal rate

The process performance in ultrasonic impact grinding can be established through the observation of the material removal rate. The material removal rate is influenced by a combination of various operational parameters. In order to identify the potential operational parameters affecting material removal rate in ultrasonic impact grinding, a cause-and-effect diagram is constructed in Figure 2-25 [52].

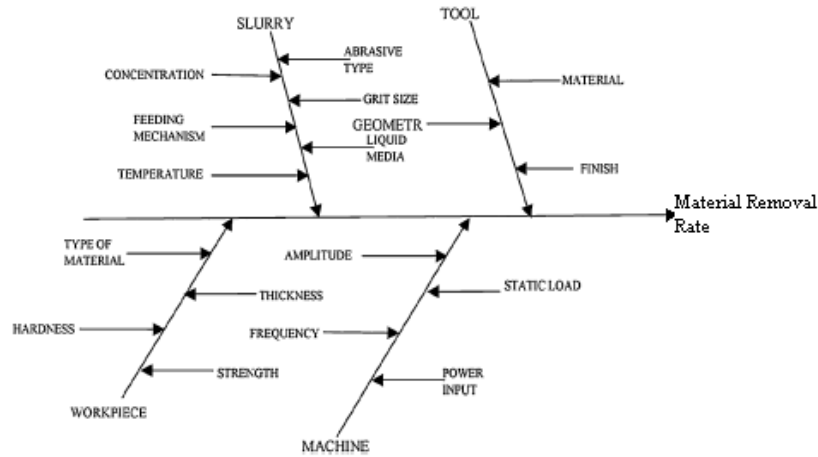


Figure 2-25: Effect of ultrasonic power on material removal rate on Ti15/Ti31 using alumina slurry of 320 grit size and high speed steel tool [74]

As the diagram indicates the material removal rate in ultrasonic impact grinding is dependent on four primary factors: workpiece, tool, slurry and machine related factors.

Singh and Khamba [8, 16, 48] studied the influence of the power input in the ultrasonic impact grinding of both pure Titanium (Ti15) and Titanium alloy (Ti31). In their investigations 3 power ratings of 150W, 300W and 450W were selected and using a grit slurry size 320. It was observed that although the material removal rate for Ti31 was lower than that of Ti15 the trend for variation of material removal rate was similar in both cases as shown in Figure 2-26.

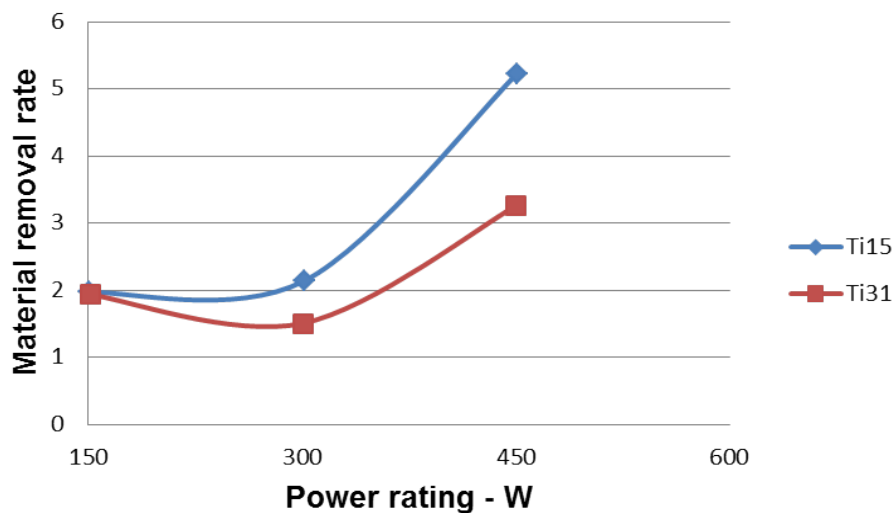


Figure 2-26: Material removal rate comparison of Ti15/Ti31 using alumina slurry of 320 grit size – modified from [8, 16]

The graph shows that there is an increase in the material removal rate when the power is increased from 300W to 450W. This illustrates that on increasing the power, the particles in

the slurry strike the workpiece with increased momentum and kinetic energy and hence eroding more material. The initial decrease in material removal rate from 150 to 300 is suspected to be caused by the initial work-hardening of the workpiece. The results conclude that the material removal rate is directly related to power capability of the ultrasonic impact grinding machine. Other researchers working in the field of ultrasonic impact grinding of Titanium and its alloys have agreed with this theory [69]. This is also accepted in the machining of other types of materials such as ceramics. T.C. Lee [76] states that any increase in the amount of work/energy imparted to the workpiece will result in an increase in the material removal rate. The findings also suggest that power primarily determines the mass of the tool–tool holder combination that can be utilized for an application and also determines the frontal-cutting area of the tool. These findings conform with Benedict [39] in that the more power available in a ultrasonic impact grinding machine, the larger the frontal-cutting area that can be supported [16].

Figure 2-27 illustrates how the material removal rate of a workpiece is influenced by a combination of operating parameters. By changing the grit size to 100 and using the same power ratings and workpiece materials as before it can be seen that the overall material removal rate is higher than that in the previous case. However, it can be seen that the material removal rate of Ti31 initially was relatively greater up to 300W. This may be because of a better tool work relationship and the relative strain-hardening of the tool and work-piece at particular slurry grit size and combination. After 300W because of the increase in power more work-hardening of Ti31 work-piece material was observed and this may be the reason for the change in pattern.

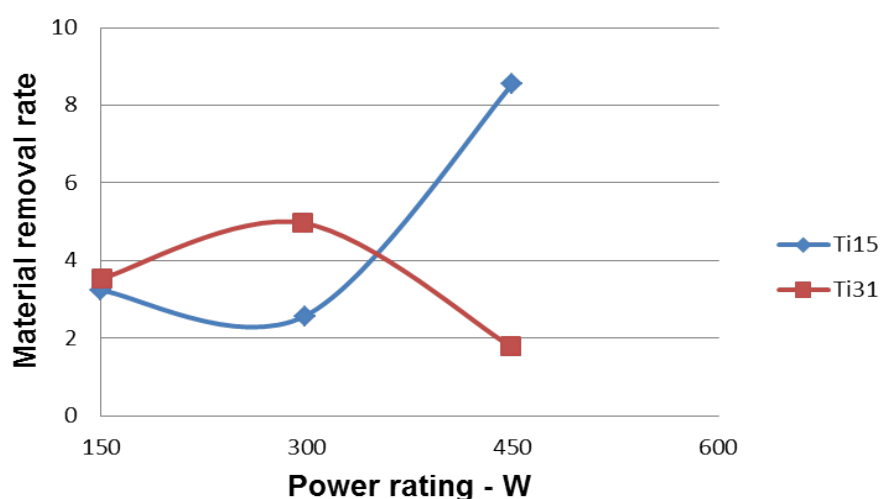


Figure 2-27: Material removal rate comparison of Ti15/Ti31 using alumina slurry of 100 grit size – modified from [8, 16].

Both the amplitude and static load are also major contributory factors to the material removal rate in ultrasonic impact grinding. In practice, any increase in the static load from zero, with other parameters held constant, yields an approximately linear relationship between material removal rate and static load [13, 73]. Komaraiah and Reddy [22] found in the ultrasonic impact grinding of materials such as glass, ferrite, porcelain, alumina and Tungsten Carbide that as the static load is increased, the material removal rate increases until it reaches a maximum and then reduces. The reduction is due to the crushing of the abrasive grains and other effects. In their investigations it is proposed that the optimum static load is 650g beyond which the material removal rate was found to fall. T.C. Lee [76] states that a heavy static load may not contribute to a greater material removal rate and that by increasing the static load the amplitude of the tool vibration decreases and the impact time lengthens. Moreover, the tool vibrates improperly when the static load is heavy and suggests the static load is set between 1 – 1.5kg. Other research suggests that amplitude of the tool motion affects the material removal rate and determines the maximum size of the abrasive particles that can be used [20, 39]. Ideally the amplitude should be equal to the mean diameter of the abrasive grit used in order to optimize cutting rate [28, 55, 77, 78].

Adithan [79] and Venkatesh [80] reported that tool wear is at maximum at a particular static load, which may be considered optimum for the point of view of maximum material removal rate. Aspinwall and Kasuga [81], and Kumar [69] agree with this assessment adding that the use of a coarser abrasive, high static load and a hollow tool with a high power rating would yield the optimum material removal rate and tool wear rate in the ultrasonic impact grinding of Titanium aluminide. The use of coarser abrasives to increase the material removal rate is in accordance with the findings of most investigators [40, 76, 82]. As reported earlier in Figure 2.6 Section 2.1 the two main material removal mechanisms in the ultrasonic impact grinding process are material removal by hammering and material removal by free impact of the abrasive particles. The primary mechanism is the hammering action of abrasive particles into the workpiece material. Decreasing the surface density of abrasive particles by increasing the grit size induces a greater augmentation of the effective stress due to each particle acting on the workpiece surface, thus increasing the material removal rate. The secondary mechanism is the impact of free abrasive particles which are accelerated by the vibrating tool over the work surface. In this case, an increase in grit size increases the weight. The impact force against the workpiece surface also increases. Thus, under both mechanisms, the effective load acting on the work surface increases with grit size, which in turn increases the effectiveness of micro-cracking thereby increasing the material removal rate. As shown in Figure 2-28, material removal rate drops rapidly with change in the grit mesh size from 220 to 320 and drops further from 320 to 500, but at a diminishing rate.

Coarser grains result in more energy input to workpiece per impact thereby, removing larger chunks of material. As the mean particle size of the abrasive grains come closer in size to the mean gap between the work and tool as well as the amplitude of vibration, it promotes efficient machining of workpiece [69].

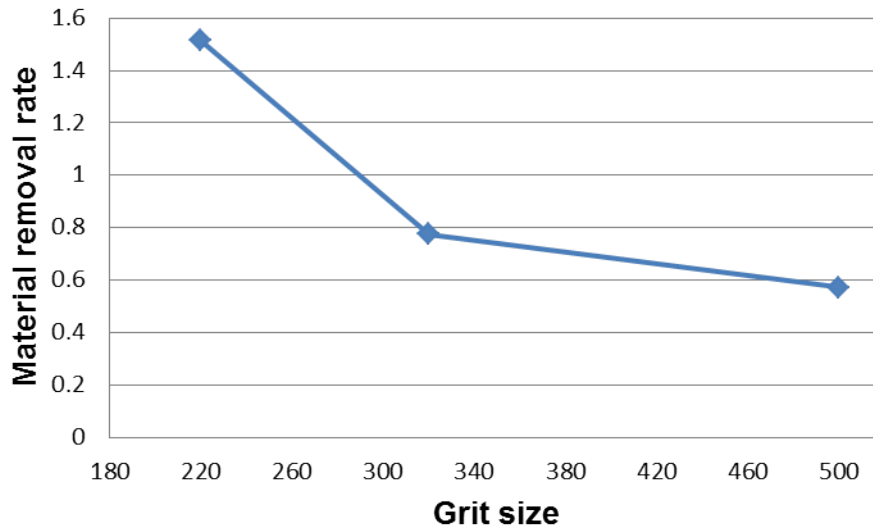


Figure 2-28: Effect of grit size on material removal rate – modified from [69]

Another variable which influences the material removal rate in the ultrasonic impact grinding process is tool wear. As a result of the tool wear, the tool length and weight decreases, which affect the resonance frequency of the machine and reduces the amplitude of vibration, resulting in the decrease of material removal rate. In the ultrasonic impact grinding process, the parameter settings that result in the maximum material removal rate also involve maximum tool wear rate. This is the inherent characteristic of the ultrasonic impact grinding process [19]. Tool wear is affected by work piece hardness and can also be affected by the toughness of work piece [15, 83]. During the successive impacts between the abrasive grains and the tool face, the tool material undergoes a large amount of plastic deformation resulting in appreciable work hardening of the tool face. Different tool materials have varying work hardening tendencies. If a material has a high tendency to work harden and has sufficient capacity to undergo plastic deformation before fracture takes place, its performance is expected to be better. If the hardness of the tool increases by work hardening, the penetration of the abrasive grains into the tool will decrease resulting in higher work piece material removal rate. In ultrasonic impact grinding, the indentation of abrasive grains in the workpiece and tool is inversely proportional to the hardness ratio of tool and workpiece materials. Hence, the use of a harder tool results in more indentation in the workpiece as compared to tool, increasing the material removal rate [67]. When the tool material hardness is high, the indentation of the grain into the tool will be small and, as a

result, the indentation of the grain into the workpiece will be large. This leads to the fracture of a larger volume of workpiece material and hence to a greater material removal rate as illustrated in Figure 2-29 [67, 84].

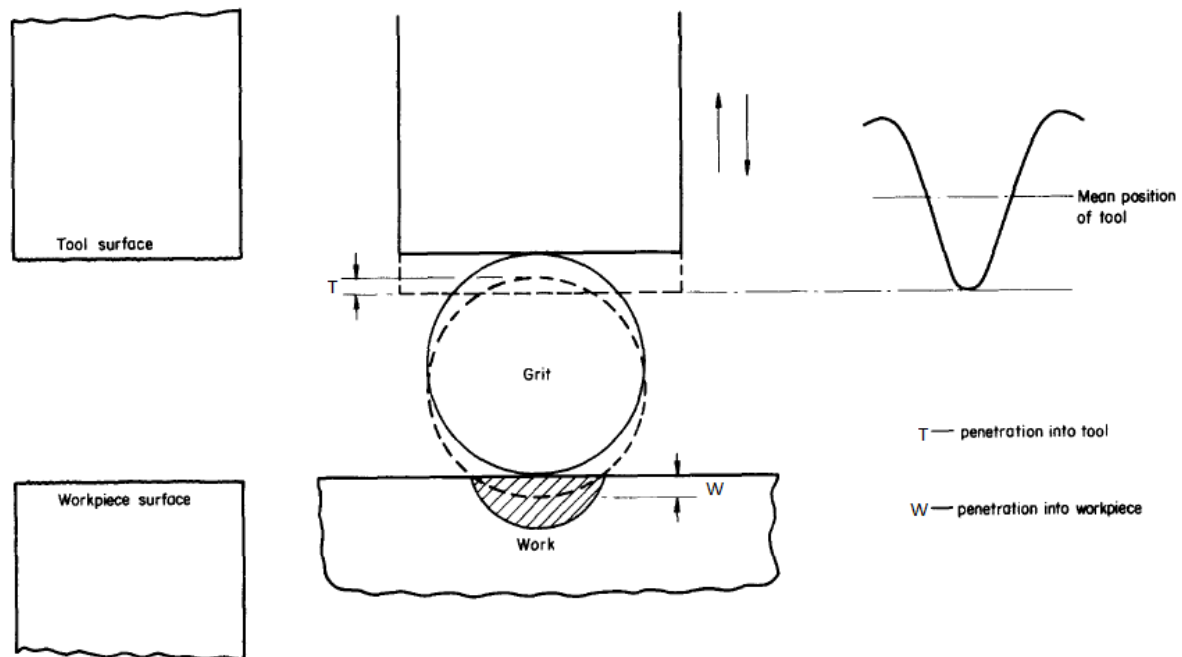


Figure 2-29: Schematic diagram of impact in ultrasonic impact grinding [67, 84]

Various investigators [24, 29, 42, 63, 66, 68, 70] have reported results indicating that the rate of material removal for a certain abrasive is a function of its concentration, grain size, and hardness besides the feed system. On increasing the abrasive grit size or slurry concentration, an optimum value of material removal rate is reached. Any further increase in either aspect results in difficulty in the larger grains reaching the cutting zone [3, 18] or a subsequent fall in material removal rate [68, 70]. The hardness of slurry material should be more than the work piece, in general larger abrasive grit sizes and higher slurry concentrations results in to higher material removal rate [16]. Guzzo and Shinohara [24] reported a substantial increase in material removal rate obtained while using abrasive of larger grain size on account of the increase in the stress caused by the impact of abrasive particle over the workpiece surface. Neppiras [42] and Markov [70] reported that when the grain size is comparable to the amplitude of vibration, the optimum level of material removal rate can be reached. Experimentally, the ratio of the double amplitude to the mean size of the principal fraction of abrasive is 0.6 to 0.8. Goetze [63] has reported the optimum value of slurry concentration to be close to 12% by volume for all the abrasive grit sizes used in the investigations into the ultrasonic impact grinding of tool steel. The optimum concentration is thought to be one providing a single layer of abrasive over the entire work surface [64]. Kazantsev & Rozenberg [71, 73] claim that forced delivery of the slurry increased the output

of ultrasonic impact grinding five-fold without the need to increase grit size or machine power.

A large amount of research has been carried out to identify the optimal parameters and the relationship between these parameters to optimise the material removal rate in the ultrasonic impact grinding process. Singh and Khamba [23, 48] developed a model for the material removal rate in the ultrasonic impact grinding of Titanium and its alloys. On the basis of this model, the relationship between the material removal rate and the controlling machining parameters were studied. This experimental study was conducted with the objective to understand the material removal rate and tool wear rate comparison of TITAN15 and TITAN31 when drilled ultrasonically. TITAN15 and TITAN31 were chosen for the study as they have different compositions and different toughnesses. For the study, three different types of slurries, namely Silicon Carbide (SiC), Boron Carbide (B_4C), and alumina (Al_2O_3) were used all of which were of 320 grit size. 3 different power ratings of 150W, 300W and 450 W were used during the experiment along with 3 different tool materials namely stainless steel (SS), Titanium (Ti) and high speed steel as the tool combinations using a fixed slurry concentration and temperature.

From repetitive number of experiments conducted under six different set-ups, the comparative results have been plotted. From Figure 2-30 it has been observed that the trend for material removal rate in all three experiments of the first set-up were similar. The increase of the material removal rate with an increase in power rating of the machine is quite obvious because with a higher value of power rating, the abrasive particles strike with more momentum and kinetic energy on work piece. Figure 2-31 illustrates that in the ultrasonic impact grinding of TITAN31 with the SS tool the trend for material removal rate was different from previous case of TITAN15 with SS tool. The main reason for this variation may be strain hardening of work piece/tool material at specific ultrasonic power rating based upon its material/chemical composition characteristics. The best parameter setting for machining of TITAN31 with the SS tool has been observed at 300W with Boron Carbide slurry.

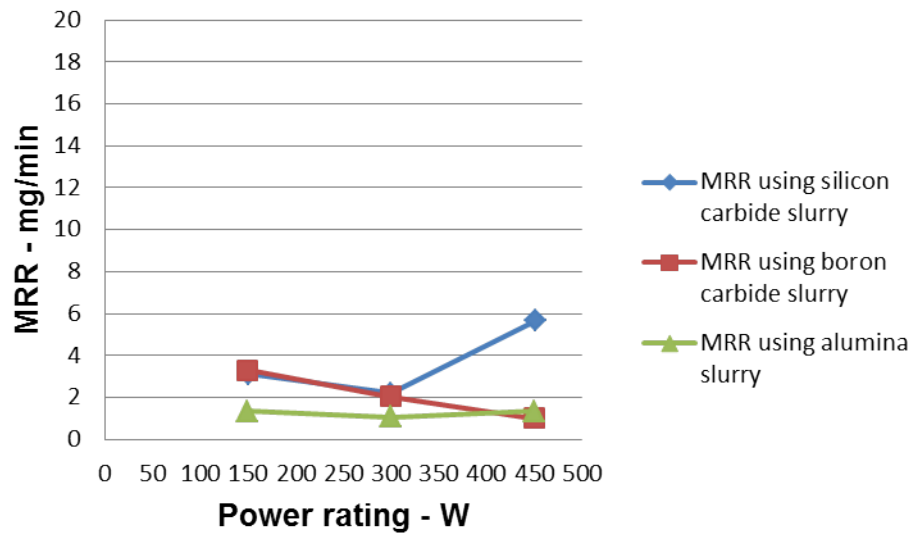


Figure 2-30: Material removal rate vs. power rating using workpiece TITAN15 and stainless steel tool – modified from [23]

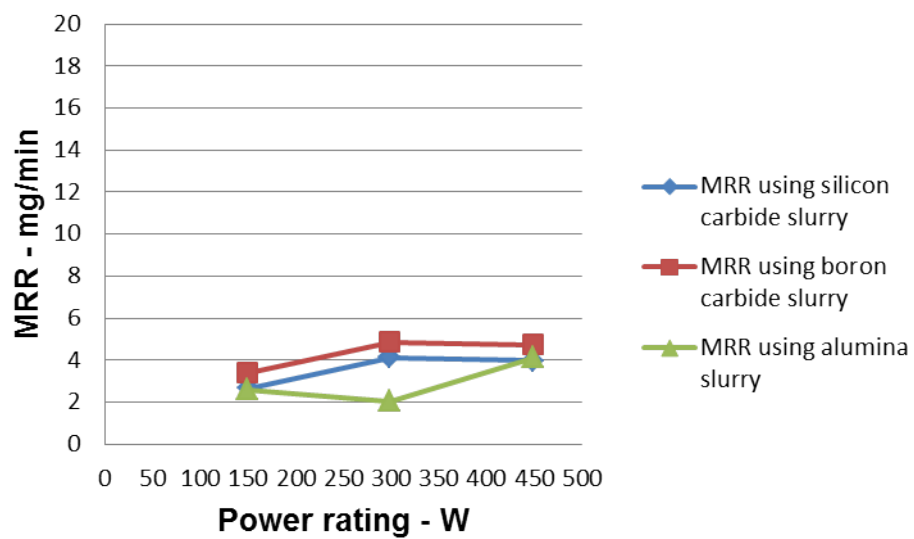


Figure 2-31: Material removal rate vs. power rating using workpiece TITAN31 and stainless steel tool – modified from [23]

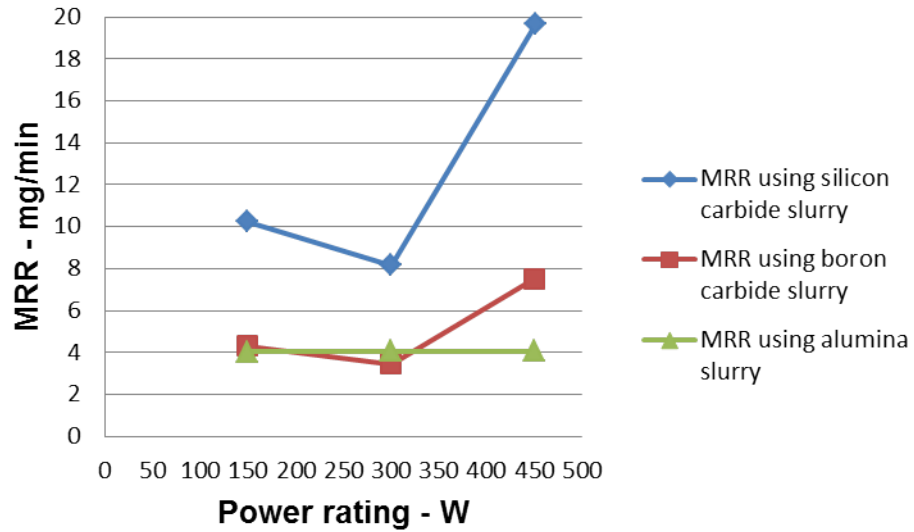


Figure 2-32: Material removal rate vs. power rating using workpiece TITAN15 and Ti tool – modified from [23]

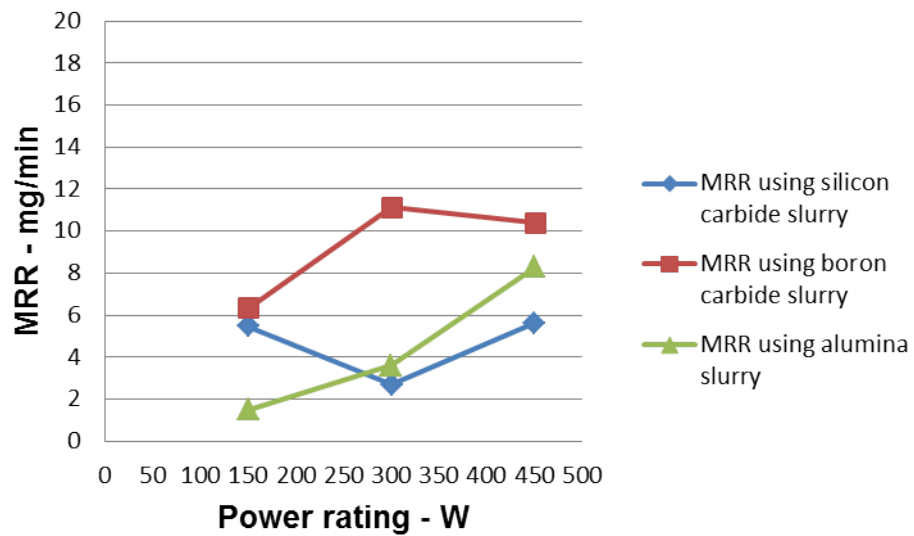


Figure 2-33: Material removal rate vs. power rating using workpiece TITAN31 and Ti tool – modified from [23]

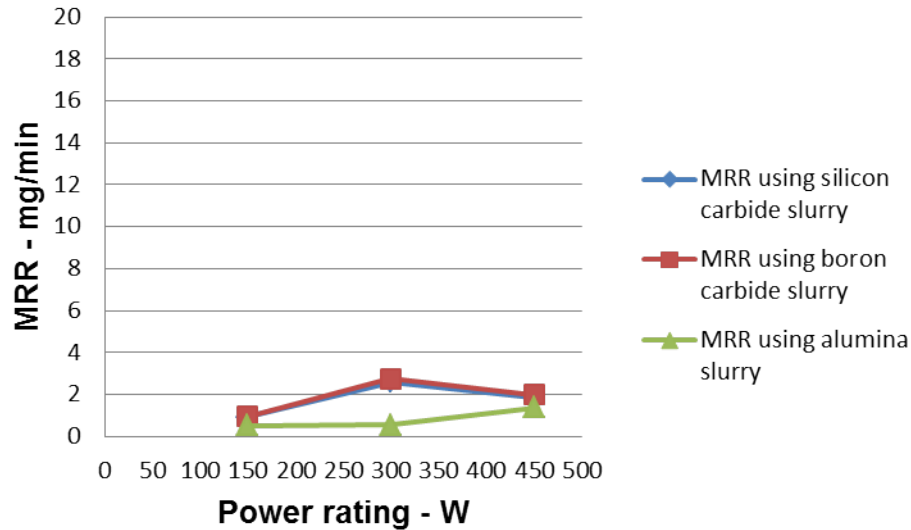


Figure 2-34: Material removal rate vs. power rating using workpiece TITAN15 and high speed steel tool – modified from [23]

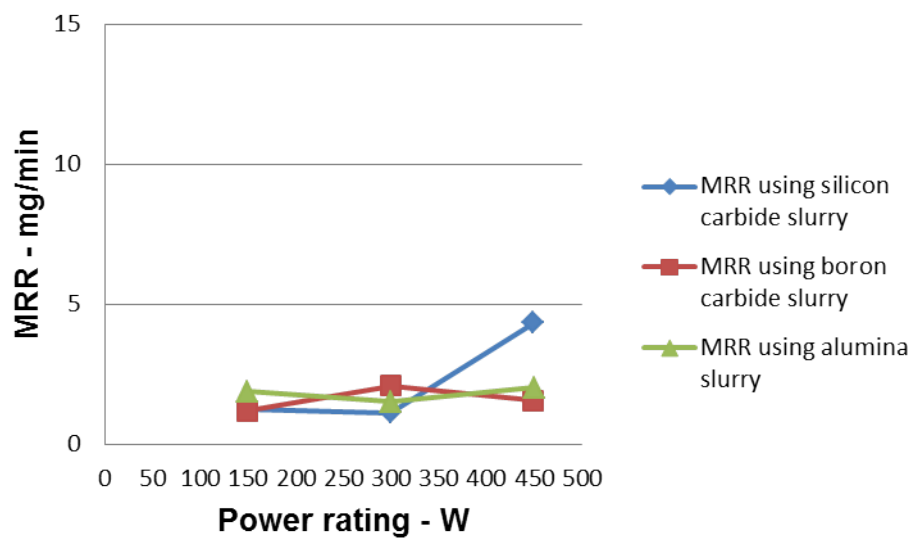
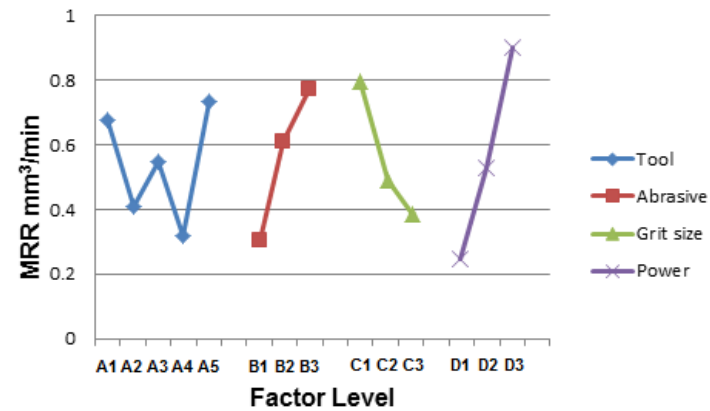


Figure 2-35: Material removal rate vs. power rating using W/P TITAN31 and high speed steel too – modified from [23]

Figure 2-32 shows that while using a Titanium tool it has been found that for TITAN15 the material removal rate showed insignificant effect of slurry type, whereas in Figure 2-33 for TITAN31 the choice of slurry has come out as important factor. The best settings have been attained with Boron Carbide slurry at 300W for TITAN31. Figure 2-34 and Figure 2-35 illustrate the trend obtained for material removal rate is almost similar using Aluminium Oxide and Boron Carbide slurries but some variation has been observed when using Silicon Carbide.

The report concludes that Titanium can be machined well using the ultrasonic impact grinding process. It is not always necessary that if a work piece with higher toughness value is machined, it will have less material removal rate rather it is combination effect of material composition such as the hardness of work piece relative to the tool material. A better material removal rate can be attained by using specific tool–work piece combinations at specific power rating values and controlled experimental conditions such as the slurry type used. The results suggest that for the best results a Boron Carbide slurry and stainless steel tool was giving the best material removal rate on both grades of Titanium under test and that Boron Carbide slurry comes out as the best option mainly because of the better workpiece and tool combinations [23, 48].

A macro-model for the prediction of material removal rate in the ultrasonic impact grinding of Titanium using dimensional analysis was constructed by Kumar and Khamba [52]. Using this information an attempt has been made to develop a micro-model for prediction of material removal rate over a wide range of input parameters. Again Silicon Carbide (SiC), Boron Carbide (B₄C), and Alumina (Al₂O₃) were used but at various grit sizes of 220, 320 and 500. Power ratings of 100W, 320W and 400W were selected along with 5 different tool materials namely high Carbon steel, high speed steel, Titanium, Titanium alloy and cemented Carbide. It can be observed from Figure 2-36 that tool material used affects the material removal rate very significantly. Moreover, the different tool materials used in the experimentation can be ranked in the order of increasing material removal rate as Titanium alloy, high speed steel, Titanium, high carbon steel, and cemented Carbide. As illustrated in Figure 2-36 the highest material removal rate was achieved with a combination of cemented Carbide as the tool material, Boron Carbide as the tool material at a grit size of 220 and a power setting of 400.



A1 – H.C.S.	B1 – Alumina	C1 – 220	D1 – 100W
A2 – H.S.S.	B2 – Silicon Carbide	C2 – 320	D2 – 250W
A3 – Ti	B3 – Boron Carbide	C3 – 500	D3 – 400W
A4 – Ti alloy			

Main effects: A = tool, B = abrasive, C = grit size, D = power

Figure 2-36: Effects of process parameters on material removal rate – modified from [23]

Further investigations to understand the impact of tool hardness factor on the material removal rate were performed. By changing the tool material and keeping all other factors constant the following results were obtained in Table 2-1 [52].

Table 2-1: Effect of tool hardness factor on material removal rate [52]

<u>Abrasive type</u>	<u>Tool material</u>	<u>Tool hardness</u> <u>[GPa]</u>	<u>Mean material</u> <u>removal rate</u> <u>[mm³/min]</u>
Alumina	High Carbon steel	1.9	0.85
	High speed steel	1.68	0.7
	Titanium	1.15	0.57
	Titanium alloy	1.36	0.38
	Cemented Carbide	18.5	1.02
Boron Carbide	High Carbon steel	1.9	1.55
	High speed steel	1.68	1.33
	Titanium	1.15	1.2
	Titanium alloy	1.36	0.86
	Cemented Carbide	18.5	1.67
Silicon Carbide	High carbon steel	1.9	1.42
	High speed steel	1.68	1.2
	Titanium	1.15	0.92
	Titanium alloy	1.36	0.6
	Cemented Carbide	18.5	1.54

The data collected has been further used for finding the best fitting curve as depicted in Figure 2-37. Similarly, the experimentation was performed with Silicon Carbide slurry and Boron Carbide slurry using all the tool materials used in this investigation, keeping the power rating at 400 W and the grit size of 220 unchanged. The best fitted curves for these two cases are given below in Figure 2-38 and Figure 2-39 [52].

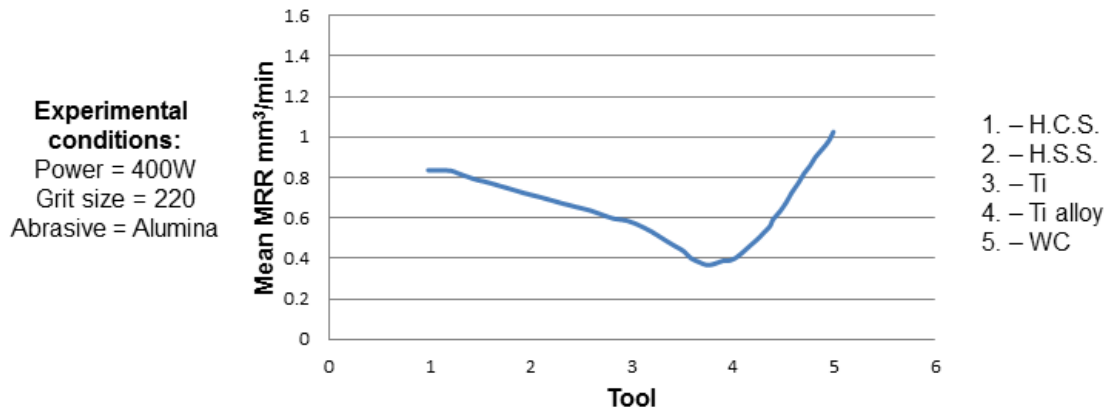


Figure 2-37: Material removal rate vs. tool hardness factor – modified from [52]

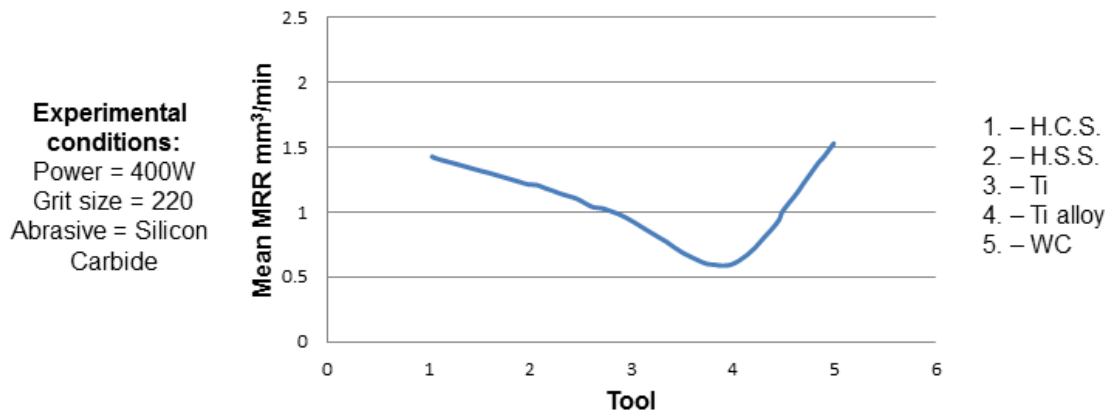


Figure 2-38: Material removal rate vs. tool hardness factor – modified from [52]

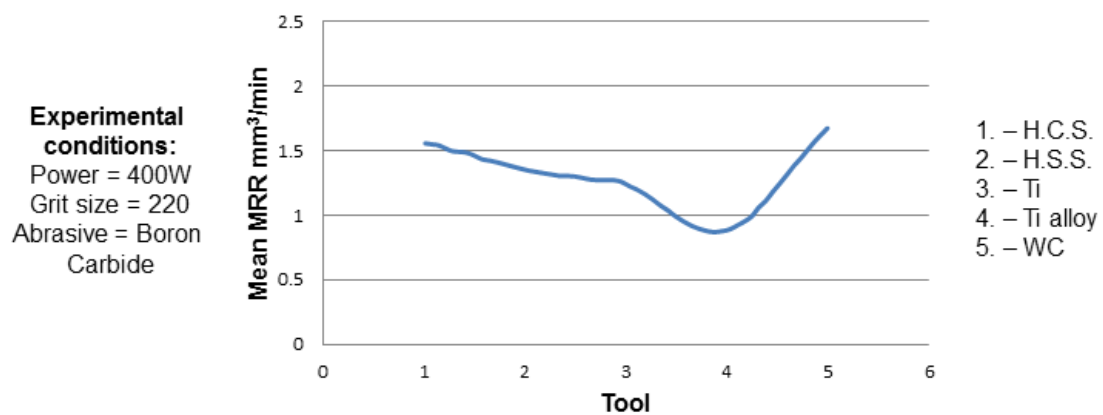


Figure 2-39: Material removal rate vs. tool hardness factor – modified from [52]

2.5.2 Tool wear rate

Tool wear is an important variable affecting the performance of the ultrasonic impact grinding process (machining rate and accuracy). In combination with other factors such as work material and its thickness, tool material and tool size, abrasive size and type, the method and rate of slurry feed and the cutting time influences the actual machining operation [79, 85].

Cronjäger [86] divided the complex tool wear pattern of ultrasonic drilling into longitudinal wear and lateral or side wear. Longitudinal wear is the reduction in length or linear dimension of the tool and is due to the repeated hammering of the tool against the abrasive particles. It is also due to the micro-chipping and crumbling of the tool edges when the static load applied is more than the optimum for the particular cross section of the tool. Lateral or side wear refers to the change of the side surface of the tool, i.e. a diameter reduction from the original contour and is due to the abrasive action of the particles in the gap between the tool and the workpiece. Lateral vibration in the tool due to improper alignment complements side wear by abrasive flow.

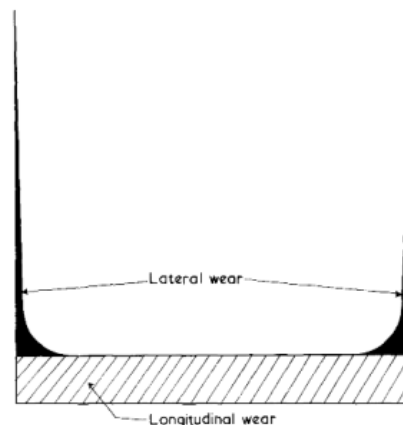


Figure 2-40: Schematic representation of longitudinal and lateral wear [79]

In addition to longitudinal and lateral wear, cavitation or suction wear may also be superimposed. Cavitation or suction wear is caused by the reciprocating motion of the tool which creates violent cavitation near its face and sides; absorbed gases are also liberated as small bubbles causing strong local currents across the face and between the lateral surface of the tool and the workpiece. The damage produced by bubbles collapsing near the work surface causes cavitation erosion also known as cavitation or suction wear, the extent of which depends on several factors such as work material properties, abrasive slurry, gap between tool and workpiece, tool size, abrasive flow, frequency, vibration amplitude and energy input [79].

Markov [87] has proposed a qualitative classification of work materials with regard to their machinability by ultrasonic drilling:

- Group 1 materials predominantly exhibit elastic deformation and failure results from minute cracks inherent in these materials. These hard, brittle materials such as glass, quartz and ceramics can be effectively ultrasonically drilled with little tool wear.
- Group 2 materials exhibit plastic-elastic deformation and failure is by cracks developing in these materials. These materials such as Titanium, Tungsten Carbide and some heat resisting alloys can be ultrasonically drilled economically under certain specific conditions. Tool wear is greater than that for Group 1 materials.
- Group 3 materials such as lead, copper, brass and hardened steels exhibit plastic deformation. They do not suffer fracture from impulsive grain impact and their ultrasonic drilling rate is negligible.

From experimental data machining rates and the tool wear values for different work materials were obtained [86, 88-90]. Numerical values are given in and shown graphically in Figure 2-41. The ranges of Groups 1, 2 and 3 materials are indicated in the graph. It is interesting to observe that all points plotted lie about a single line; the product of machining rate and relative tool wear is a constant.

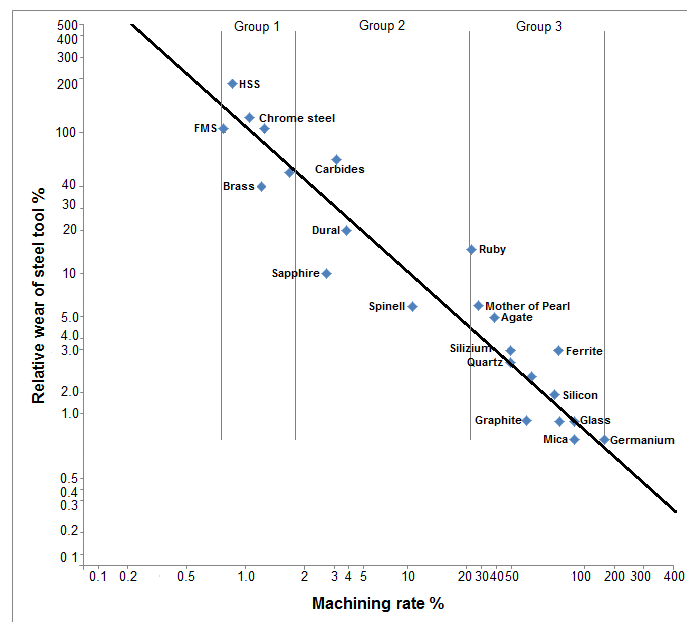


Figure 2-41: Machining rates and tool wear values for different work materials – modified from [87]

Table 2-2: Machining rates and the tool wear values for different work materials

<u>Work Materials</u>	<u>Machining rate (%)</u>	<u>Tool wear as % of metal removal or relative wear of steel tool (%)</u>
Glass (minimum 5mm/mt)	100 (Base)	0.5-1.0
Marble	300	-
Fluorite	280	-
Barium Titanate	110	-
Germanium	80-200	0.5-3.0
Jasper	90	-
Amazonite	80	-
Mica	80	1.0
Ferrite	75-80	1.5-5.0
Porcelain	60-70	3.0-9.0
Graphite	50	1.0
Silicon	50-100	1.0-2.0
Quartz Crystal	40-70	2.0-2.5
Silizium	40	3.0
Topaz	40	-
Agate	25-50	4.0-5.0
Hard Ceramic	25	6.0
Mother-Pearl	25	6.0
Sapphire	20	10.0
Ruby	3-30	8-10.0
Spinell	10	6.0
Corundum	9	-
Duraluminium	4	20.0-25.0
Cemented Carbide	2-5	40.0-80.0
Brass and Bronze	1.2	40.0

Chrome Steel (12% Cr)	1.0	120.0-200.0
Free Machining Steel	0.6	100.00
High speed steel	0.4-0.8	200.00
Steel	1.0-1.5	100.00
Diamond	0.02 approx.	>1000.0

For group 1 materials, for which the process is best suited, tool wear increases with hardness of the materials machined. When these materials such as glass or porcelain are machined only longitudinal wear occurs. Figure 2-42 shows the development of the tool wear profile when glass was machined; only longitudinal wear is evident, lateral wear being negligible [85].

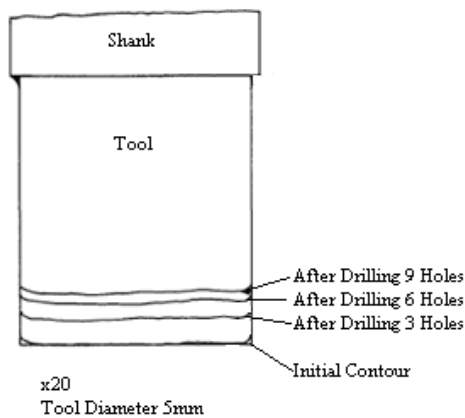


Figure 2-42: Tool wear propagation when machining glass

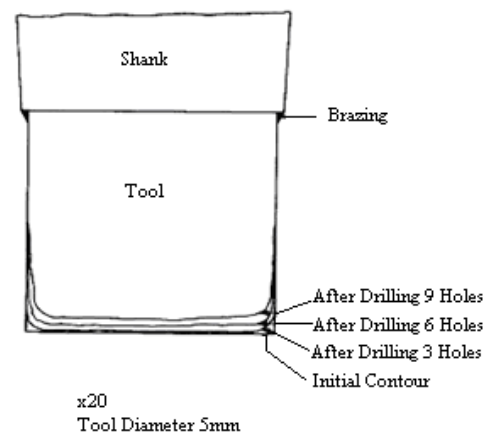


Figure 2-43: Tool wear propagation when machining Tungsten Carbide

When harder Group 2 materials such as Carbides are machined both longitudinal and lateral wear occurs. Figure 2-43 shows the development of the tool wear profile when Tungsten was machined; both longitudinal and lateral wear values are appreciable [85].

Tool wear studies have indicated that machining of non-brittle materials is often uneconomical, from the tool wear perspective, as illustrated in Figure 2-44 [28]. The tougher the materials, the greater is the tool wear and the machining rates and the precision of the holes will drop [9, 28]. Soft and elastic materials such as mild steel are often plastically deformed first and are later removed at a very slow rate.

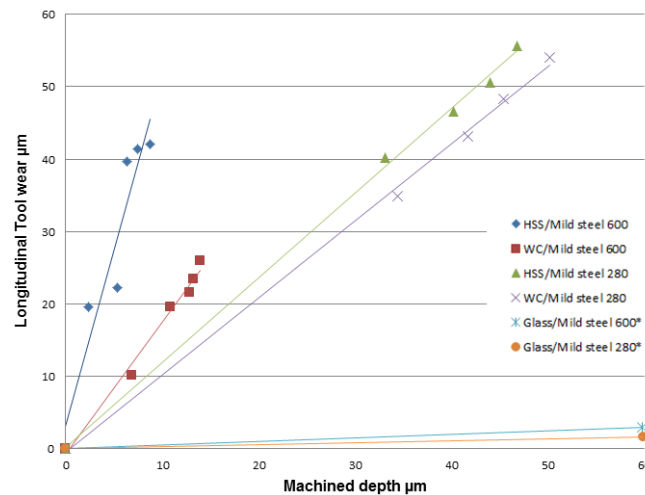


Figure 2-44: Tool-wear in ultrasonic impact grinding – modified from [28]

In order to minimize tool wear, tools should be constructed from relatively ductile materials such as stainless steel, brass and mild steel [20, 39]. Depending upon the abrasive used and the work piece material, work piece/tool wear ratio can range from 1:1 to 100:1 [23, 39]. Figure 2-45 illustrates that generally tool wear with Tungsten Carbide and stainless steel tools is lower when compared with mild steel tools [79, 91]. Compared with Tungsten Carbide, stainless steel tools exhibit low tool wear since they have high resistance to cavitation erosion. With Tungsten Carbide tool tips, there is a possibility of micro-chipping especially when they are subjected to pulsating static loads as encountered in ultrasonic drilling. Stainless steel tools are also preferable on account of their easiness in tool preparation and high resistance to cavitation erosion.

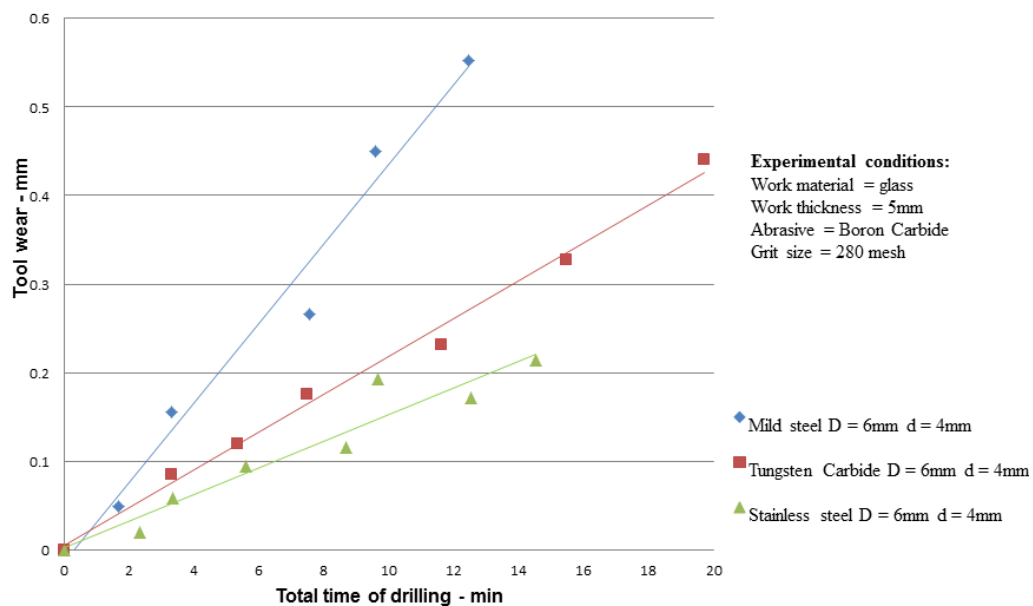


Figure 2-45: Influence of different tool materials on tool wear – modified from [91]

Similarly tool wear values obtained with silver steel tools were lower when compared with tool wear values obtained with mild steel tools as shown in Figure 2-46 [91].

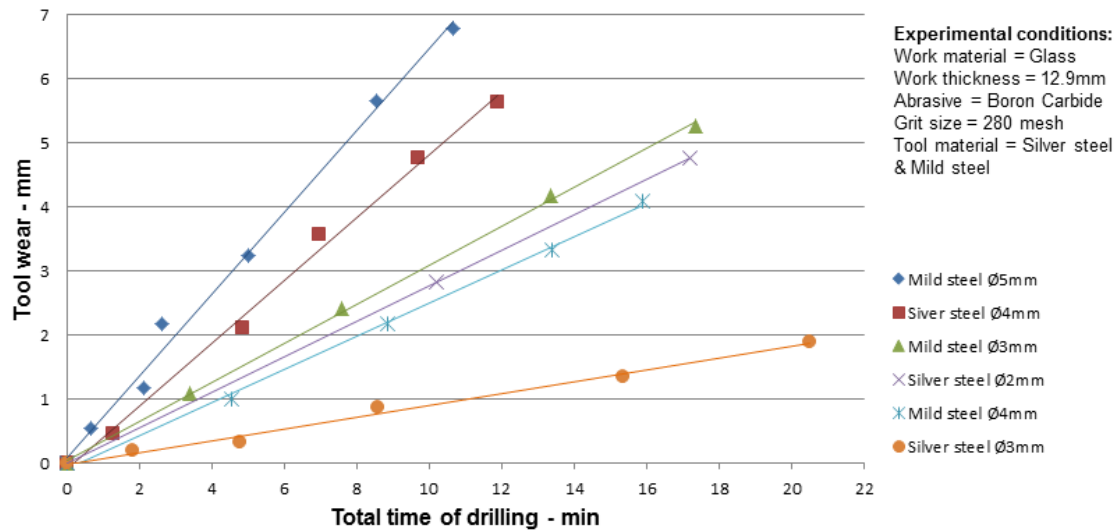


Figure 2-46: Influence of mild steel and silver steel tool materials on tool wear - tools are of different cross sections – modified from [91]

If the hardness of the tool increases by work hardening, the penetration of the abrasive grains into the tool will decrease resulting in higher work piece material removal rate. In addition, material removal from the periphery of the work zone will be greater so that a convex surface will be formed in the work piece. This causes plastic deformation of the centre of the tool face, forming a dish [15, 20]. It has been found that the degree of hardening is highest at the periphery and lowest at the centre for the tool material [22]. As a result, soft materials, e.g. copper and brass, are unsuitable as tools since they develop burrs at large oscillatory amplitudes [42]. It had been found that a martensitic tool structure has the greatest wear resistance. For other tempered structures, tool wear increases linearly with decreasing hardness of the tool. For martensitic tools wear resistance was found to be independent of hardness [79].

The relationship between tool wear and cutting time is found to be linear hence the rate of tool wear increases with time [79, 91]. Figure 2-47 and Figure 2-48 show the dependence of tool wear on cutting time.

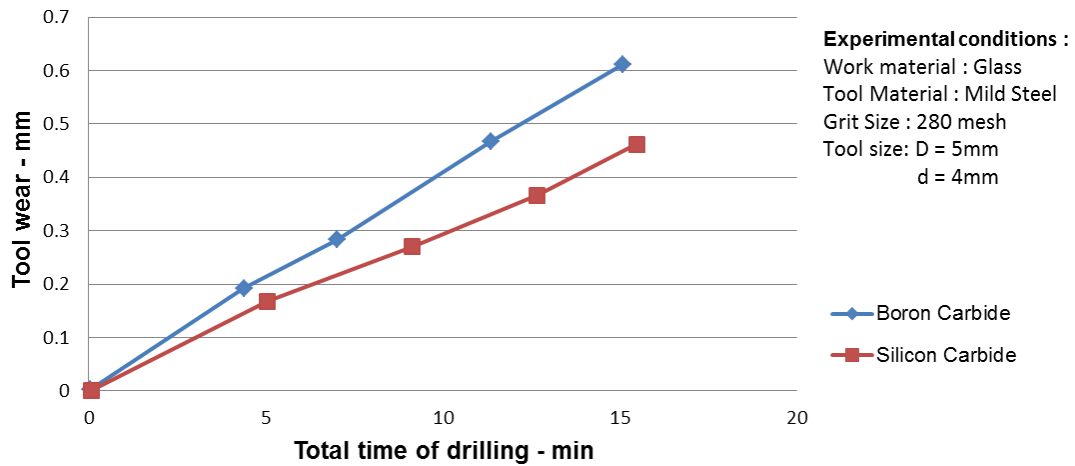


Figure 2-47: Influence on tool wear – short duration test – modified from [91]

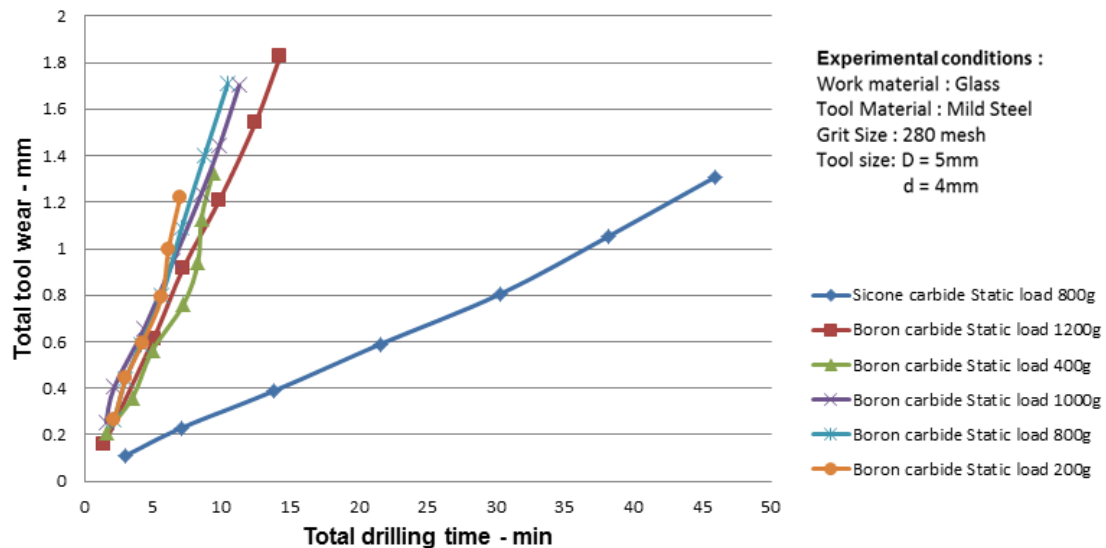


Figure 2-48: Influence on tool wear – long duration test – modified from [91]

In Figure 2-48 the curves shown are for different static loads and for the two abrasives, Boron Carbide and Silicon Carbide, of the same grit size. In both cases tool wear linearly increases with the cutting time. For tools of the same cross section, the tool wear with Boron Carbide abrasives was greater than that with Silicon Carbide abrasives. Boron Carbide is harder than Silicon Carbide and therefore tool wear increases with abrasive hardness. It is also found that Boron Carbide wets better than Silicon Carbide and wettability is an important parameter in the formation, growth and collapse of a cavitation bubble (cavitation wear). Hence tool wear with Boron Carbide abrasives is greater than that with Silicon Carbide abrasives. Boron Carbide is lighter than Silicon Carbide and is easier to retain in

suspension in the water. Silicon Carbide segregates and when segregation occurs the abrasive content of the flowing slurry reduces resulting in reduced tool wear [79].

The use of a coarser grit also promotes the increase in tool wear rate [15]. The use of a coarse abrasive grain results in stronger impacts on the tool surface and hence the rate of fracture increases as illustrated in Figure 2-49 [80, 91].

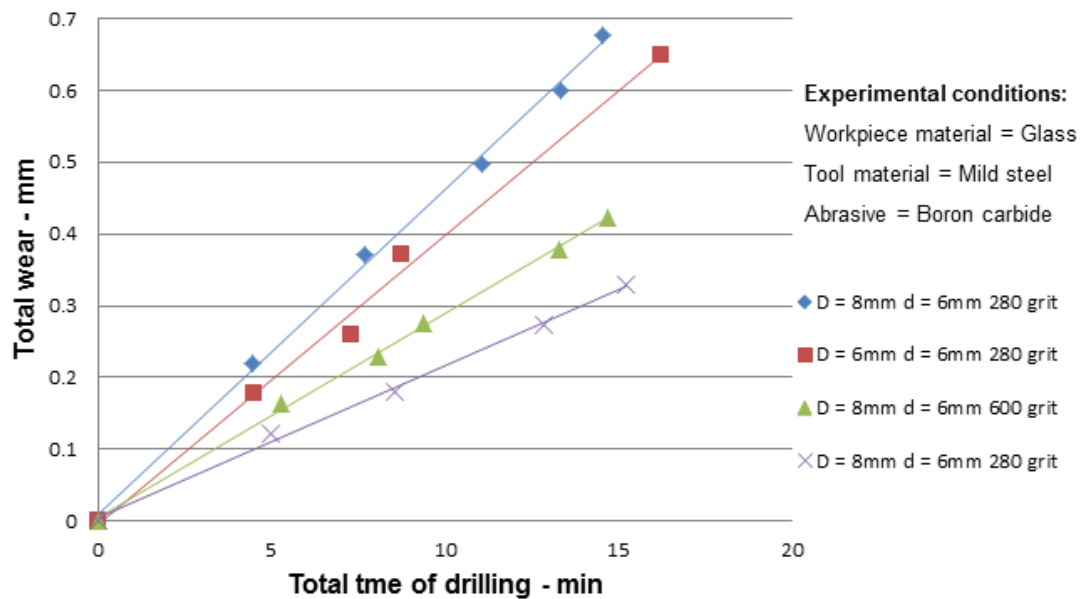


Figure 2-49: Influence of abrasive grit size on tool wear – modified from [80, 91]

Tool wear results in frequent tool replacement. As the tool length and weight decrease and the tool is not in resonance with the driving oscillator this leads to a reduction in the amplitude of vibration and thereby the machining rate decreases. However, resonance following generators has become available which automatically adjust the output high frequency to match the exact resonance of the horn/tool assembly [45]. They can also accommodate any small error in set up and tool wear, giving minimum acoustic energy loss and very small heat generation [64]. Theoretical analyses as well as experimental measurements have shown a strong correlation between the tool length and resonance frequency of the ultrasonic systems, and this observation has led to the concept of tool wear monitoring by measurement of the system's resonance frequency [92]. When the tool length is reduced due to tool wear it causes a change of the vibration frequency, eventually leading to reduction of ultrasonic impact grinding efficiency.

A set-up for a tool wear monitoring system using frequency feedback was developed by Hocheng [92] as shown in Figure 2-50. When the tool wears, the total mass of the horn and the tool decreases and the resonant frequency of the transducer changes. The resonant

frequency is fed to a generator, and the generator adjusts itself to a new driving frequency coping with the frequency of the transducer. Using the frequency signal from the generator, the tool wear can be monitored continuously. In the case of serious tool wear beyond a certain limit or tool breakage, the power supply of the machining system can be shut down to stop the machining process. An alarm can be set up in parallel.

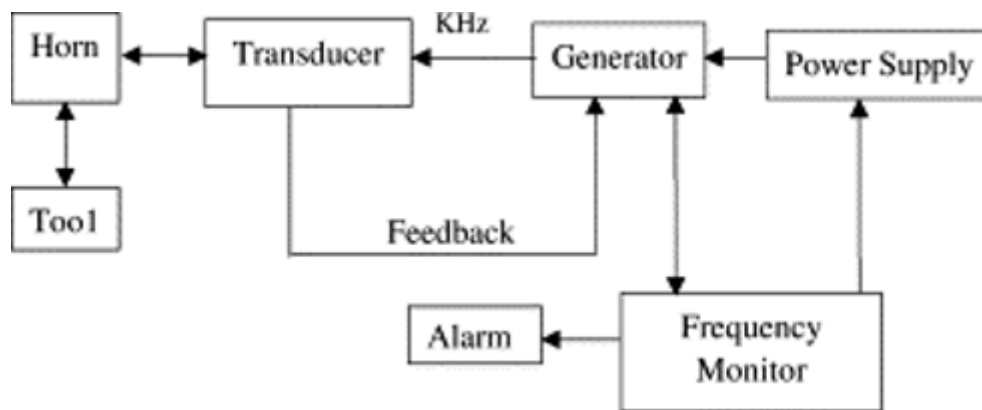


Figure 2-50: Schematic diagram of the tool wear monitoring system [92]

2.5.3 Accuracy

Accuracy in ultrasonic impact grinding involves both dimensional accuracy and form accuracy. Dimensional accuracy relates to hole oversize. Form accuracy relates to out of roundness, conicity and asymmetric holes [62, 93]. Kennedy and Grieve [43] state that there are factors affecting accuracy that are common to all forms of machining and this includes ultrasonic impact grinding. The factors are summarised as follows:

- The precision of the machine tool, i.e. the accuracy of the feed motion.
- The accuracy of the fixtures used.
- The quality of the assembly elements.

Other factors which are specifically concerned with ultrasonic impact grinding are [94]:

- Abrasive grit size
- Tool wear
- Transverse vibration effects
- Depth of cut

2.5.3.1 *Influence of the abrasive grit size on accuracy*

The size of the abrasive grains has the principal effect on accuracy in ultrasonic impact grinding [61, 62, 87, 95]. The cavity or hole cut is larger than the tool owing to the flow of abrasive along the sides of the hole to the bottom face of the tool [35]. The overcut which is the clearance between the tool and the workpiece, is regularly used to assess accuracy. Overcut has been found to be approximately one and a half times the mean grit size [95, 96]. Habell and Wilson [97] stated that the side clearance was 1.6 to 1.8 times the maximum grain size. From other results on the ultrasonic impact grinding of glass and Tungsten Carbide, the oversize of overcut is considered to be about 2 to 4 times greater than the mean grain size [61, 62]. However, in general, the magnitude of the overcut depends on many conditions, including the type of workpiece material and the method of abrasive feed [94]. When determining the tool size, allowance must be made for the overcut that will result from the grit size used [43]. A study has been made of the increase in overcut with depth for various tool profiles [98]. The use of combined tools, or tools with a negative taper, are claimed to improve the accuracy, i.e. reduce overcut [99].

Pandy [35] suggests that for accuracy and good surface finish, it is better to use a set of tools and more than one size of abrasive grits in stages as follows:

- Stage 1
 - Undersize tool
 - High frequency
 - Course grit
- Stage 2
 - Undersize tool
 - High frequency
 - Finer grit
- Stage 3
 - Full size tool
 - Low frequency
 - Very fine grit

2.5.3.2 *Effects of tool wear*

Adithan [62] reported that the oversize at the entry is greater than that at the exit of through holes drilled ultrasonically. This results in a taper on the hole which is caused by the progressive reduction of the diameter of the tool due to wear. From the profile projections of the holes drilled as shown in Figure 2-51 the diameter of the hole at entry is always greater than that at the exit; this accounts for the taper of the holes produced [62]. The form accuracy or trueness of the holes produced is determined by measuring their conicity, which is the difference in the hole diameters at the entry side and the exit side per unit length of the hole.

When the slurry is fed externally with the point of feeding kept constant, rounding off at tool entry occurs causing the hole size at entry to be enlarged. As drilling proceeds a tapering effect due to lateral wear of the tool was observed. The conicity of the holes produced is reduced when internal slurry delivery systems are used [61, 82]. When the slurry is fed internally the rounding off on the workpiece and wear areas occurs internally i.e. on the scrap plug only and therefore are of no consequence.

As conicity is due mainly to lateral wear of the tool using harder tool materials such as Tungsten Carbide and stainless steel reduces lateral wear and the conicity of the holes produced. Conicity also depends on the workpiece material, i.e. using glass results in very low conicity while a Tungsten Carbide workpiece results in high conicity. Conicity is reduced at higher static loads and for prolonged operating times since tool wear is less with finer abrasives. Re-passing with the use of fine abrasive can help to eliminate conicity [97]. Kennedy and Grieve [43] claim that the effects of this tool wear on accuracy while drilling is small and suggest that as the tool penetrates the workpiece, the undamaged portion of the tool corrects any errors produced in the earlier part of the machining operation.

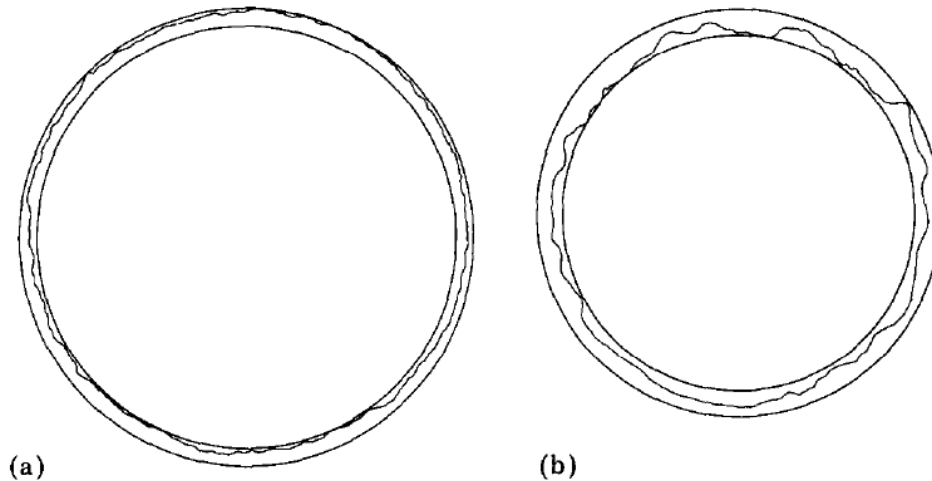


Figure 2-51: Profiles of holes drilled at (a) the entry side and (b) the exit side (8 x) [62]

In cavity sinking, tool wear is much more significant. In this case as the ultrasonic impact grinding proceeds, the tool becomes increasingly tapered due to tool wear and this change in its shape is reproduced on the workpiece. Both Kennedy and Grieve [43] and Koval'chenko et al. [100] point out the difficulty of machining the base of a hole flat because of uneven slurry distribution across the machining face, resulting in fewer active grits at the tool's centre (see Figure 2-52). The best value that can be obtained is of the order of 0.05mm (deviation from the mean line).

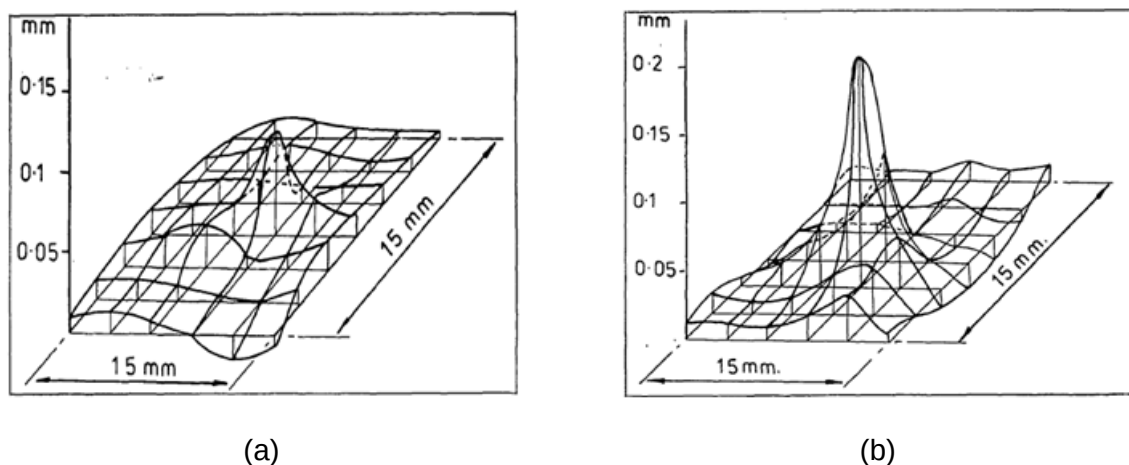


Figure 2-52: Contours of a machined surface of a hard alloy workpiece. (a) the depth of cut is 0.1mm (b) the depth of cut is 0.5mm [43]

2.5.3.3 *Transverse vibration effects – ‘out of roundness’*

The term “out of roundness” is often used to describe asymmetrical holes. Asymmetry can arise due to lateral vibrations of the tool during machining. These vibrations often occur

when the centre-line of the tool is not perpendicular to the face of the workpiece, when the acoustic parts of the machine are misaligned, or if the centre of gravity of the tool is off centre of the vertical direction of motion. The complexity of the machining action makes the analysis of the dependency on the process variables very difficult [43, 94]. Consequently experimental observations are the main source from which general conclusions can be drawn [94]. Komaraiah and Reddy [84] conducted a study to determine the influence of static load on the oversize of the ultrasonic drilling of holes and the geometry of the holes. Experiments were carried out at different static loads and the out of roundness obtained is shown in Figure 2-53. As the static load is increased there is a reduction in the out of roundness of the drilled holes. At higher static loads the lateral vibrations of the tool are suppressed and hence out of roundness of the drilled hole are reduced. This is in keeping with Markov's [87] view that out of roundness decreases with static pressure and machining time. There can also be a reduction of the size of the abrasive particles on account of the crushing action occurring during machining. There will be a natural improvement in the geometry of the hole drilled with the decrease in the grain size. It is recommended for the finishing cuts that the static load be increased.

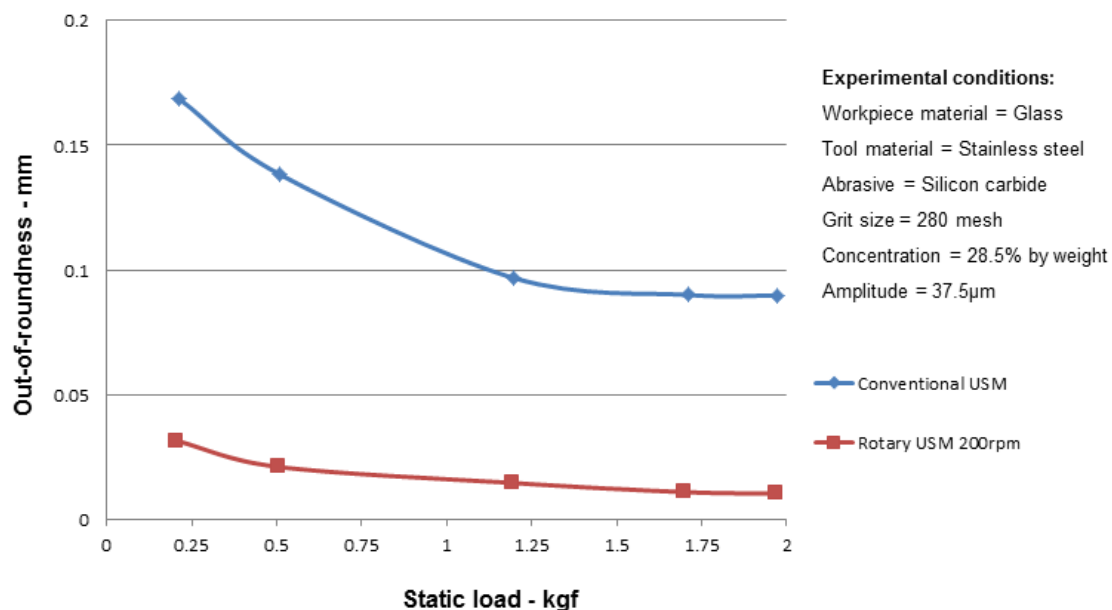


Figure 2-53: Effect of static load on the out-of-roundness – modified from [84]

The main cause for out of roundness is the flow of abrasive particles in the gap between the tool and workpiece; these particles scour the tool surface and produce lateral or side wear. In addition to this, as the tool breaks through the exit face of the workpiece chipping of the edges of the exit face of the hole or profile occurs [82]. This problem can be eliminated by reducing the feed force, i.e. the static load towards the end of the hole, and in some cases by slightly withdrawing the tool head at the end of the hole.

The mechanical behaviour of the workpiece material also influences the accuracy of the drilled holes. The materials which have higher hardness to modulus of elasticity ratio (H/E) tend to have more out-of-roundness, as shown in Figure 2.54, where H is hardness on the Mohs scale and E is Young's modulus. Porcelain gives the largest amount of out-of-roundness resulting from chipping, where large particles become detached. Tungsten Carbide gives the least amount of out of roundness as no chipping occurs.

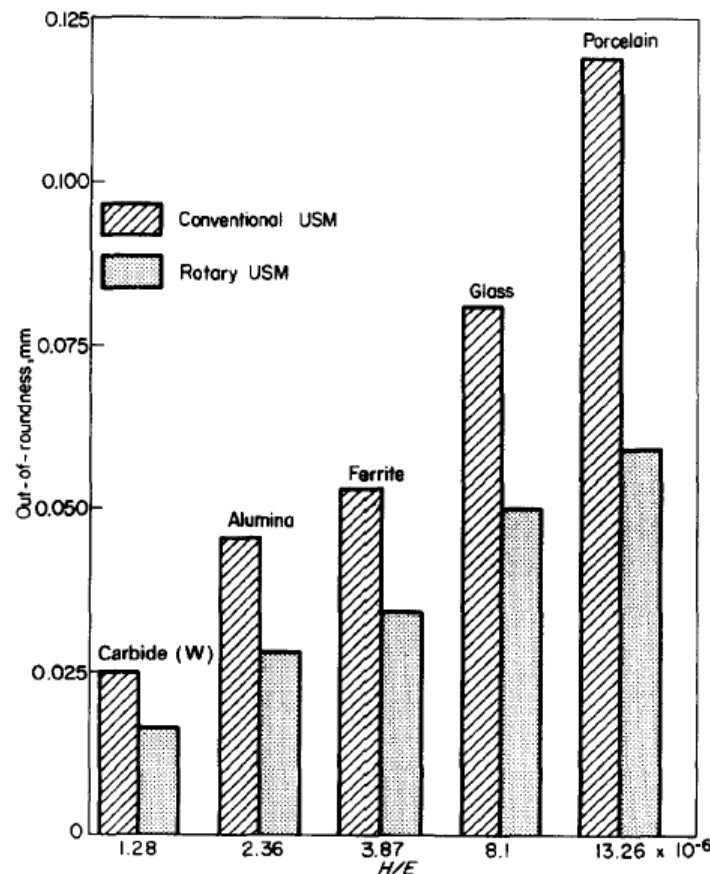


Figure 2-54: Effect of H/E on out-of-roundness, Tool material: stainless steel, Slurry: Silicon Carbide, Grit size: 180 mesh, concentration 28.5% by weight, amplitude: 37.5 μ m [84]

2.5.3.4 Influence of depth of cut

The depth of the cylindrical holes is presently limited to 2.5 times the diameter of the tool. From work quoted by Kremer et al [26] the machining of graphite with a 20mm diameter tool produces a conicity of approximately 0.2 degrees for a depth of cut of 10mm. Tool wear increases the angle of the hole and causes sharp corners to become rounded. This implies that the tool replacement is essential for producing accurate blind holes. As mention earlier due to the problem of fewer active grits coming under the centre of the tool on account of ineffective slurry distribution, the bottom of a cavity cannot usually be machined flat [43, 100]. This problem is compounded the deeper the hole is drilled.

2.5.4 Surface finish

Surface finishes for the ultrasonic impact grinding process range from 0.2 to 1.5 $\mu\text{m Ra}$ [45]. The process conditions which are related to the operating parameters in ultrasonic impact grinding have a significant effect on the surface finish.

- The surface finish depends on
 - The abrasive grit size
 - The properties of the work material
 - Fracture toughness of the workpiece
 - Hardness of the workpiece
 - The properties of the tool material
 - Hardness of the tool
 - Surface texture of the tool
- Amplitude of vibration and the static load of the tool
- Properties of liquid carrier of the abrasive grit
- Depth of hole (cavitation effects)
- Material removal rate, feed rate

2.5.4.1 Influence of grit size on surface finish

The type and size of abrasive particle strongly influences the surface finish [16, 28, 44, 94, 101, 102]. For ultrasonic impact grinding, despite the complexity of the influence of the various working parameters, grain size is known to be the main factor which affects surface finish. Smith [82] states that surface finish was influenced by the linear component of the grain size. Thus, selection of the correct grain size will greatly influence the resulting surface finish, and adjustment of the other main parameters will optimise the cutting rate for that particular grain size. Various researchers have shown that as the particle size used increases the surface finish decreases [20, 39, 82]. Komaraiah et al [84] state that the depth of indentation increases with increase in the size of the abrasive grain. Larger abrasive grains remove a large volume of the workpiece material in each indentation, leaving behind a crater on the workpiece surface. Thus higher surface roughness results from larger grain size. Singh [16] goes further stating that the best surface finish results when using 800-grit abrasives resulting in surface roughness of down to of 0.25 $\mu\text{m Ra}$. Kopps [103] studied the effect of wear of abrasive grains on the surface finish and reported that there is an improvement in surface finish with the wear of the abrasive grains. This is explained by a

decrease in the grain size with the wear of the particles further highlighting the importance of using a small grain size when surface finish is important. The relationship between grit size and surface roughness is shown formally in Figure 2-55 where a reduction in surface roughness is related to grit size as discussed [94].

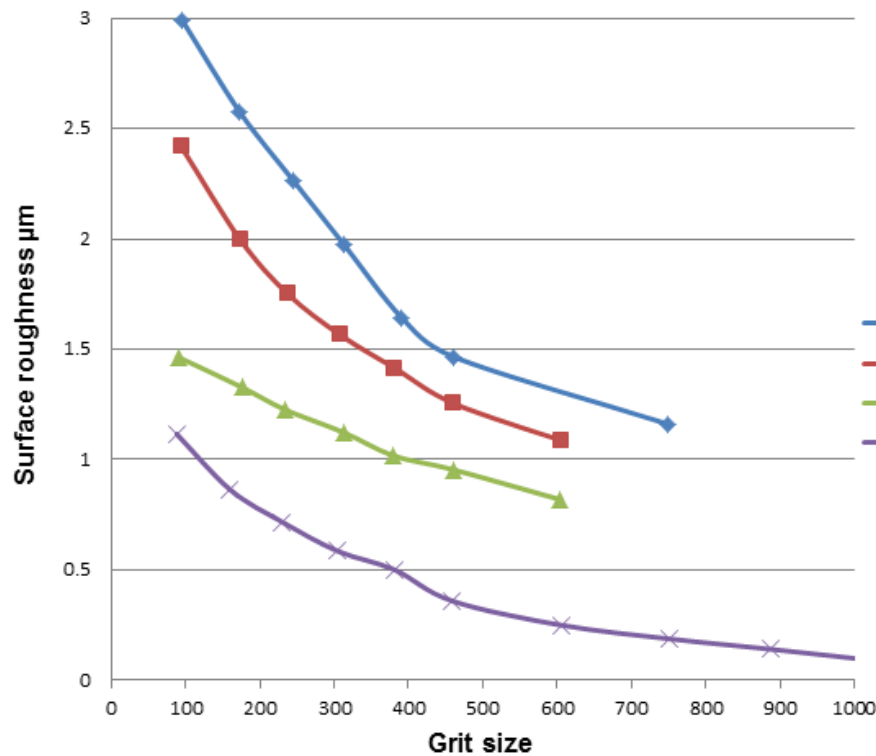


Figure 2-55: Effect of surface roughness vs. grit size for Boron Carbide on various workpiece materials [43, 44, 84, 94, 104]

Theoretically, it is expected that the surface roughness is small when small particles are used because of the small crater generated. However this is not always the case. Yu et al [105, 106] report that because of debris accumulation, the surface roughness generated by small abrasive particles can be larger than that of big particles. If abrasive particles of small size are used, particles get embedded in the workpiece or in the tool under the static load and may stay in their original craters without moving to other locations during several cycles of vibration. The thickness of accumulated debris in the working area reaches the exposed height of abrasive particles in a short time, resulting in the debris getting involved in the machining. This leads to a change in the abrasive particle distribution and movement, which may increase the surface roughness. When large abrasive particles are used, more debris is removed from the working area and the abrasive particles are easily moved to new locations by the vibration due to the large number of impacts. It is generally accepted however, that the Ra values decrease for any workpiece material with increase in the mesh number, i.e. decrease in grain size.

The increase in the roughness values with increase in the grain size can be explained from the depth of indentation of the abrasive grains into the workpiece. The depth of indentation W increases with increase in the size of the abrasive grain. Larger abrasive grains remove a large volume of the workpiece material in each indentation leaving behind a crater on the workpiece surface. Thus the higher surface roughness results from larger grain size [84]. As particle size increases, material removal rate increases proportionally and surface finish is decreased [20, 39, 82]. The parameters that improve the surface finish generally decrease the cutting rate [43].

2.5.4.2 *Influence of workpiece on surface finish*

The mechanical properties of the workpiece material, and most importantly its fracture behaviour have an effect on the surface finish of ultrasonically machined components. The brittleness ratio, defined as the ratio of the hardness to the toughness of the workpiece material is an important parameter which influences the machining process. How easily the workpiece breaks down under the ultrasonic oscillations and then how the fracture develops and propagates influences the material removal rate and thereby the surface finish which can be achieved. Materials which have higher material removal rates have higher workpiece roughness values. The materials that have low fracture toughness propagate the cracks easily and this results in larger chunks of material being chipped off. This causes larger craters to be left behind on the workpiece surface and hence the materials with higher material removal rates are associated with inferior surface finish [84]. The material removal rates in various workpiece materials and the associated surface roughness values are shown in Figure 2-56 [84].

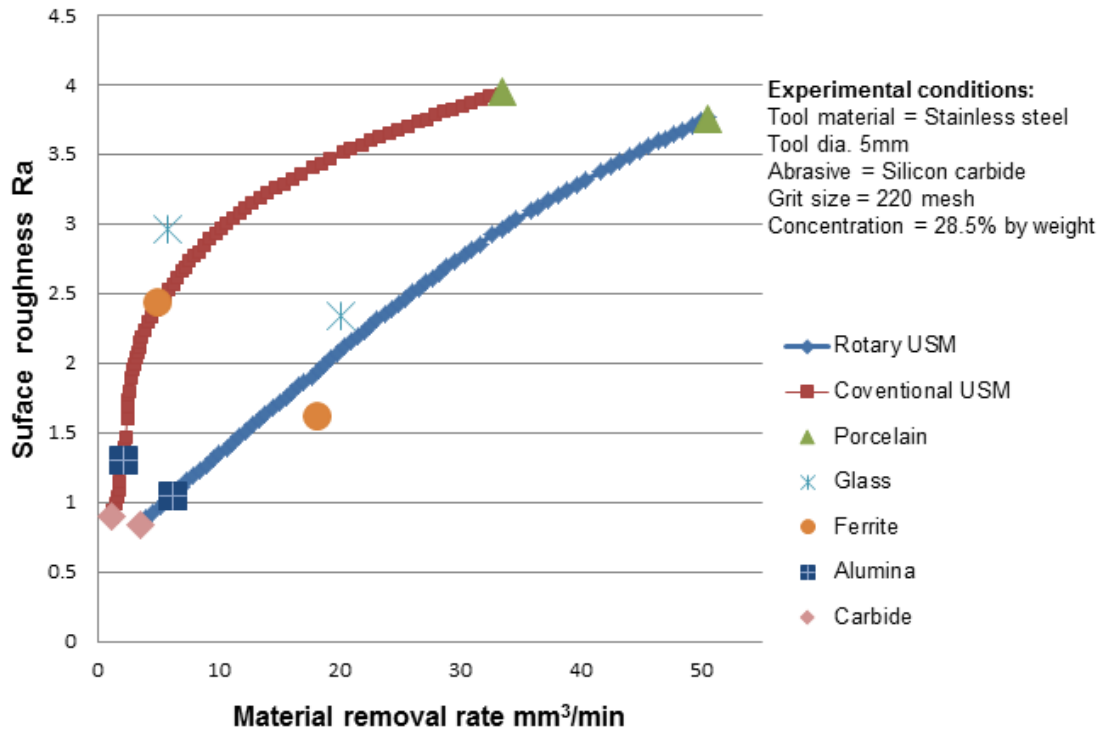


Figure 2-56: Surface roughness as a function of material removal rate – modified from [84]

Jianxin et al. [38] state that the fracture toughness of the workpiece plays an important role with respect to material removal rate and surface roughness in the ultrasonic impact grinding of alumina-based ceramic composites. As the fracture toughness increases, there is a reduction in material removal rate and in surface roughness. Soundararajan [28] reported that hard ceramics yield slightly better surface conditions than soft ceramics with finishes as low as $0.4\mu\text{m}$ Ra possible [28]. Figure 2-57 shows the surface roughness achieved in the conventional ultrasonic impact grinding of alumina-based ceramic composites. With similar results to that of the material removal rate, it can be seen that the most productive materials give the greatest roughness and vice versa [38]. According to Adithan, the surface roughness achieved when machining graphite with Boron Carbide of 280 mesh was $2.5\mu\text{m}$ (Ra) and for the same abrasive and static pressure the surface roughness for glass was almost double that of graphite [62]. This assertion is agreed upon by Dam et al. [9] who state that the highest productivity is not obtained without cost as the most productive materials give the highest surface roughness and vice versa.

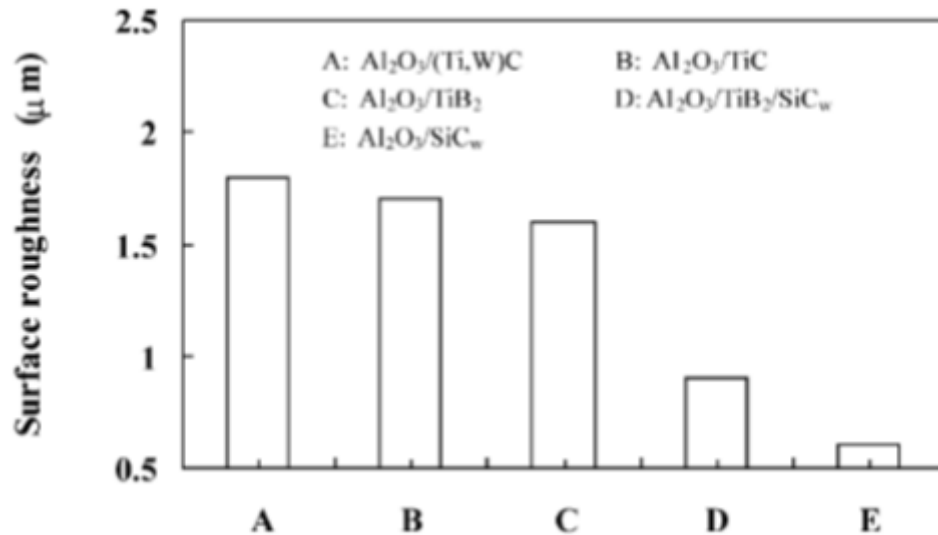


Figure 2-57: Machined surface roughness in ultrasonic impact grinding of different alumina-based ceramic composites [38]

2.5.4.3 Influence of tool material on surface finish

Experiments carried out by Komaraiah and Reddy [67] to study the influence of tool materials on the roughness of the machined surfaces concluded that the surface finish will depend on the progressive changes which take place on the tool peripheral surface which in turn depends on the wear resistance of the tool materials. It was found that the harder the tool material, the lower the surface roughness. The tool materials used were Titanium, stainless steel and Nimonic-80A. The workpiece materials ultrasonically drilled were porcelain (soft), glass, ferrite, alumina and Tungsten Carbide. Typical profiles of the alumina workpiece machined by Nimonic-80A, stainless steel and Titanium tools are given in Figure 2-58. The profile is much smoother in the case of Nimonic-80A followed by stainless steel and Titanium. The R_a values were 0.56, 0.64 and 0.71 μm respectively. The better performance of Nimonic-80A can be attributed to its higher wear resistance. The surface of the tool was not affected early and hence a better finish can be produced by it on the peripheral surface of the workpiece. The least wear resistant of the three was Titanium which gives rise to an inferior finish.

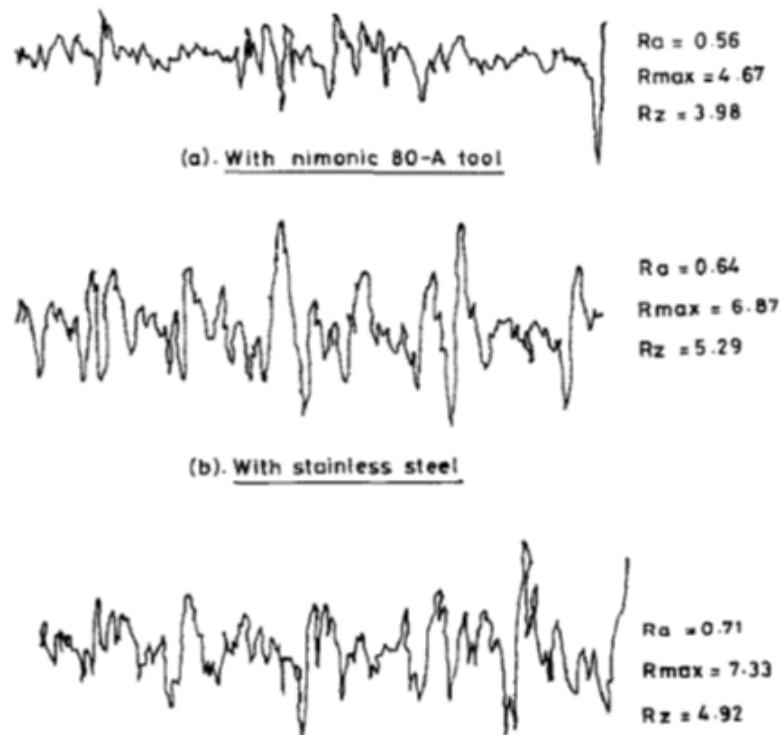


Figure 2-58: Surface roughness on alumina using various tools in conventional ultrasonic impact grinding (a), With Nimonic-80A tool; (b), with stainless steel; (c), with Titanium tool. [67]

Figure 2-59 shows the variation in surface roughness in various workpiece materials plotted as a function of the tool material hardness. All workpiece materials show an improvement in surface finish when a harder tool material is used. The order of the quality of the surface finish is as follows: Tungsten Carbide > alumina > ferrite > glass > porcelain. The brittleness ratios of these materials, i.e. the hardness to fracture toughness ratios are in the same order as that of the increase in surface roughness. Tungsten Carbide has the lowest brittleness ratio of 1.56, followed by 2.4 for alumina, 2.58 for ferrite, 5.0 for glass and 7.077 for porcelain. It can be concluded that the lower the brittleness ratio of the workpiece material, the better the surface finish.

Since the geometrical and surface features of the tool, including its surface irregularities are reproduced on the workpiece, it is generally required that the surface texture on the tool is of a better quality than that required on the finished component [87, 94].

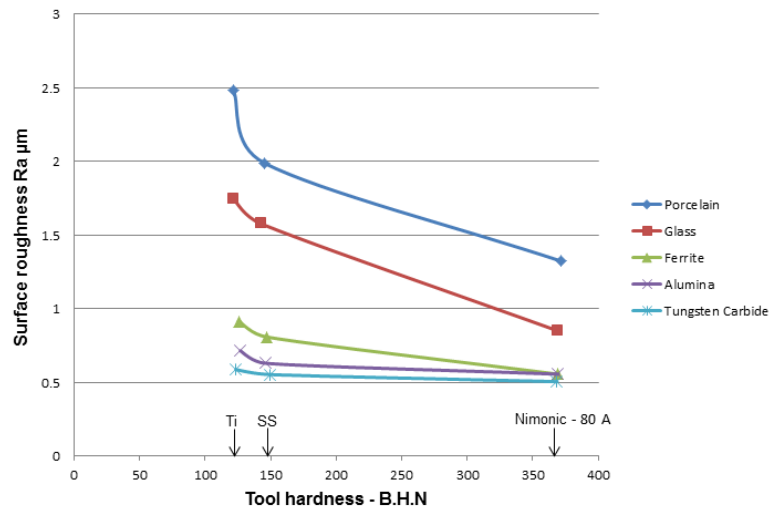


Figure 2-59: Surface roughness as a function of tool hardness – modified from [64]

2.5.4.4 *Amplitude of vibration and static load of the tool*

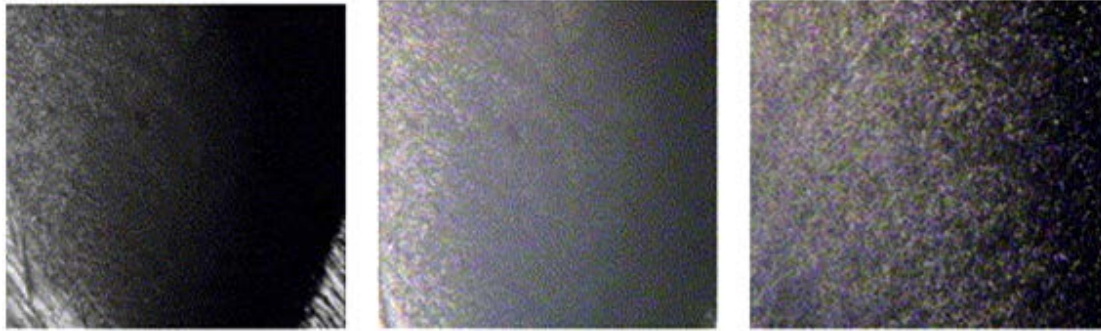
The effect of increasing the amplitude of oscillations of the tool is found to increase the surface roughness of the machined workpiece. As the amplitude is increased, the surface roughness increases, due to individual grains being pressed further into the surface of the workpiece [94, 95].

The applied static load is found to have little effect on the surface finish. Higher loads do not result in a rougher finish. With higher loads the surface finish improves because the grains are crushed to a small size [35]. In addition to an improvement in the surface finish, Shaw [27] and others [26, 62, 67, 94, 95] have shown that the increased static load also suppresses the lateral vibrations of the tool.

2.5.4.5 *Properties of liquid carrier of the abrasive grit*

Smoother surface finishes can be achieved when the viscosity of the liquid carrier for the abrasive is reduced. The use of machine oil in place of water in a finishing operation was found to improve the workpiece surface finish but caused a reduction in the cutting rate since a viscous drag is introduced at the tool/workpiece interface [26, 43, 87, 94, 95].

The temperature of the slurry also affects the surface finish of the work piece obtained [35]. Figure 2-60 shows the photomicrographs of an ultrasonically machined Titanium surface at various slurry temperatures (power rating: 150W, magnification: 100×). The results shows that the best uniform distribution of surface texture i.e. non-directional is at low temperature 10 °C, followed by high temperature 60 °C and then at room temperature of 27 °C. This also leads to better strength and improved mechanical properties.



(a) Slurry temperature of
60°C

(b) Slurry temperature of
27°C

(c) Slurry temperature of
10°C

Figure 2-60: Photomicrographs of ultrasonically machined surface of Titanium at various slurry temperatures, power rating: 150W, magnification: 100× [16]

Chapter 3: Ultrasonic Impact Grinding Machine Development

3.1 Introduction

The design of the Ultrasonic Impact Grinding machine tool involved the design and development of a number of subsystems that were integrated to form the ultrasonic machine tool system. Figure 3-1 below shows the main subsystems of an UIG machine tool based on a synopsis of the literature.

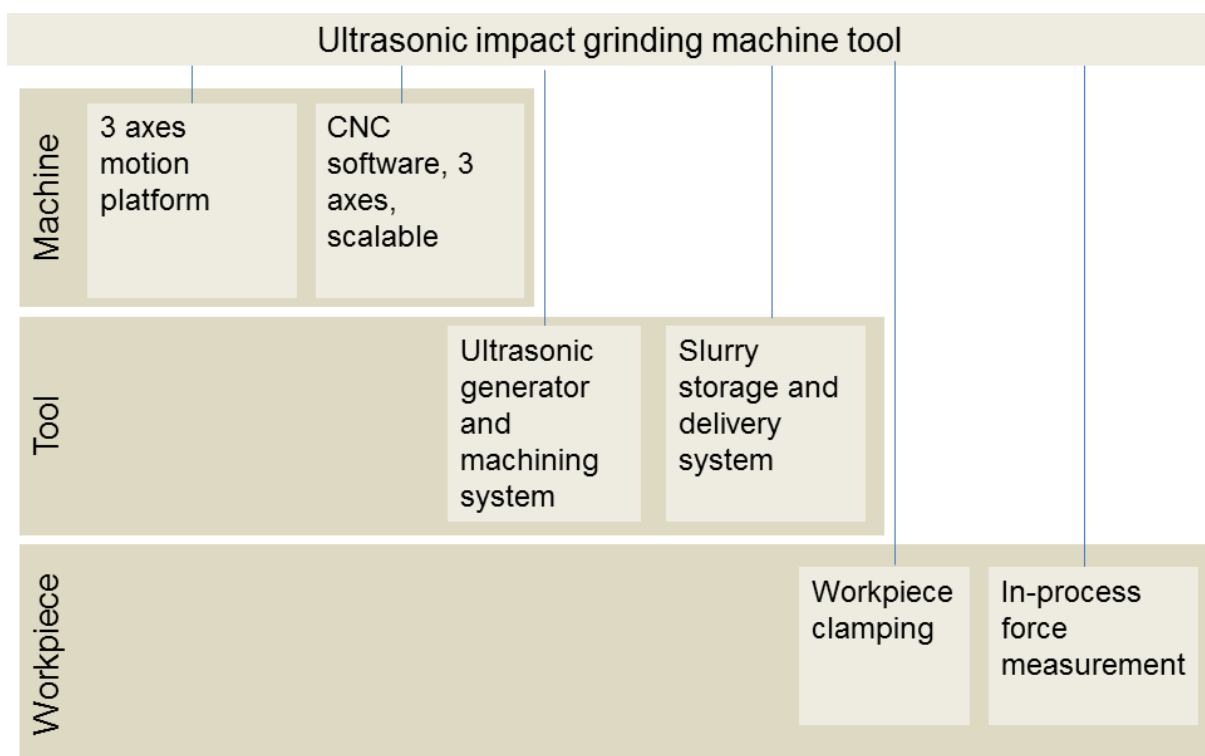


Figure 3-1: Ultrasonic impact grinding machine tool showing subsystems in categories of Machine, Tool and Workpiece

The machine structure was required to have the appropriate stiffness in order to allow for the integration of the ultrasonic stack components – converter, booster and sonotrode. The minimum axes of motion were specified to be in the x, y and z with appropriate CNC control software with the option to add a 4th axis if required. As the ultrasonic impact grinding process is dependent on the use of abrasive slurry an abrasive fluid delivery system was designed and integrated into the machine tool. The custom workpiece clamping arrangement was also a focus of development due to the nature of facilitating slurry access. A further dimension of interest in this research was the integration of in-process force measurement for the purpose of process characterisation.

3.2 Machine tool platform

A Denford Triac P.C. CNC milling machine was selected as the base platform due to the stiff structure and bench-top size of the machine. In the traditional use of the machine, metal cutting of 2D and 3D parts could be realised, particularly on Aluminium and easy to cut alloys as well as polymers. Figure 3-2 below illustrates the main features of the traditional Denford machine tool and shows the compact nature of the machine.



Denford Triac P.C.

- Mains supply – 240 Volts, AC, 1 Phase
- Spindle motor – 1.1Kw, DC, 1.5hp
- Spindle speed – 100 to 4000 rpm
- Stepper motors – 200 steps/rev, DC
- Tool capacity ATC: 8

Figure 3-2: The Denford Triac P.C. Computer Numerical Control Milling M/C [107]

3.3 Computer numerical control (CNC)

Computer Numerical Control (CNC) is the general term used for a system which controls the functions of a machine using coded instructions, processed by a computer. CNC machines are a very important part of the modern manufacturing process and are commonplace in most applications. However it is notable the the UIG process is not normally used with CNC control, as the traditional view on the UIG process is based on sinking with form tools only. Through the use of CNC, new levels of process capability can be realised. The following sequence defines the main steps involved in producing a component using a CNC system:

- A part program is written using G and M codes. This describes the sequence of operations that the machine must perform in order to manufacture a component.
- The part program is loaded into the machines computer known as the controller. At this stage, the program can still be edited or simulated using the machine controller.
- The machine controller processes the part program and sends signals to the machine motion control system, e.g. servo or stepped motors via appropriate drives. These signals direct the machine through the required sequence of operations necessary to manufacture the component or generate the features.

The schematic layout for the CNC machine control of the UIG machine is show in the Figure 3.3 below. A custom system was implemented where Mach 3 windows based software was used to interpret the part programs and used the LPT port on the PC to generate the pulse streams to the stepper drivers. The Z axis of the machine has been re-designed with a reduction gear box with a ratio of 15:1. Mach 3 allows for customised calibration parameters allowing the motor turns to be related to machine drive travel. The schematic shows a breakout card connecting the PC LPT pin out connections to the signal pins on the stepper cards. The breakout board and PC logic run on 5V and the stepper drives are supplied with a 24V 4amp power supply independent of the 5V logic control.

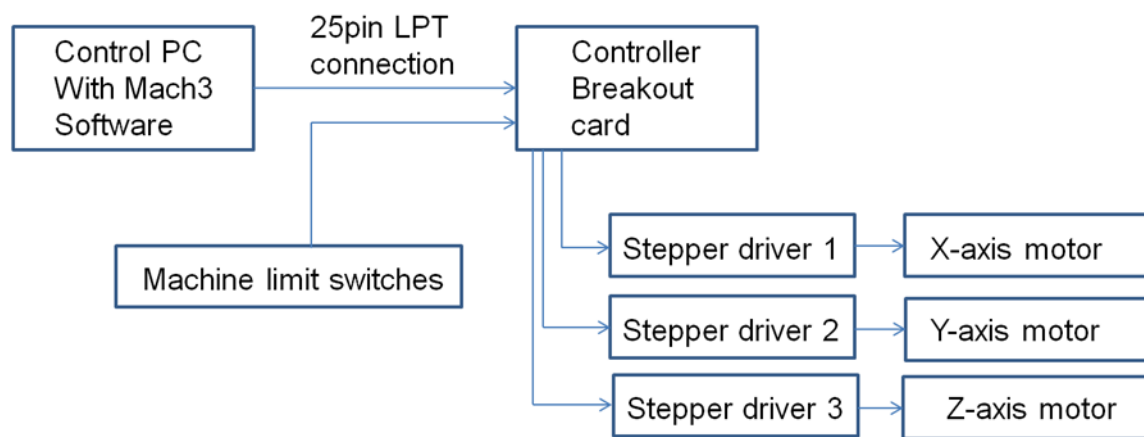


Figure 3-3: Schematic layout for the Mach 3 CNC machine control

Figure 1.4 below shows the users front screen on Mach 3 when under machine control. The user can upload and modify G-code part programs and change machine parameters such as the feed rates and pause or restart programs if needed. Live tool paths are also shown to check that the G-code has been entered correctly. A flexible easy to use custom built control system has been retrofitted to the original Denford hardware specifically designed with the ultrasonic impact grinding process conditions considered.

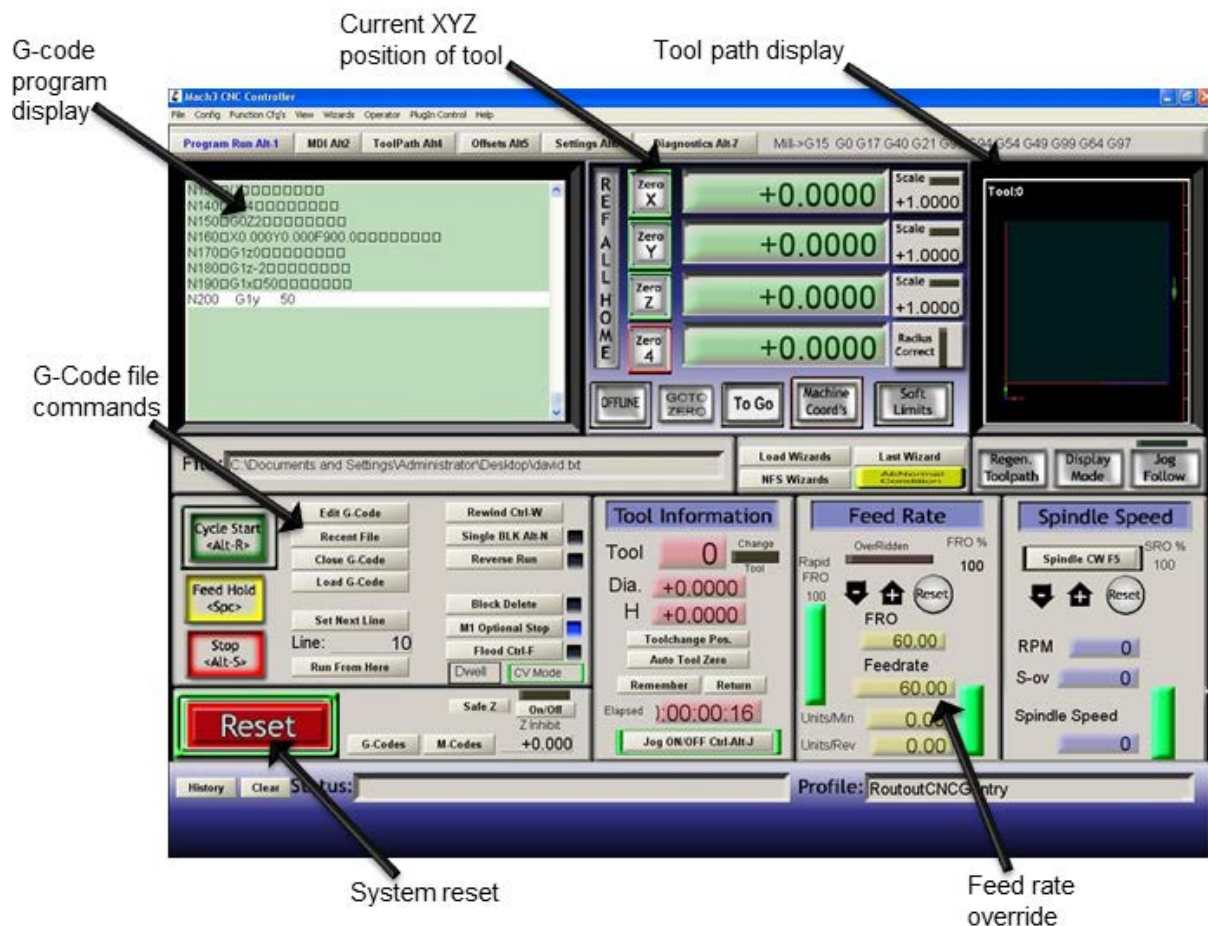


Figure 3-4: Mach 3 controller user interface

3.4 Ultrasonic system

The basic principle of the ultrasonic system involves the conversion of high frequency electrical energy to high frequency mechanical energy in the form of reciprocating vertical motion. The ultrasonic system is composed of the following major elements; an ultrasonic generator and the ultrasonic stack which is composed of the converter, booster and sonotrode. The high frequency electrical energy from the ultrasonic generator travels through the piezoelectric converter. The converter expands and contracts at the same frequency, converting the high frequency electrical energy into high frequency mechanical vibration. This vibration is amplified by a booster and transferred to an energy focussing device known as the sonotrode and on to the tool in the form of reciprocating longitudinal motion as shown in Figure 3-5.

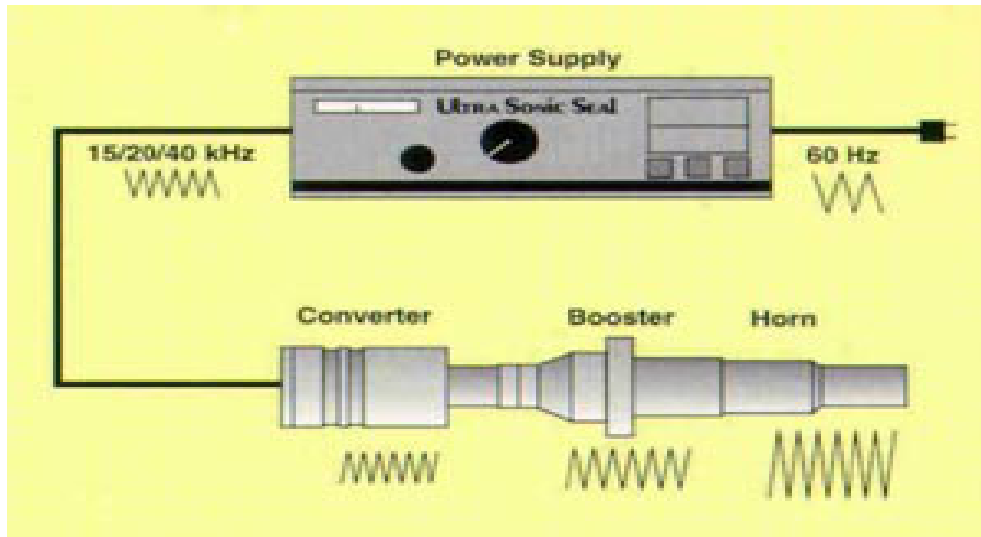
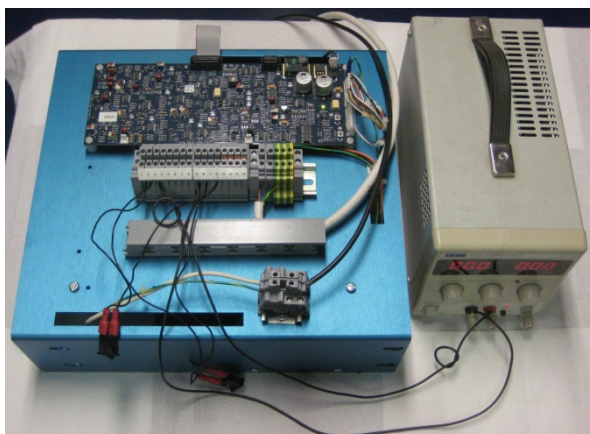


Figure 3-5: Ultrasonic assembly [108]

3.4.1 Ultrasonic Generator

An ultrasonic generator, type PSKIT-F1020-3, was purchased from Sonics and Materials (UK) Ltd. The unit is a solid state power supply which converts the conventional line voltage of 220/240v @ 50Hz to produce an ultrasonic frequency of 20 kHz with a power output of 1000 Watts. The generator is equipped with automatic frequency tuning which caters for the variety of tools to be used on the ultrasonic stack assembly. Figure 3-6 shows the ultrasonic generator. It can be seen that the system is operated through a series of manual switches and also a variable power supply that sets the amplitude of displacement of the tool.



Ultrasonic power supply kit

- • Mains supply – 240 Volts AC
- • 20 kHz frequency output
- • Power output 1000 watts
- • Automatic frequency tuning
- • External overload reset

Figure 3-6: Ultrasonic generator setup for investigations

3.4.2 Ultrasonic stack – Converter

The convertor used in the ultrasonic system is an air-cooled type; Model CV 154 and is made from piezoelectric lead zirconate titanate crystals (PZT). It expands and contracts at the same frequency of the generator converting the electrical energy into high frequency

mechanical vibration. It is recommended that if the converter is to be run continuously, air cooling of the converter must be applied. Cleaned dry compressed air filtered down to $5\mu\text{m}$ is supplied by a Kaeser compressor model EPC.1 complete with inline refrigerated air dryer, Ultrafilter model UD-0110. The air cooling inlet is shown in Figure 3-7.

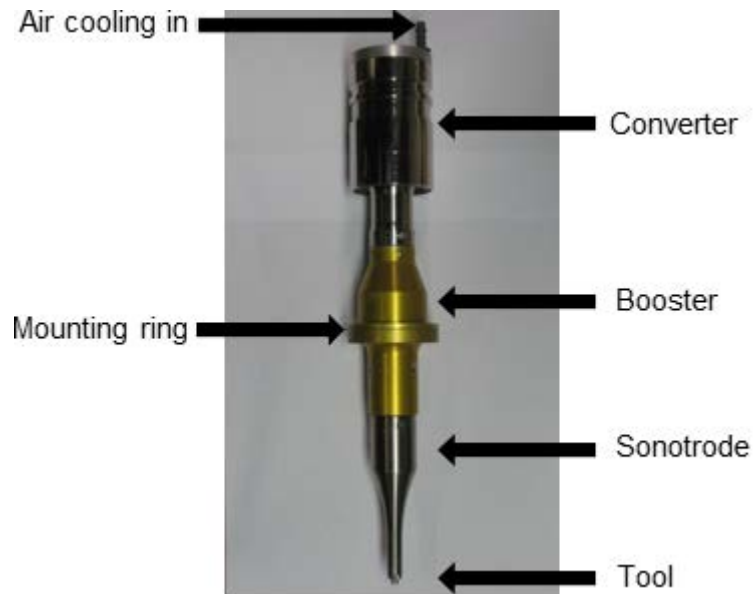


Figure 3-7: Ultrasonic stack

3.4.3 Ultrasonic stack – Booster

A booster is a mechanical amplifier used to increase peak-to-peak amplitude from a converter. It is a one-half-wavelength long resonant section made of aluminium or titanium. To provide an amplitude change, the booster has different diameters on either side of its centre or nodal point. Booster gain is the calculated ratio of mass above and below the mounting ring or nodal point. A smaller diameter at the end attached to the horns, means that the booster is amplitude increasing. A greater diameter at the end attached to the horn means the booster is amplitude decreasing. Figure 3-8 illustrates the six standard boosters which are available either to increase or decrease the amplitude of vibration. Boosters are colour coded or engraved for ease of identification.



Figure 3-8: Ultrasonic stack

Booster, model BHN15GD made from aluminium was selected for the application as it has a moderate amplitude gain ratio of is 1.5:1. When clamped at the nodal point by means of a mounting ring, the booster provides rigid support and alignment in the ultrasonic impact grinding system in addition to changing and maintaining the amplitude of vibration.

3.4.4 Ultrasonic stack – Sonotrode

The sonotrode couples the booster to the tool and is an energy focussing device which transfers the amplified vibration from the booster to the sonotrode. The sonotrode gain factors are calculated the same way as booster gain, i.e. the mass ratio above and below the nodal point. In the initial ultrasonic stack assembly, the sonotrode Model W-30702 was made from Grade 5 Titanium Ti6Al4V. Titanium is the preferred choice of material due to its high fatigue resistance, good ultrasonic characteristics and strength to allow for threaded tool attachments.

3.5 Integration of the Ultrasonic stack

The spindle system was removed from the machine tool and a fixturing system for the integration of the Ultrasonic stack was designed. Care had to be taken to utilise the clamping positions on the ultrasonic stack as specified by the manufacturer. These positions were at the mounting ring on the booster and the lower groove on the converter.

The fixture system was made of aluminium. It consisted of an upper stock-clamp arrangement which held the converter in place and a lower ring clamp system which utilised

the machined bore of the headstock for the alignment of the ultrasonic stack. The mounting ring of the booster was strategically placed in the lower ring clamp system whereby a c-shaped clamp could be bolted on with 2 x M8 caphead bolts. The arrangement can be seen in Figure 3-9.

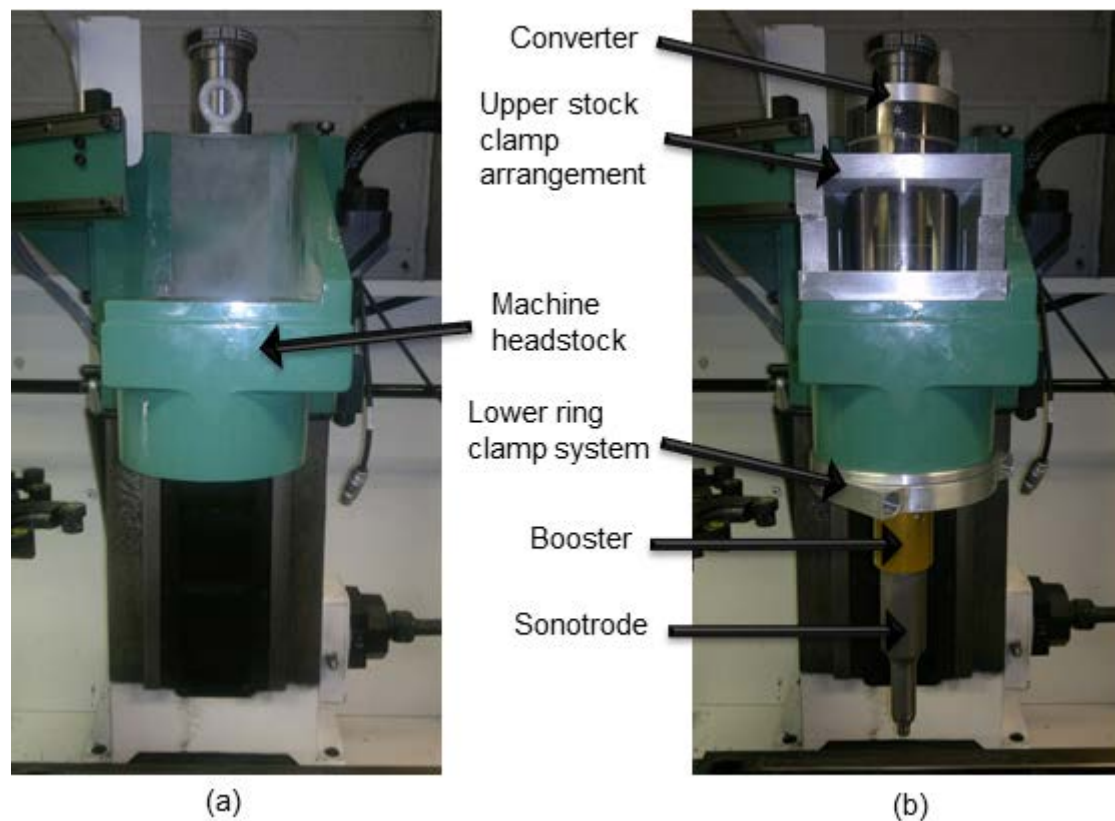


Figure 3-9: (a) Machine headstock with spindle system removed (b) Machine headstock complete with ultrasonic stack and holding fixture.

3.6 Abrasive slurry handling system

A handling system to provide an even supply of abrasive slurry was designed as shown in Figure 3-10. As the abrasive grit within the slurry was extremely hard-wearing Boron Carbide, care had to be taken to ensure all component parts of the abrasive slurry handling system were made from durable and corrosion proof materials. An immersion pump, model IMM-50, generally used in milling machines, lathes and drills to pump water, emulsions and oily substances was chosen for the delivery system. The submersible parts to the pump were made from materials as follows;

- Pump housing – polybutylene terephthalate, a thermoplastic polymer which is highly resistant to solvents, is mechanically strong and hardwearing.
- Impeller – nylon
- Shaft – 304 grade stainless steel

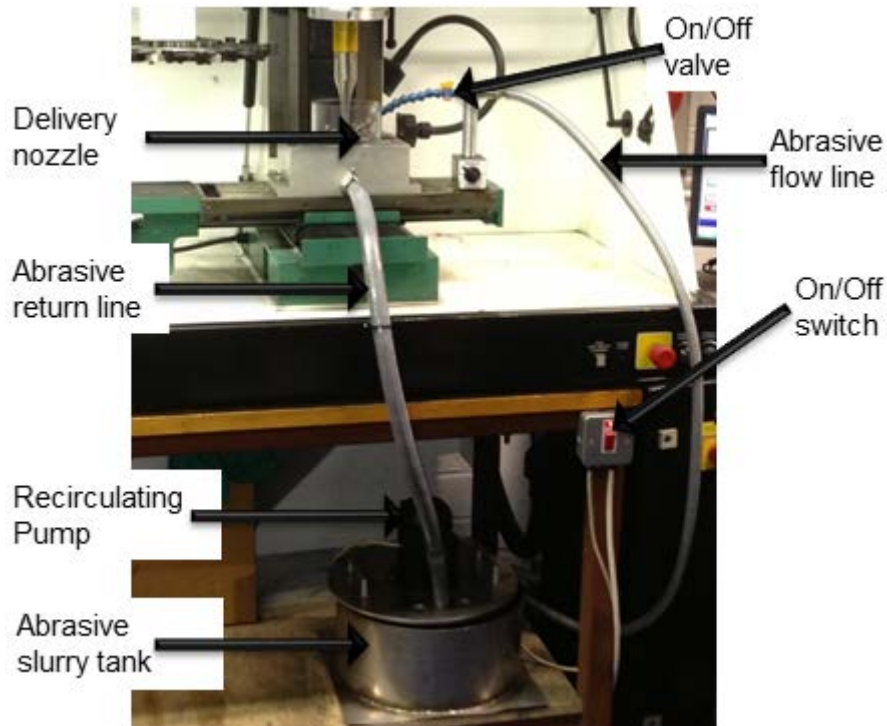


Figure 3-10: Abrasive slurry handling system

In order to maintain the abrasive grit to water mix an agitating tool was manufactured from 304 grade stainless steel and attached by thread to the base of the pump. This agitator stirred at the same revolutions per minute as the pump. The storage tank, made from 304 grade stainless steel was shaped cylindrically to decrease the build-up of abrasive grit in corners and also aided in maintaining the correct abrasive to water ratio mix. Reinforced polyvinyl chloride – PVC hose of diameter 25mm is used for the flow and return lines of the abrasive slurry. A quarter turn valve was fitted to adjust the flow of abrasive slurry and an adjustable nozzle was attached to a magnetic stand which can be strategically placed on the worktable to direct the flow of abrasive slurry into the cutting zone between the tool and the workpiece.

3.7 Z-axis feed system

The z-axis was operated via a 5mm pitch lead screw. In its initial setup as a milling machine the z-axis was coupled directly to the stepper motor. This arrangement made it difficult to control the axis motion smoothly at very low feeds required for the ultrasonic impact grinding process. This combined with the problem that the new CNC controller was unable to run at the low feeds required for ultrasonic impact grinding lead to the installation of a 15:1 step-down gearbox as shown in Figure 3-11. To incorporate the new gearbox a number of components were required to be designed and manufactured also. The original feed system platform which was made of 6mm thick mild steel plate was removed and replaced by an

8mm mild steel plate to handle the heavier weight from the new gearbox and the associated components.

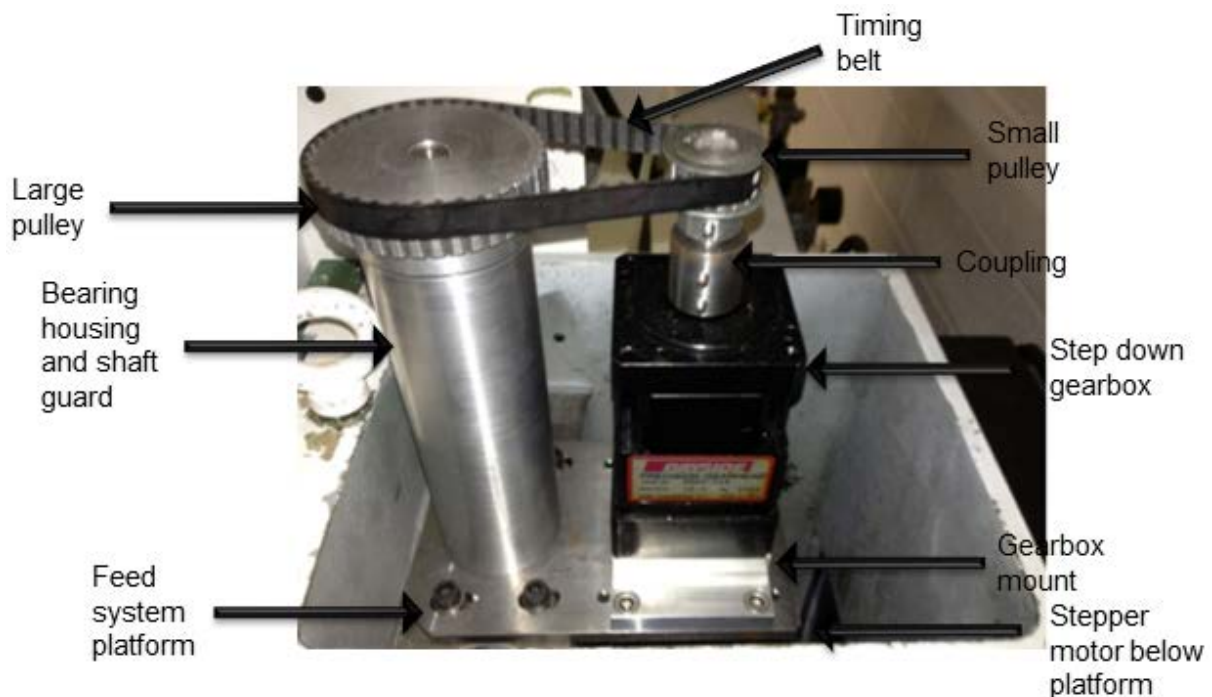


Figure 3-11: Step down gear box

A mounting block was manufactured to couple the gearbox to the stepper motor below the platform. A coupling connected the gearbox shaft to the shaft of the small pulley. The small pulley with 5mm pitch drives the timing belt and thereby driving the large pulley. A drive shaft is coupled between the large pulley and lead screw of the Z-axis aligned by a bearing at the top of the bearing housing. Workpiece clamping and in-process force measurement

In order to carry out the machining tests a workpiece clamping table was designed while to carry out the in-process force measurement tests a separate workpiece platform to incorporate a Kistler piezo quartz force sensor was necessary. The design of the workpiece holding was influenced by a number of factors most notably the flow of the abrasive slurry back to the abrasive slurry tank whereby it could be recirculated back into the cutting zone and the use of non-corrosive materials.

3.7.1 Workpiece clamping table

The workpiece clamping table consisted of 2 parts, the table-top which was made from 304 grade stainless steel and the base made from aluminium as shown in Figure 1.13. The table top contained a series of rows and columns of evenly spaced M6 threaded holes. Clamps made from 304 grade stainless steel are used to clamp the workpiece to the table-top by

means of M6 threaded bolts as shown in Figure 1.13. The M6 holes also provided the path for the abrasive slurry to pass through into the base.

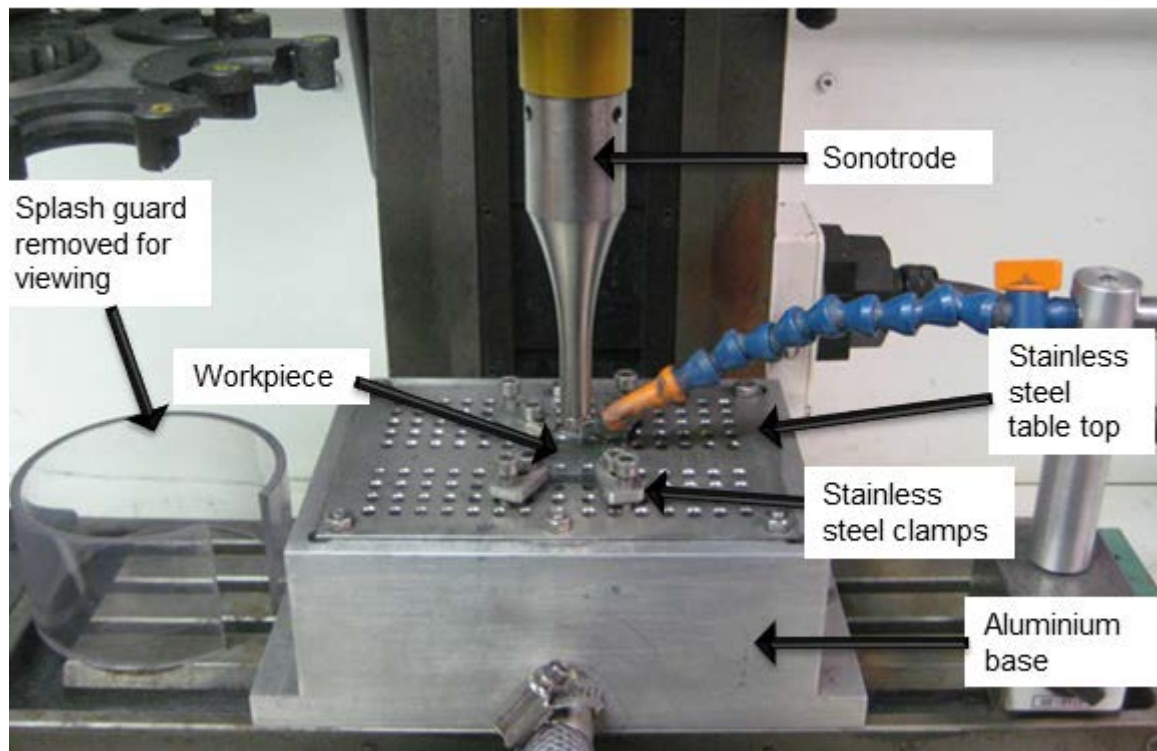


Figure 3-12: Workpiece clamping table (this figure to be replaced with one more suitable)

The base made from a solid piece of aluminium was secured to the machine table by means of 4 x M8 bolts and Tee-nuts. The inside of the base is machined with a slope to direct the spent abrasive slurry towards the front and out a drain point. A hose tail adaptor was threaded into the drain point and the reinforced PVC hose of diameter 25mm was used to carry the abrasive slurry back to the abrasive slurry tank. A polycarbonate splash guard of 100mm outside diameter was introduced during the machining trials. A 25mm wide section was removed from the splash guard to allow access of the recirculated abrasive fluid into the cutting zone.

Chapter 4: Experimental methods and materials

4.1 Introduction

The experimental investigations were carried out in three phases, initially the validation and commissioning of the newly design ultrasonic impact grinding machine was undertaken. Ultrasonic impact grinding process investigations were subsequently carried out using float glass as the workpiece material and Titanium tool and Boron Carbide abrasive with a concentration of 25%. Process parameter studies were undertaken as a screening investigation. Finally wear investigations were undertaken with a focus on the influence of ultrasonic vibration amplitude, feed rate and machining strategy. The methodology is illustrated in Figure 4-1 below.



Figure 4-1: Ultrasonic impact grinding investigation methodology showing investigations in 3 phases of machine, process and wear.

The machine accuracy assessment included an elementary assessment of the axes accuracy given the modification to the z-axis drive train and the details are provided in the Appendix A. The sonotrode vibration analysis involved the use of a Polytec PSV 400 scanning laser vibrometer (SLV) to examine the amplitude change with increasing power settings on the Ultrasonic control and is reported in the Appendix B.

Machining investigations were undertaken using plunge and pecking machining strategies. Plunge machining involved the constant feed of the tool into the workpiece, and the peck machining involved a feed followed by short retracting of the tool and subsequent feed to deeper level. This was undertaken to address possible issues around access of the abrasive slurry to the base of the hole during machining.

Process investigations initially focussed on undertaking a wide ranging screening study to examine which parameters were appropriate for the ultrasonic machining of glass using Boron Carbide abrasive. The table below shows the range of parameters proposed for the screening investigation in the plunging process.

Table 4-1: Machining parameter ranges and proposed structure for recording test data

	Feed rate [mm/min]					
Amplitude of displacement [μm]	3	4	5	6	7	8
0% = 75 μm						
10% = 91 μm						
20% = 104 μm						
23% = 108 μm						
30% = 118 μm						
40% = 131 μm						

Following the screening study on the plunge process, a narrow range of parameters was selected as shown in the Table 4-2 and Table 4-3 below for more detailed analysis of the influence of depth of cut. Similar investigations were carried out for the peck machining strategy.

Table 4-2: Plunge tests with various depths - 0% (75µm) amplitude of displacement trials

	Feed rate [mm/min]			
Depth of cut [mm]	3	5	5.5	6
0.4				
2				
3.6				

Table 4-3: Plunge tests with various depths - 23% (108µm) amplitude of displacement trials

	Feed rate [mm/min]	
Depth of cut [mm]	3	5
0.4		
2		
3.6		

In process force measurements were recorded during the machining investigations, and both tool and workpiece analysis was undertaken. Wear investigations were carried out using a narrow range of parameters in order to examine the influence of feedrate and the influence of vibration amplitude on the tool wear. The wear investigations also considered the machining strategies of plunge and pecking machining strategies. The table below shows the methodology used for the wear investigations.

Table 4-4: Tool wear test - pecking

Tool No.	Length of tool before machining [mm]	Distance machined [mm]	Length of tool after machining [mm]	Tool wear [mm]	Tool wear [%]	Mass of tool before machining [grams]	Mass of tool after machining [grams]
		10					
		20					
		30					
		40					
		50					
		60					
Test parameters: Fixed parameters - feed rate of 3 mm/min, peck 0.1 mm with retract of 0.2 mm Variable parameters – amplitude of displacement, 75 μm, 108 μm							

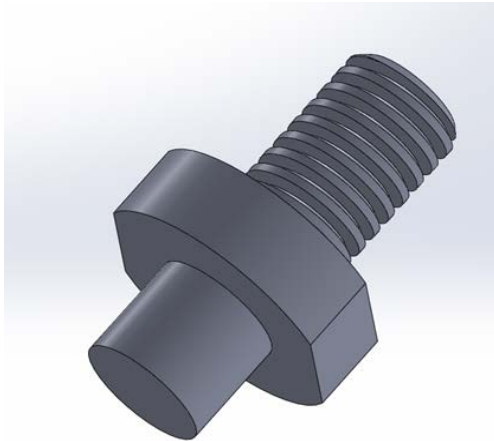
Table 4-5: Tool wear test - plunging

Tool No.	Length of tool before machining [mm]	Distance machined [mm]	Length of tool after machining [mm]	Tool wear [mm]	Tool wear [%]	Mass of tool before machining [grams]	Mass of tool after machining [grams]
		10					
		20					
		30					
		40					
		50					
		60					
Test parameters: Fixed parameters - feed rate of 3 mm/min Variable parameters – amplitude of displacement, 75 μm, 118 μm							

4.2 Ultrasonic tool and workpiece material

4.2.1 Tool

The initial tool was designed, manufactured and fitted by BEK Ultrasonics to ensure the ultrasonic stack was in resonance with the ultrasonic generator. In order for effective machining to take place, the antinodal point – position of maximum amplitude of displacement should be located at the tool tip.



Technical specifications

- Material – Titanium Ti6Al4V
- Tool tip diameter – 6mm
- Tool tip length – 5.2mm
- Tool weight – 3.6 grams
- Thread size – M6
- Tool Hardness – 35.4 HRC

Figure 4-2: Ultrasonic impact grinding tool

Multiples of this tool were subsequently produced in the mechanical workshop of the Dept. of Mechanical & Manufacturing Engineering, Trinity College Dublin.

4.2.2 Workpiece

The workpiece material used for all tests was Pilkington Optifloat™ float glass. Float glass was chosen because of its high surface hardness but very brittle characteristics. It has a hardness of 4.93 +/- 0.34 on the Vickers scale – HRV [109]. The chemical composition of Optifloat™ glass is shown in Table 4-6. Glass workpieces of dimension 25mm x 20mm x 4mm were used for the in process force measurement tests while for the tool wear tests the glass workpieces were 38mm x 35mm x 4mm.

Table 4-6: Chemical composition of Pilkington Optifloat™ glass [110]

Optifloat™	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ /FeO	MgO	CaO	Na ₂ O
%	72.47	0.91	<0.01	4.05	9.08	13.48

4.3 In process force measurement setup

In order to monitor the process force while machining a Kistler type 9051A load cell was selected and a measurement chain was prepared as shown in Figure 4-3 below. It can be seen that the load cell was sensitive in the range of 0 to 12kN. It was necessary to measure the relative motion of the tool relative to the workpiece at the macro scale and an LVDT based displacement transducer was also integrated into the measurement chain.

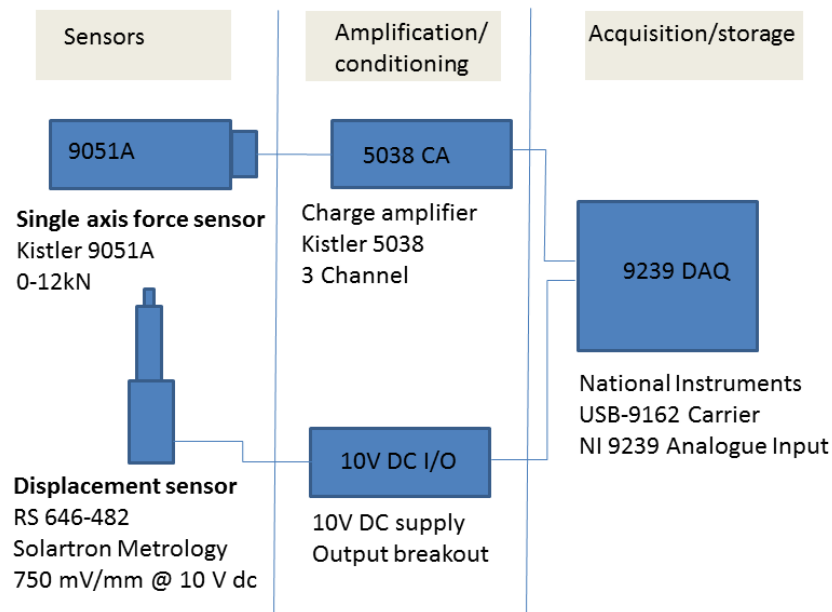


Figure 4-3: Measurement chain showing the force and displacement sensor system.

A dedicated workholding device which could incorporate the Kistler load cell was designed and manufactured. The base of the stage was manufactured using H13 tool steel of thickness 30mm providing a stable base upon which the sensor was mounted, and providing a solid foundation for the preloading bolt which is required to be tightened to a preload of 40kN. The base was secured to the machine table by means of 4 x M8 bolts and Tee-nuts. The workpiece holding platform was machined from grade 304 stainless steel. The platform was designed to have a central work area where the workpiece was held in place using the same clamps as used on the workpiece clamping table. The workholding arrangement was designed such that the abrasive slurry runs off the table into a 15mm wide channel which encircles the central work area. 3 exit channels of diameter 22mm were positioned to the front of the workpiece holding platform and provide sufficient drainage of the abrasive slurry back to the abrasive slurry tank and recirculation system. The figure below shows the arrangement in detail.

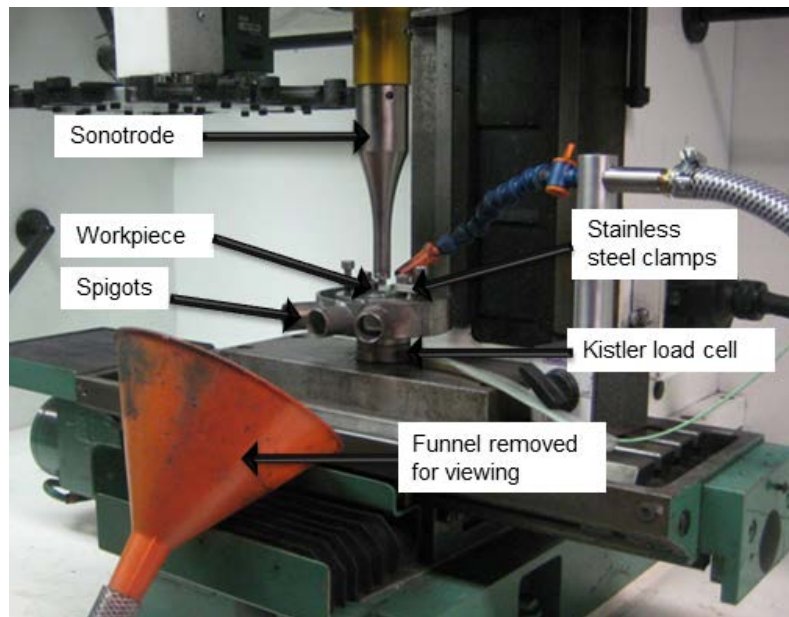


Figure 4-4: Force measurement platform

4.4 Wear measurement setup

To evaluate the tool wear during machining a Dino – Lite digital microscope was set up and a picture was taken of the tool after predetermined depths of cut as shown in Figure 4-5. The technical specifications of the microscope were as follows

- Model – A4013MT Dino-Lite Premier
- Interface – USB 2.0
- Resolution – 1.3M pixels
- Magnification rate – 20x ~50x,.200x
- Sensor – Colour CMOS

In order to record the longitudinal wear of the tool, a dial test indicator as shown in Figure 4-6 was used in combination with the Mach 3 controller to measure the distance between the tool tip and the tool shoulder. The dial test indicator manufactured by Insize, model no. 2380 with graduations of 0.01mm had an accuracy of $3\mu\text{m}$. This measurement combined with the captured image from the USB microscope was analysed and processed using MATLAB to determine the volumetric tool wear.

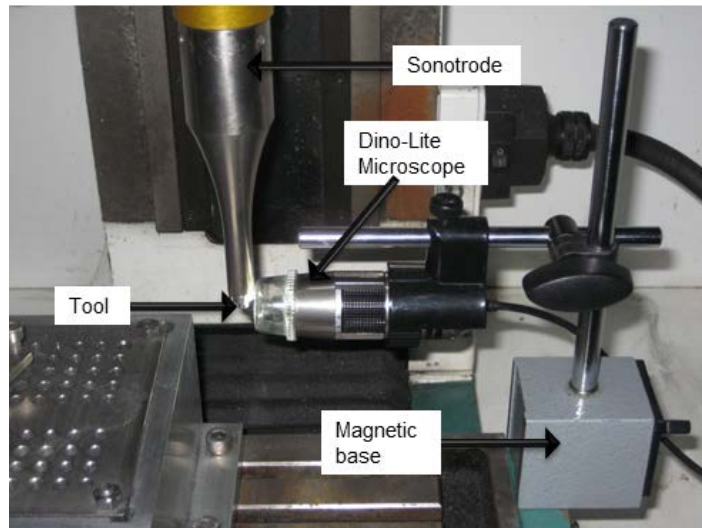


Figure 4-5: Wear measurement with Dino-Lite microscope

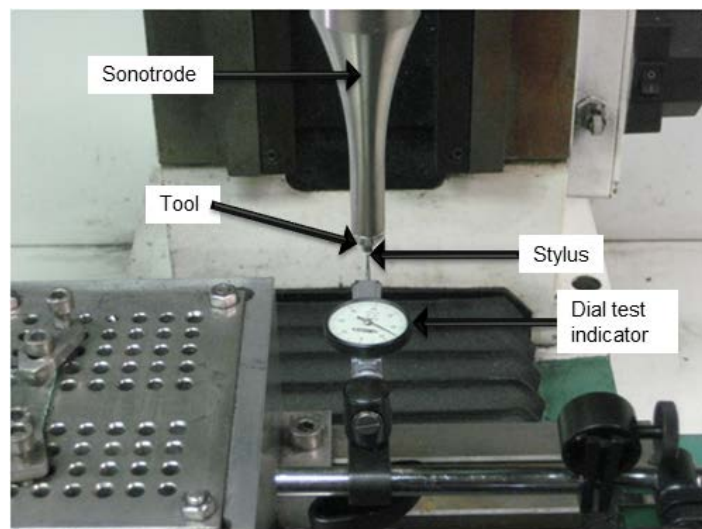


Figure 4-6: Wear measurement with dial test indicator

Chapter 5: Results & Discussion

5.1 Background

As discussed previously, the experimental investigations were carried out in three phases, initially the validation and commissioning of the newly design ultrasonic impact grinding machine was undertaken and the results are presented in the Appendix A. Ultrasonic impact grinding process investigations were subsequently carried out to examine aspects of machining parameters and aspects of tool wear and machining strategy. The process is illustrated below.

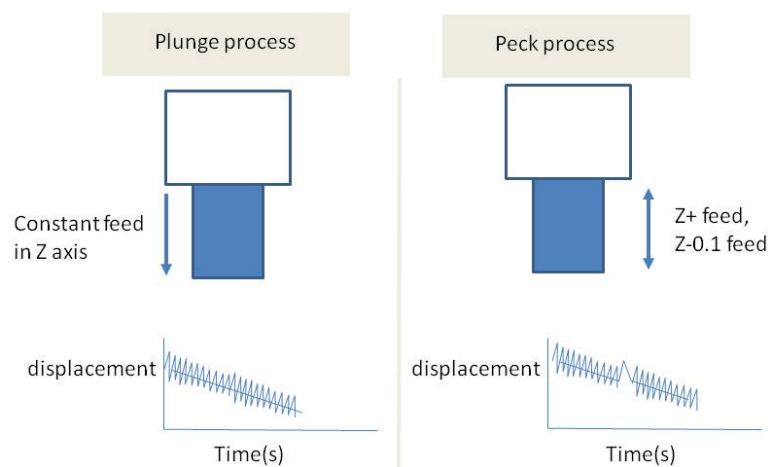


Figure 5-1: The plunge and pecking process illustrated for the investigations undertaken

It can be seen that the plunge process involves a unidirectional motion in the z axis into the workpiece whereas the pecking process involved a bidirectional motion in the z axis in order to facilitate greater access for slurry in the process.

5.2 Machining parameter screening study

An investigation was undertaken to examine the parameter set where the ultrasonic impact grinding process could be considered to be a stable process. Stability for the purpose of definition within this thesis, was defined as a process where workpieces remained intact during processing, i.e. no cracking or fracture of the brittle workpiece, and where the ultrasonic stack and tool operated normally, that is the machining forces did not overload the ultrasonic system. Table 5-1 below shows the region where investigations were carried out. The green areas in the table illustrate the stable regions that machining could be carried out using the work-piece clamping table.

Table 5-1: Results from screening investigations

	Feed rate [mm/min]						
Amplitude of displacement [μm]	3	4	5	6	7	8	8.5
0% = 75 μm	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓x	xxx	
10% = 91 μm	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓xx	xxx	
20% = 104 μm	✓✓✓	✓✓✓	✓✓✓	✓✓✓	xxx	xxx	✓✓✓
23% = 108 μm	✓✓✓	✓✓✓	✓✓✓	✓✓✓	xxx	xxx	✓✓✓
30% = 118 μm	✓✓✓	✓✓✓	✓✓✓	✓✓✓			
40% = 131 μm							
0.4mm depth	Green areas are where machining tests were successful using the workpiece clamping table						
0.4mm depth	Red areas are where machining tests were successful using the workpiece clamping table						
✓	Machining tests with force measurements successful using the process monitoring stage						
x	Machining tests with force measurements unsuccessful using the process monitoring stage						

These tests were carried out using the plunge feed machining strategy to a depth of 0.4mm. Each test was carried out 3 times to ensure repeatability of results. On completion of the tests using the work-piece clamping table the test were then carried out using the process monitoring stage. As can be seen from the table of results, machining of the glass slides was not as successful across the same spectrum of feeds and amplitudes when using the process monitoring stage as when using the work-piece clamping table. It was discovered that this was down an issue of access of the slurry into the working area. Unfortunately in order for the slurry to access the working area of the process monitoring stage there was a danger that the feed nozzle would touch the platform thereby distorting the resultant force readings.

The red sections in the table show the regions where the process stability was not adequate to support successful machining. Among the reasons for this was that when machining at high feeds the forces were too high, the outcome of which lead to either the glass breaking or the ultrasonic system over-loading and cutting out. The mechanism of increased force

generation was hypothesised to be the contact between the sonotrode and the abrasive grit directly with the workpiece surface. It was also observed during these trials that when the ultrasonic system was set at 40% amplitude of displacement it would have the detrimental result of repelling the abrasive slurry away from the cutting zone. In this case, the lack of slurry getting to the cutting zone caused the tool to feed directly into the workpiece causing it to break or over loading of the ultrasonic system. Another outcome of these tests showed that the initial force required to penetrate the surface of the glass was higher than the force required when machining the glass after the surface was penetrated. This phenomenon concurred with the Choi et al. [65] in the literature review which stated that the bonding forces of the silica (Si) molecules on the surface of the of the glass are what makes the initial penetration of the glass difficult. After the tool penetrates the smooth hard surface of the glass the machining load decreases dramatically. The results from these tests allowed a narrow set of parameters to be selected for further experimentation on feed and amplitude changes.

In order to reduce the amount of time taken to carry out wear tests it was necessary to establish a procedure whereby multiple holes could be machined into one large glass slide of dimension 38mm x 35mm x 4mm and thereby reduce the setup times. To do this a campaign of plunge tests at amplitudes of displacements of 0% and 23% and to depths of 0.4mm, 2mm and 3.6mm respectively were carried out at various feed rates. From the results obtained in Table 5-1 it was decided that 6mm/min would be the upper feed rate limit. It was also observed during the screening investigations that 23% amplitude of displacement was the maximum amplitude of displacement which could successfully and consistently machine up to 8mm/min. At higher amplitudes the machining forces become more volatile. Table 5-2 illustrates the results obtained from the 0% amplitude of displacement machining tests.

Table 5-2: Plunge tests with various depths - 0% - 75µm amplitude of displacement trials

	Feed rate [mm/min]			
Machining depth [mm]	3	5	5.5	6
0.4				
2				
3.6				
	Machinable at these parameters			
	Not machinable at these parameters			

The results show the machine was unable to drill to a depth of more than 0.4mm consistently at a feed of 5mm/min or higher. However the results in Table 5-3 show that by increasing the amplitude of displacement to 23% machining at a feed rate of 5mm/min was possible.

Table 5-3: Plunge tests with various depths - 23% - 108µm displacement trials

	Feed rate [mm/min]	
Machining depth [mm]	3	5
0.4		
2		
3.6		
	Machinable at these parameters	
	Not machinable at these parameters	

5.3 Process investigations – machining force results

The initial process investigations focussed on the measurement of process forces during ultrasonic impact grinding using the measurement setup reported earlier. Figure 5-2 below shows the force and displacement data recorded from a plunge machining process on glass with feedrate of 3mm/min, displacement amplitude of 0% - 75µm with 6mm Titanium tooling.

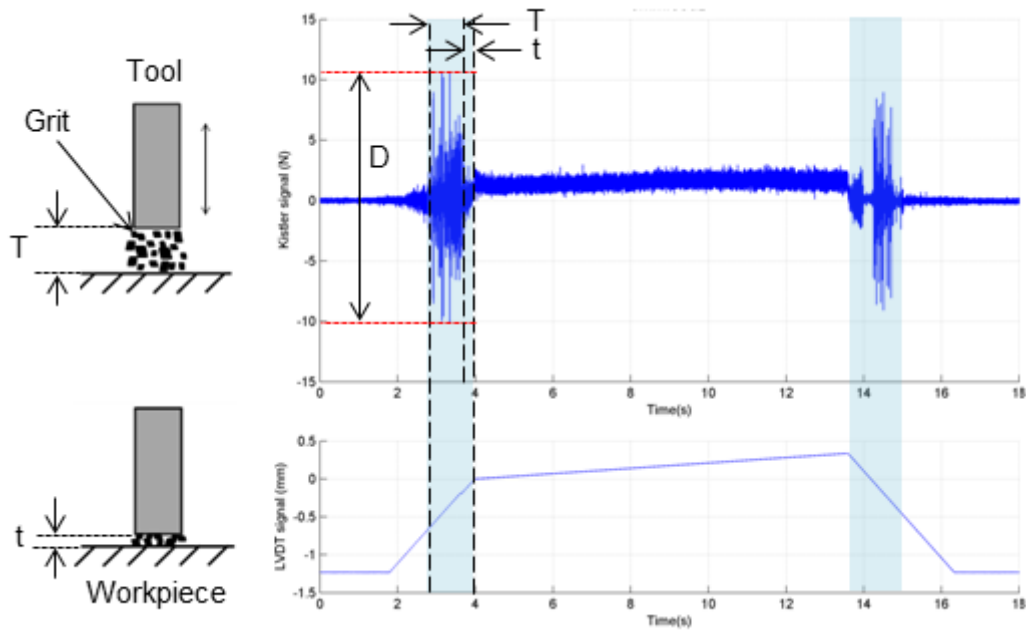


Figure 5-2: Force and displacement data recorded during plunge machining process at 3mm/min feedrate and 0% amplitude.

As can be seen from in the figure the abrasive begins to contact the workpiece at a time approximately 2.8 seconds. The diagrams of the tool machining the abrasive against the workpiece illustrate what is happening during this period. The predominant mechanism of material removal in area *T* is the micro-chipping by impact of the abrasive particles against the workpiece. However, with the amplitude of displacement set at 0% the abrasive grit does not hit the workpiece with enough force to break through the outer surface. The outer surface absorbs this force and it registers as a vibration on the process measuring platform resulting in the highly dynamic region *D*. As the tool approaches the workpiece at approximately 3.8 seconds the hammering becomes the more prevalent mechanism of material removal as illustrated in area *t* and the situation becomes less dynamic. For effective machining the tool should not touch the workpiece, however, observations during the extensive cutting investigations revealed that the time between 4 and 4.5 seconds is the region which has the greatest risk of damage to the workpiece or where overloading of the ultrasonic system would occur.

The region following, from 4 to 13.5 seconds demonstrates a more stable processing region where signal amplitudes and dynamic content appear to be more consistent and in line with the constant feed demonstrated by the displacement of the LVDT. It can be seen that when the forward feed motion ceases and the retraction in the z axes begins, there is again a highly dynamic region.

As shown in Figure 5-3 when the amplitude is set at 23% this area, D of high vibration is reduced significantly and the situation becomes much less dynamic. This may be due to the fact that the impact of the tool on the abrasive grit takes place at much higher velocity and as the grit particles strike the glass workpiece they are able to penetrate the hard surface as can be seen in the diagrams of the tool machining the abrasive against the workpiece.

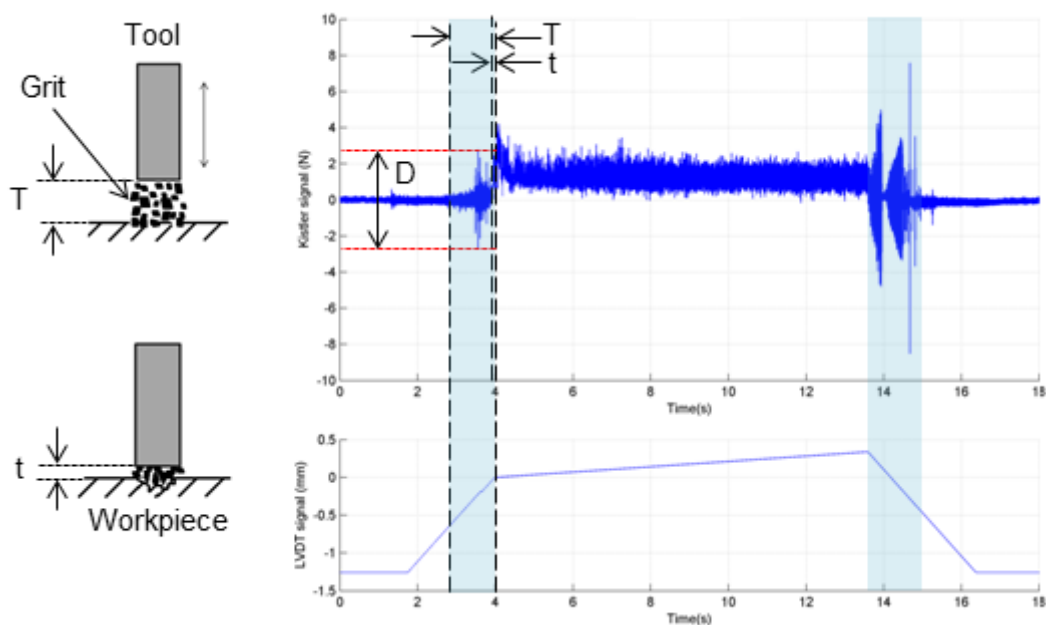


Figure 5-3: Force and displacement data recorded during plunge machining process at 3mm/min feedrate and 23% amplitude.

Figure 5-4 below shows the features that were extracted in order to establish the trends for amplitude and feedrate. It can be seen that a stable process window was identified and the average and range were selected. In addition a further feature of maximum within the window was used where the process was noted to show a dramatic change.

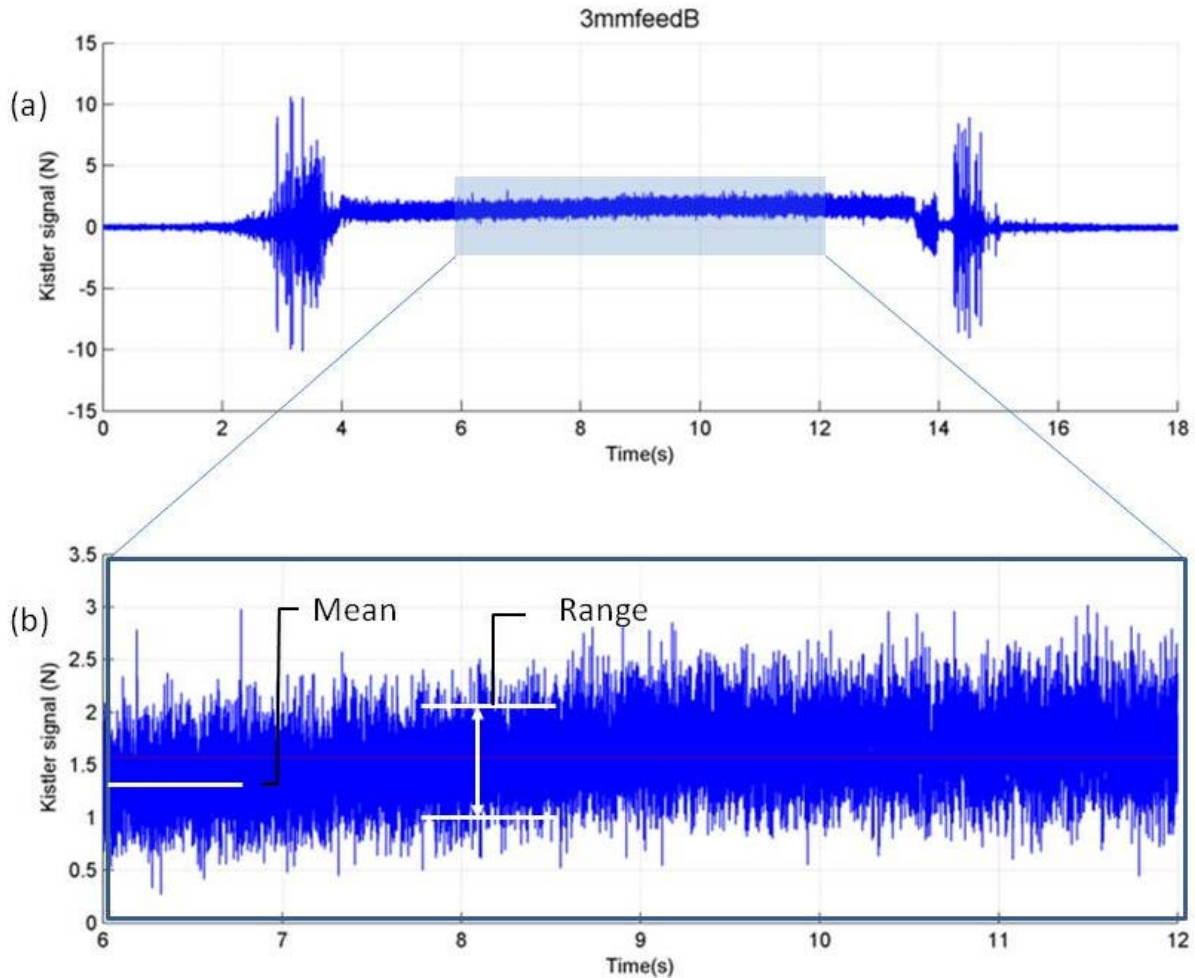


Figure 5-4: Force signal examples of features selected for subsequent trend analysis

Figure 5-4 (a) shows the benchmark stable process where it can be seen that it was possible to define a stable process window, and features such as average force and range of forces could be extracted. From the data shown above, it can be concluded that the force sensing arrangement put in place to monitor the process was capable of revealing measureable phenomena and provide insight into the process and allows the global trends to be explored.

5.3.1 Examination of trends

On examination of the features extracted from the data recorded, the average force at various feed rates and amplitudes was plotted in Figure 5-5. It can be seen that the force observed increases when machining at lower amplitudes of displacement and that machining forces reduce as the amplitude of displacement increases to 23% or 108 μ m peak to peak. It is beyond this point as stated earlier in the screening studies that the machining forces become more volatile. The plotted results also strengthen the case made that while machining at higher amplitudes and when the tool approaches the work piece, micro-

chipping by free impact of the abrasive grit is the most prevalent material removal mechanism.

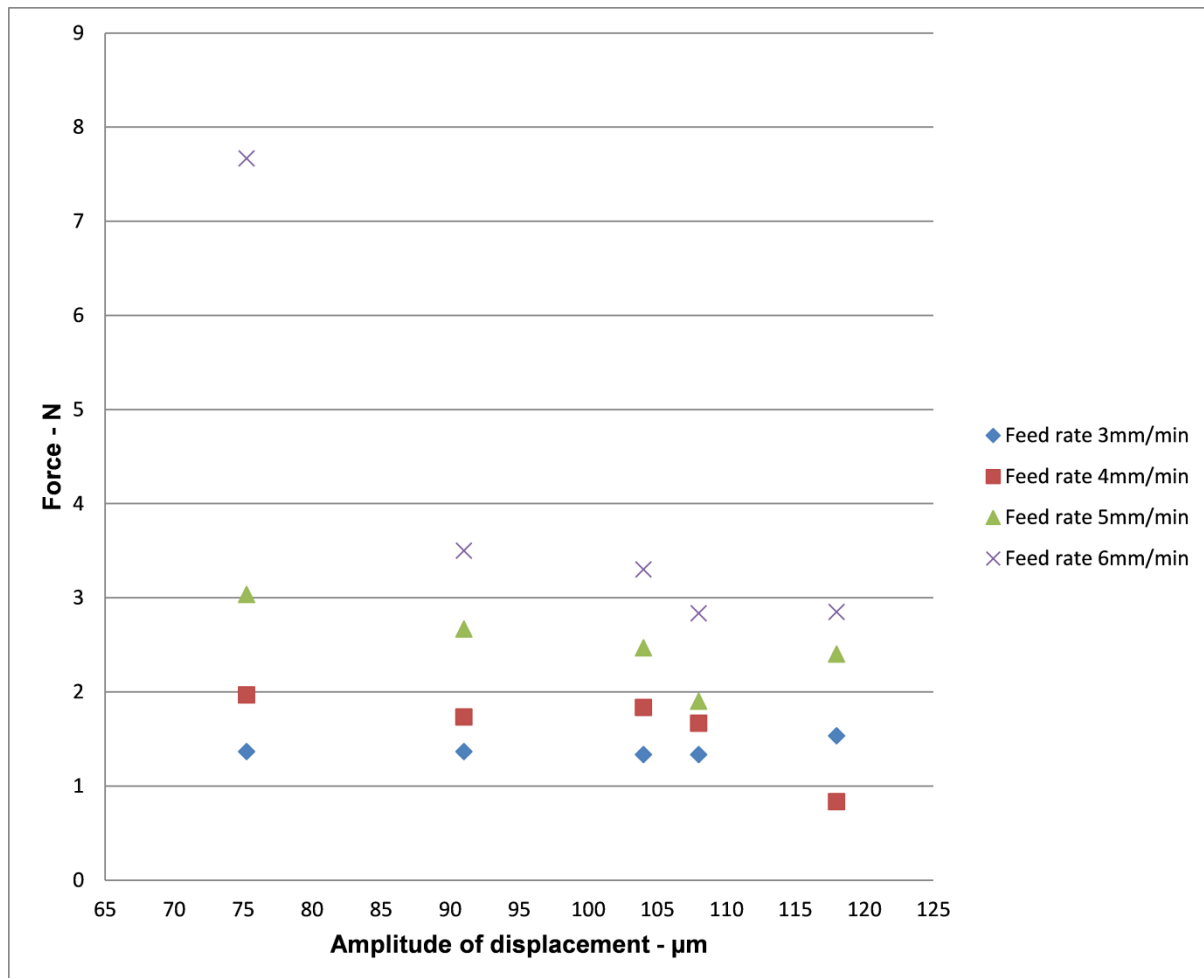


Figure 5-5: Average force plotted against amplitude of displacement

The data therefore suggests the following:

- The machining forces increase as the amplitudes of displacement decreases.
- Amplitude of displacement of 0% - 75μm is not suitable for feed rates above 5mm/min.
- The machining forces become more volatile when the amplitude of displacement of the tool goes beyond 23% - 108μm.

Figure 5-6 below shows the average force plotted against feedrate. These results were taken after the initial surface of the material was broken and a steady state of machining was established.

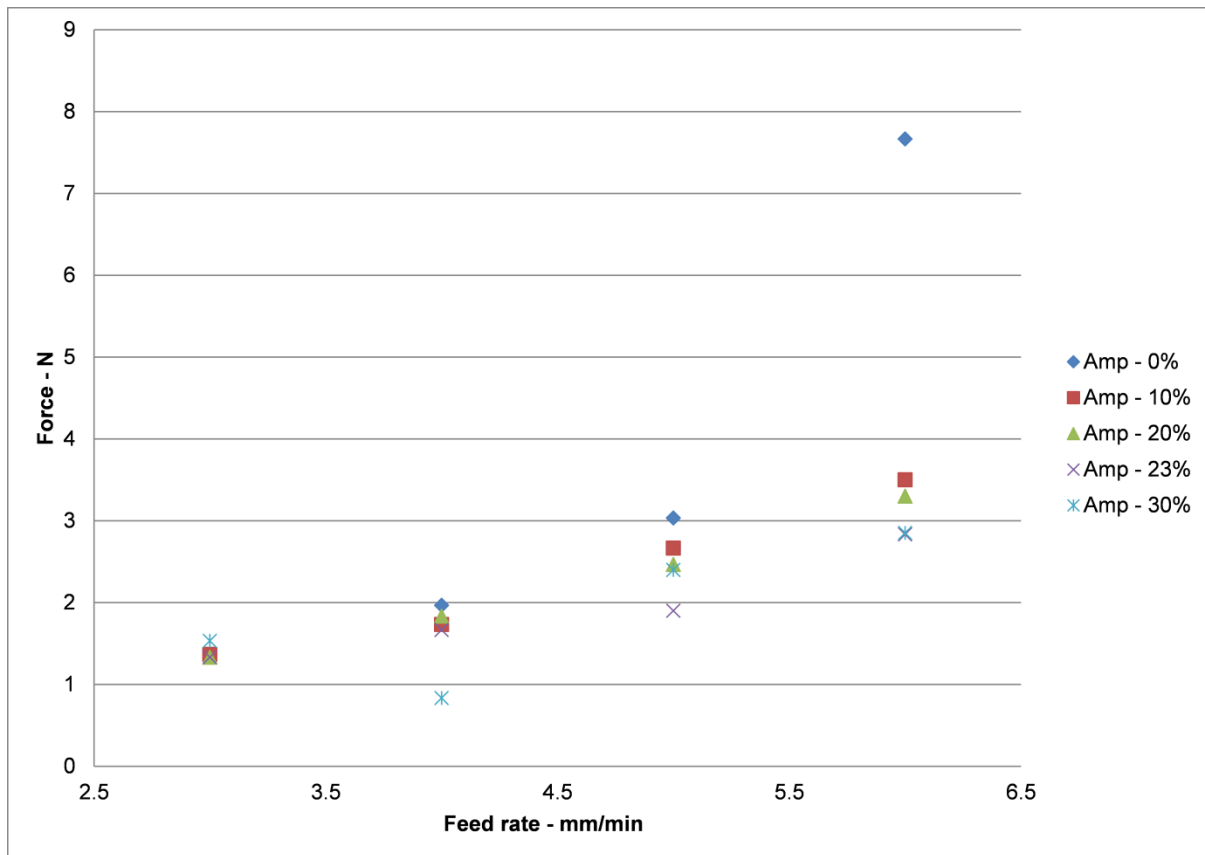


Figure 5-6: Average force data plotted against feed rate

It can be clearly seen from the figure that as the feed rate increases the force increases. The results indicate that steady states of machining at up to 6mm/min are achievable with amplitudes of displacement of between 10% and 30%. The graph shows that the machining forces increase sharply to a 6.333N spread at the lower amplitude of displacement of 0% - 75 μ m.

The maximum force spread across the full spectrum of the data taken from the force measurement tests was plotted against the feed rate as shown in Figure 5-7 to determine what further influencing factors may be involved in the machining process. The results show that 10% - 91 μ m amplitude of displacement was the most stable amplitude of displacement for the ultrasonic impact grinding of glass. This was followed by 20% and 23% amplitude of displacement respectively. 0% amplitude of displacement was stable to 5mm/min feed rate after which point it increased sharply. This would suggest that in order to machine through the hard surface of the glass 5mm/min is the maximum feed rate.

Machining at 30% - 118 μ m amplitude of displacement was volatile at the lower feed rates of 3mm/min and 4mm/min but steadies out at 5mm/min and 6mm/min. However, the machine parameter screening study indicated it was not possible to machine any faster than 6mm/min at 30% - 118 μ m amplitude of displacement.

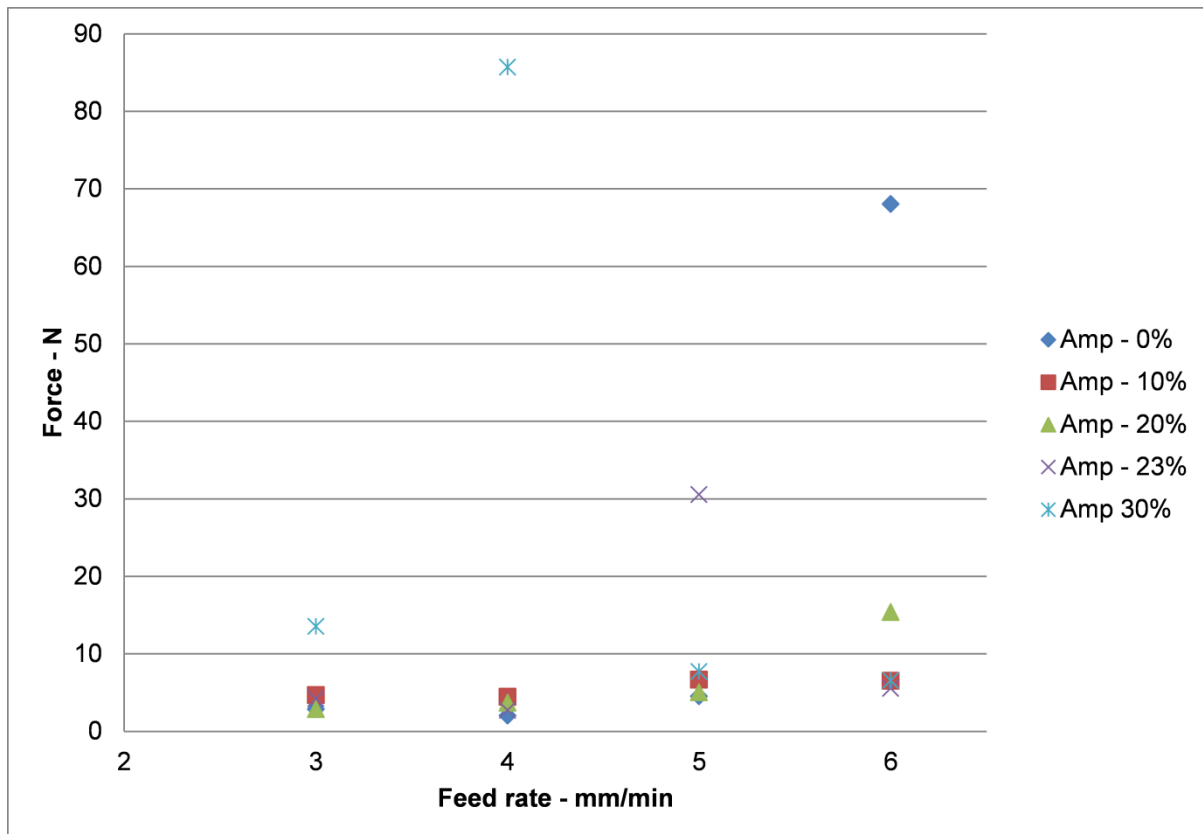


Figure 5-7: Maximum force spread plotted against feedrate

5.3.2 Force measurement during pecking

As stated in the Chapter 4, peck machining involved a feed followed by short retracting of the tool and subsequent feed to deeper level. Peck drilling in the conventional sense is used to reduce the amount of heat to the drill bit and to flush away swarf or debris from the working area. The method was incorporated into the ultrasonic impact grinding process to examine how it would influence the machining forces and tool wear. With regard to the machining forces the evidence shows that the pecking process is more complex and the forces experiences by the process present a more complex contact scenario. Resulting from the complex data and the issues with the underlying drift in the force sensor, further detailed analysis of the pecking process was considered outside the scope of the current work. Figure 5-8 shows the complexity of force measurement graph produced from machining a depth of 4mm at 3mm/min feed rate and at 0% - 75 μ m amplitude of displacement of the tool.

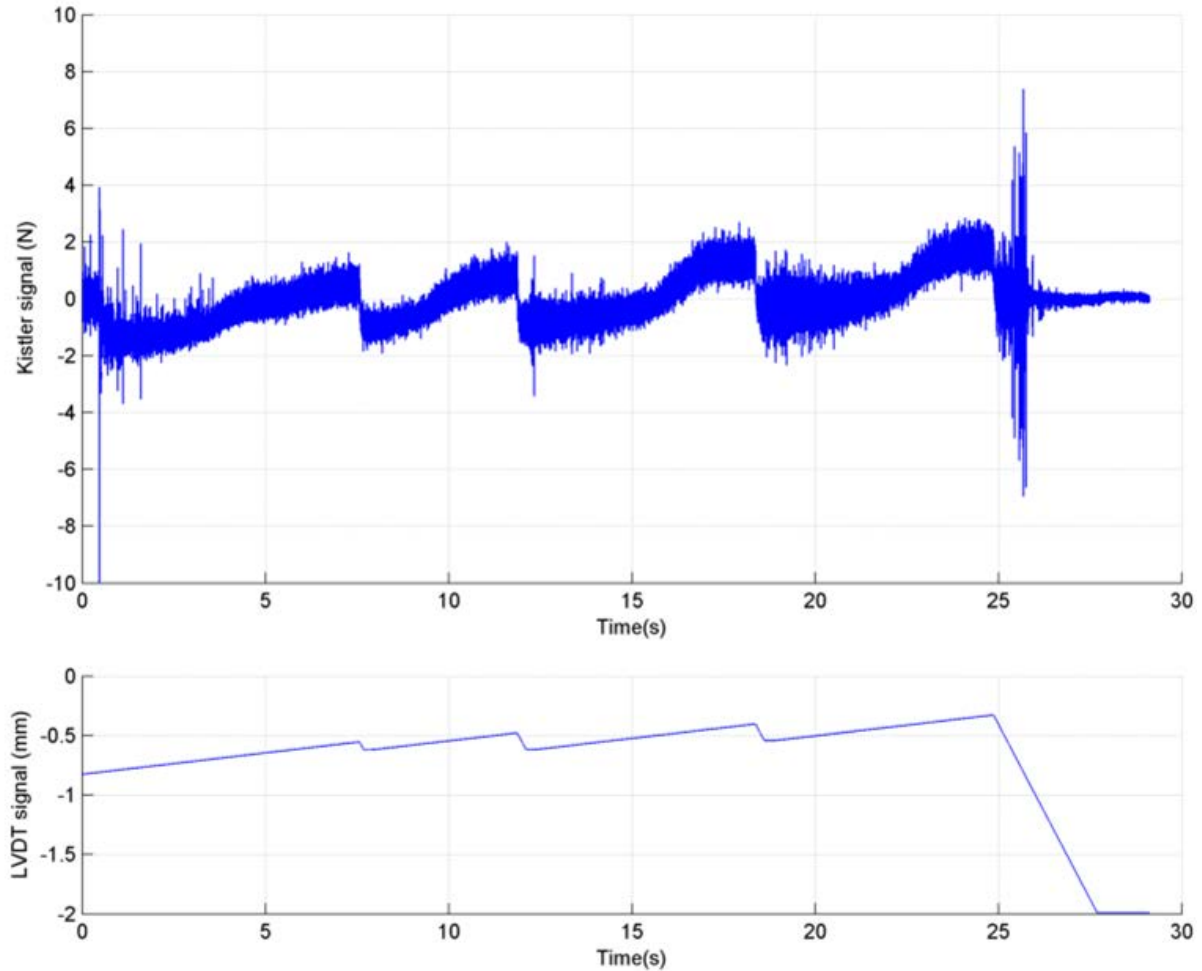


Figure 5-8: Example of the force data recorded during the pecking process

It can be seen that there was an underlying drift over the machining process window, i.e. in the first feed step from approximately 0 up to approximately 7.5 seconds. The retraction of the tool is clearly observed and the subsequent feed. Further work on developing a more sophisticated position orientated force measurement system may help to manage issues with drift in this type of scenario, but this was outside the scope of the current work.

5.4 Wear investigation

The wear investigations were carried out using the structured approach as shown in Table 5-4. From the information retrieved from the screening study a fixed set of parameters for the wear investigations in both the plunging and pecking machining processes were adopted. A total machining distance of 60mm was chosen also as an outcome of the screening study, as a quantifiable measurement of tool wear could be achieved at this distance.

Table 5-4: Structured template to document wear investigations

Tool No.	Length of tool before machining [mm]	Distance machined [mm]	Length of tool after machining [mm]	Tool wear [mm]	Tool wear [%]	Mass of tool before machining [grams]	Mass of tool after machining [grams]
		10					
		20					
		30					
		40					
		50					
		60					
Test parameters: Fixed parameters – Feed rate of 3 mm/min Pecking, 0.1 mm with retract of 0.2 mm /plunging Abrasive – Boron carbide Grit size – F240 mesh Variable parameters – amplitude of displacement, 75 μm, 108 μm							

5.4.1 Tool wear

The tools used were manufactured from Grade 5 Titanium - Ti6Al4V with a hardness of 35 HRC. To examine of tool wear, an image of the tool was taken by digital microscope and a linear measurement taken by a dial test indicator in conjunction with the Mach 3 controller at predetermined machining distances. Figure 5-9 shows the development of the tool wear in tool 2 and tool 13. These tools are chosen to illustrate the 2 extremities of tool wear achieved during the tool wear testing campaign. Tool 2 having the least amount of wear was used to peck at a feed of 3mm/min and amplitude of displacement of 0% - 75 μ m. Tool 13 having the most amount of wear was used to plunge at a feed of 3mm/min and amplitude of displacement of 30% - 118 μ m.

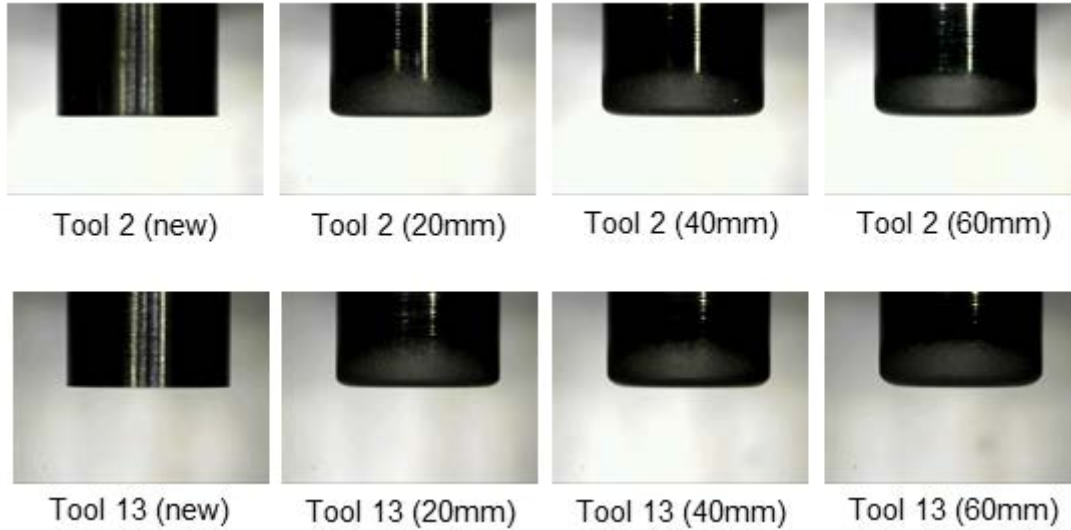


Figure 5-9: Tool wear at various stages of development for tools 2 and 13

Once all the results from the above measurements and photos were compiled it was uploaded to the MATLAB program for image analysis and a peripheral volumetric tool wear evolution could be calculated. The evolution of the tool wear was developed as shown in Figure 5-10. The technique for image analysis of the tools is highlighted in Appendix C.

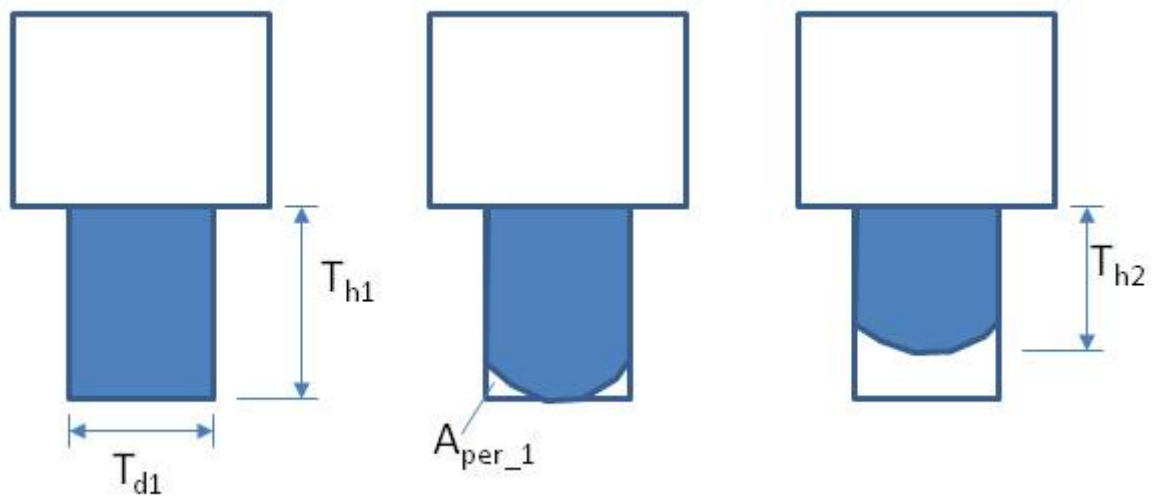


Figure 5-10: Tool wear evolution: T_{d1} = diameter of tool

T_{h1} = original height, T_{h2} = height after machining, A_{per_1} = peripheral volume

An example of the results from image analysis of the tool wear for tools 2 and 13 is shown in Table 1.5. For the purpose of viewing the table shows that 3 runs of image analysis were carried out. From the analysis an average volumetric tool wear measurement was achieved.

Table 5-5: Image analysis results for Tool 2 and Tool 13

<u>Photo/Tool</u>	<u>Run 1</u>	<u>Run 2</u>	<u>Run 3</u>	<u>Standard deviation</u>	<u>Average wear [mm³]</u>
Tool no 2 new	0	0	0	0	0
Tool no 2 after 20mm	0.461855	0.53256	0.516618	0.03708623	0.503677667
Tool no 2 after 40mm	0.796729	0.847376	0.770702	0.038990224	0.804935667
Tool no 2 after 60mm	0.957163	1.200777	1.19385	0.138694208	1.117263333
Tool no 13 new	0	0	0	0	0
Tool no 13 after 20mm	0.859802	0.863632	1.020386	0.091627604	0.914606667
Tool no 13 after 40mm	1.309457	1.341152	1.555043	0.133582943	1.401884
Tool no 13 after 60mm	1.855033	1.758274	1.782314	0.050379028	1.798540333

5.4.2 Tool wear results – impact on the tool

Figure 5-11 shows the wear evolution as measured by the change in height of the tool during machining at a constant feed rate of 3mm/min and under varying amplitudes of displacement. The figure illustrates the results for both the pecking and plunging machining strategies.

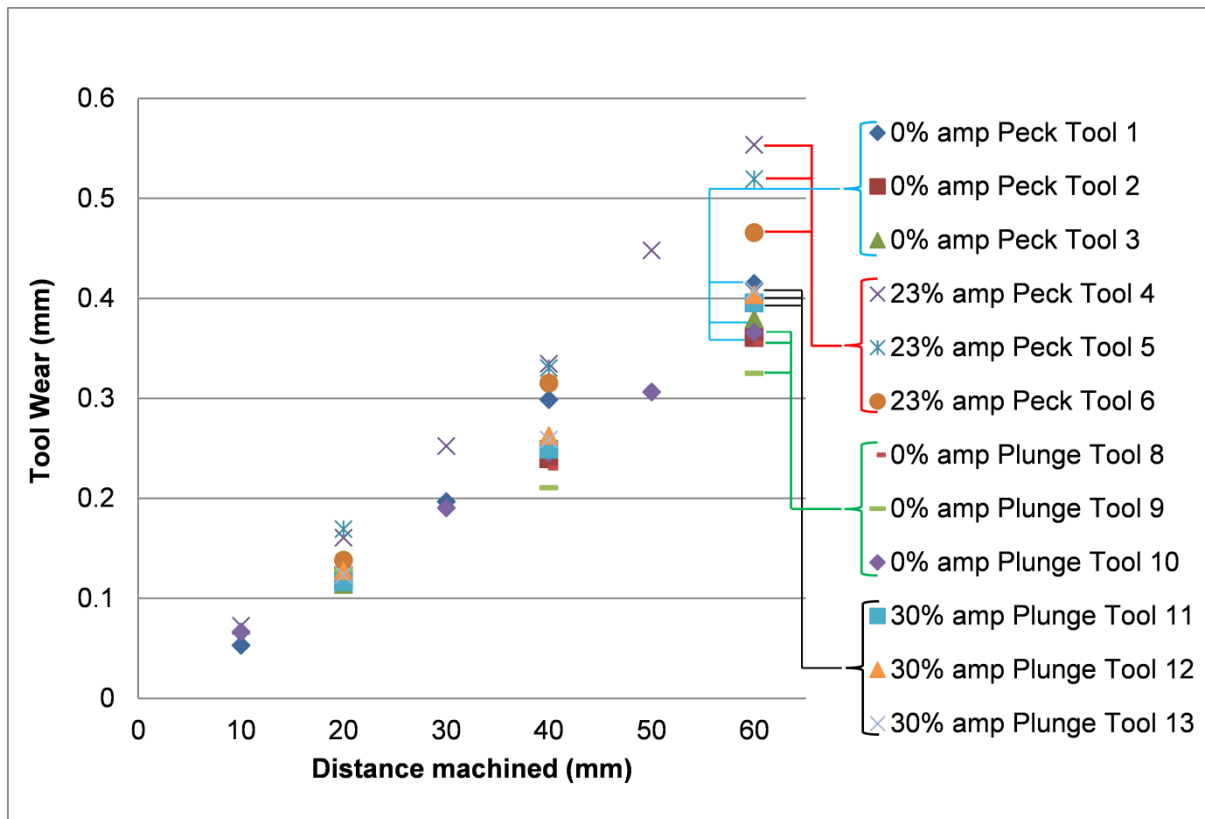


Figure 5-11: Individual Tool wear at feed rate of 3mm/min plotted against distance machined

The figure shows that after 60mm of machined distance with each tool, the longitudinal tool wear is highest when pecking at 23% amplitude of displacement and lowest when plunging at 0% amplitude of displacement. Looking also at the average tool wear values in Figure 5-12 it can be seen that higher amplitude of displacement in both plunging and pecking modes also leads to higher tool wear. The figure also indicates that pecking yields the most longitudinal tool wear of the 2 machining modes. One reason for this is that as the tool needs to cover more distance to reach the final depth, because it is constantly pecking and retracting, it comes into contact with much more abrasive grit than it would during a plunge feed mode.

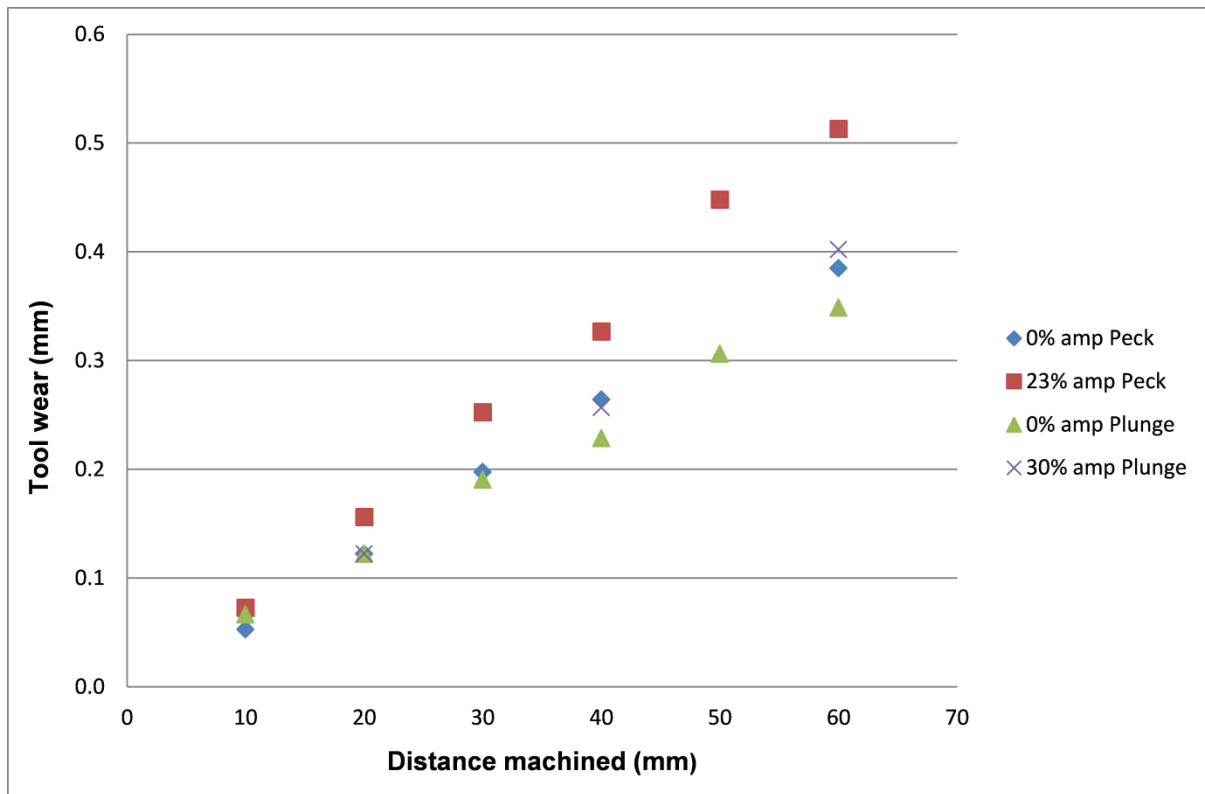


Figure 5-12: Average Tool wear at feed rate of 3mm/min plotted against distance machined

Figure 5-13 shows the peripheral volumetric tool wear at feedrate of 3mm/min, with various amplitudes and strategies. In contrast to the results shown for longitudinal tool wear, it is plunge feeding at 30% amplitude of displacement which results in the highest peripheral volumetric tool wear and 0% pecking which has the lowest peripheral volumetric tool wear. The phenomenon of the higher volumetric tool wear rate at 30% amplitude of displacement suggests that lateral wear because the lateral vibrational movement of the tool at the higher amplitudes of displacement is becoming an influencing factor. This may also explain the volatility of the machining forces above 23% amplitude of displacement as shown in the earlier examination of trends section.

What is also noted from the figure is that tool no 1 which is peck feeding at 0% amplitude of displacement shows more signs of volumetric wear over the initial 10mm of machining than tool no 4 which is peck feeding at 23% amplitude of displacement and tool no. 10 which is plunge feeding at 0% amplitude of displacement.

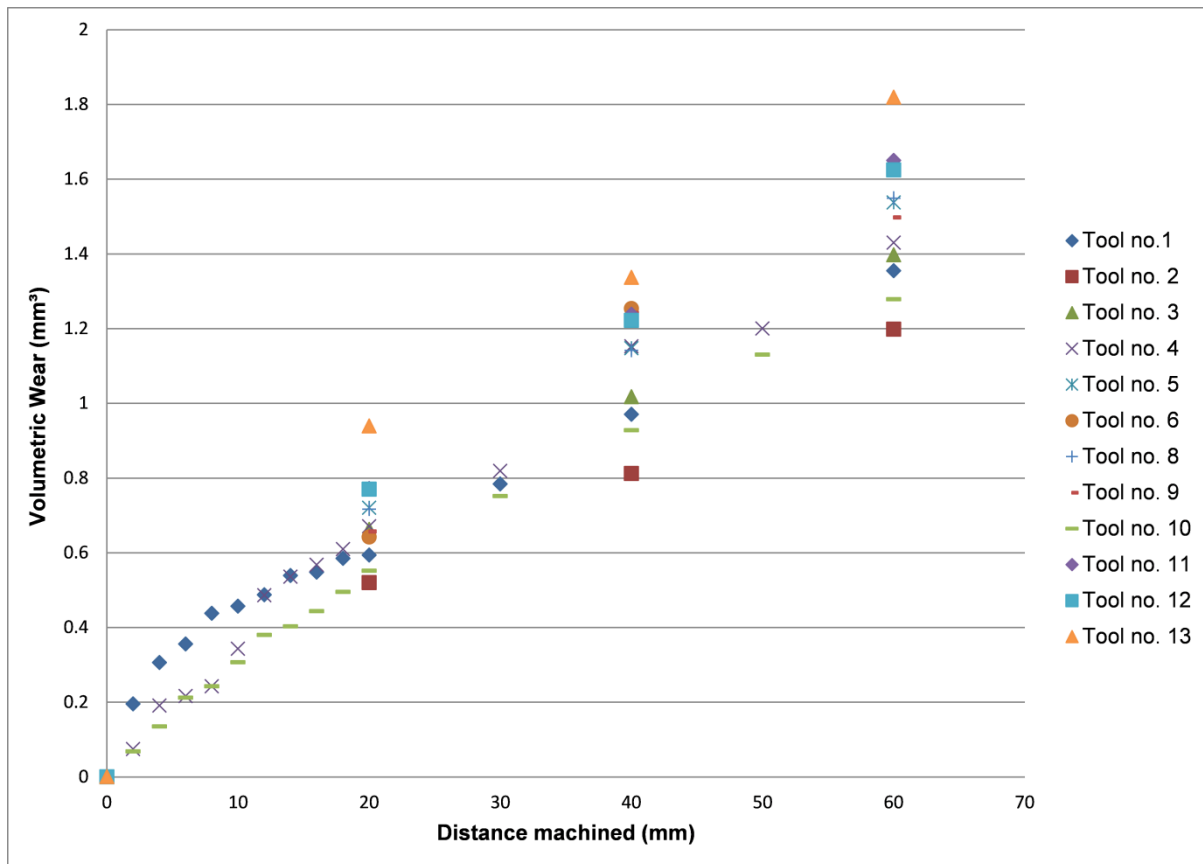


Figure 5-13: Peripheral volumetric tool wear at feed rate of 3mm/min plotted against distance machined

The process description summary for the tools outlined in Figure 5-13 is as follows:

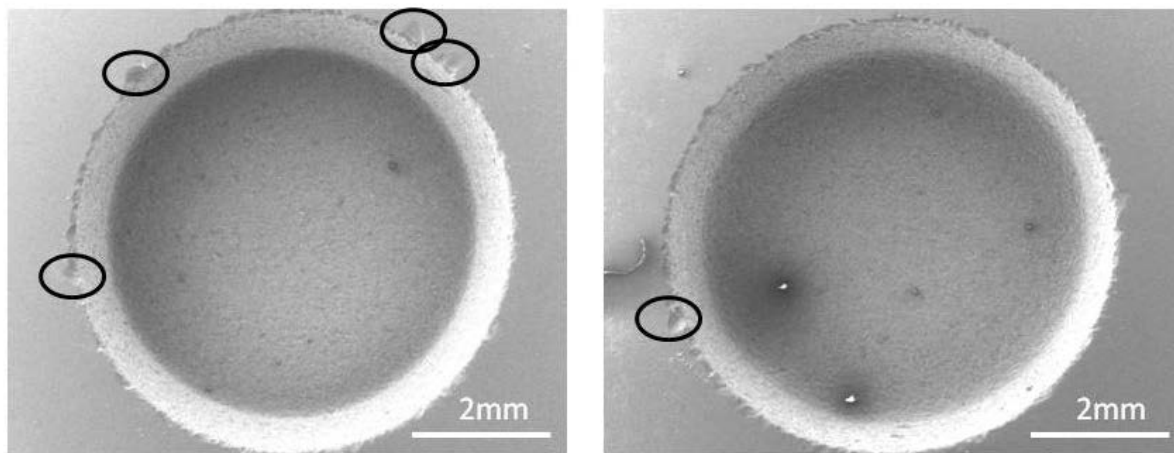
- Tool 1 – 3 are peck machining at 0% amplitude, tool 1 has a reading every 2mm depth up to 20mm deep and every 20mm thereafter.
- Tool 4 – 6 are peck machining at 23% amplitude, tool 4 has a reading every 2mm depth up to 20mm deep and every 10mm thereafter.
- Tool 8 – 10 are plunging machining at 0% amplitude, tool 10 has a reading every 2mm depth up to 20mm deep and every 10mm thereafter.
- Tool 11 – 13 are plunging machining at 30% amplitude

5.4.3 Summary of tool wear results

- Longitudinal tool wear is highest at 23% Pecking
- Longitudinal tool wear is lowest at 0% Plunging
- Peripheral volumetric tool wear is highest at 30% plunging
- Peripheral volumetric tool wear is lowest at 0% Pecking
- Tool wear increases with amplitudes of displacement of the tool

5.4.4 Tool wear impact on workpiece

The impact of tool wear on the workpiece was examined by selecting workpiece samples machined using new and used tools, and undertaking examination of their comparisons using a Tescan Mira scanning electron microscope (SEM) as shown in Figure 5-14.



(a) Hole machined using new tool

(b) Hole machined using old tool

Figure 5-14: Scanning electron microscope (SEM) images of machined workpieces

The image suggests that the micro-chipping around the periphery of entry to the machined hole is greater when using a new tool than that of using a used tool. This can be explained as follows. As the new tool approaches the workpiece all of the surface area at the bottom of the tool comes in contact with the abrasive and the workpiece at the same time. As mentioned by Choi et al. [65] in the literature, there are high bonding forces of the silica (Si) on the surface of the glass. As seen during the machining parameter screening study the force generated to penetrate the surface was higher than when machining beneath the surface. The micro-chipping in Figure 5-14(a) is caused when the abrasive is hammered through the glass surface at this high force. The reason the micro-chipping is not as prevalent in Figure 5-14(b) is because over the time spent machining the used tool has become rounded as shown in the tool wear studies. When the used tool approaches the workpiece it impacts the abrasive grit against the glass surface in a more gradual way. By the time the full diameter of the tool is passing into the workpiece the centre of the hole has already been machined away and the penetrating forces at this stage are much less.

Figure 5-15 below shows the image of the surface of the bottom of the hole of the workpiece. This workpiece was machined at a feed of 3mm/min and amplitude of displacement of 0% - 75µm. The image set a magnification of 210x illustrates that the material removal is by way of

brittle fracture. The hole in the workpiece has been machined using a new tool. The surface roughness at the bottom surface of this hole was measured at 4.14 Ra using a Mitutoyo surfest SJ401 profilometer.

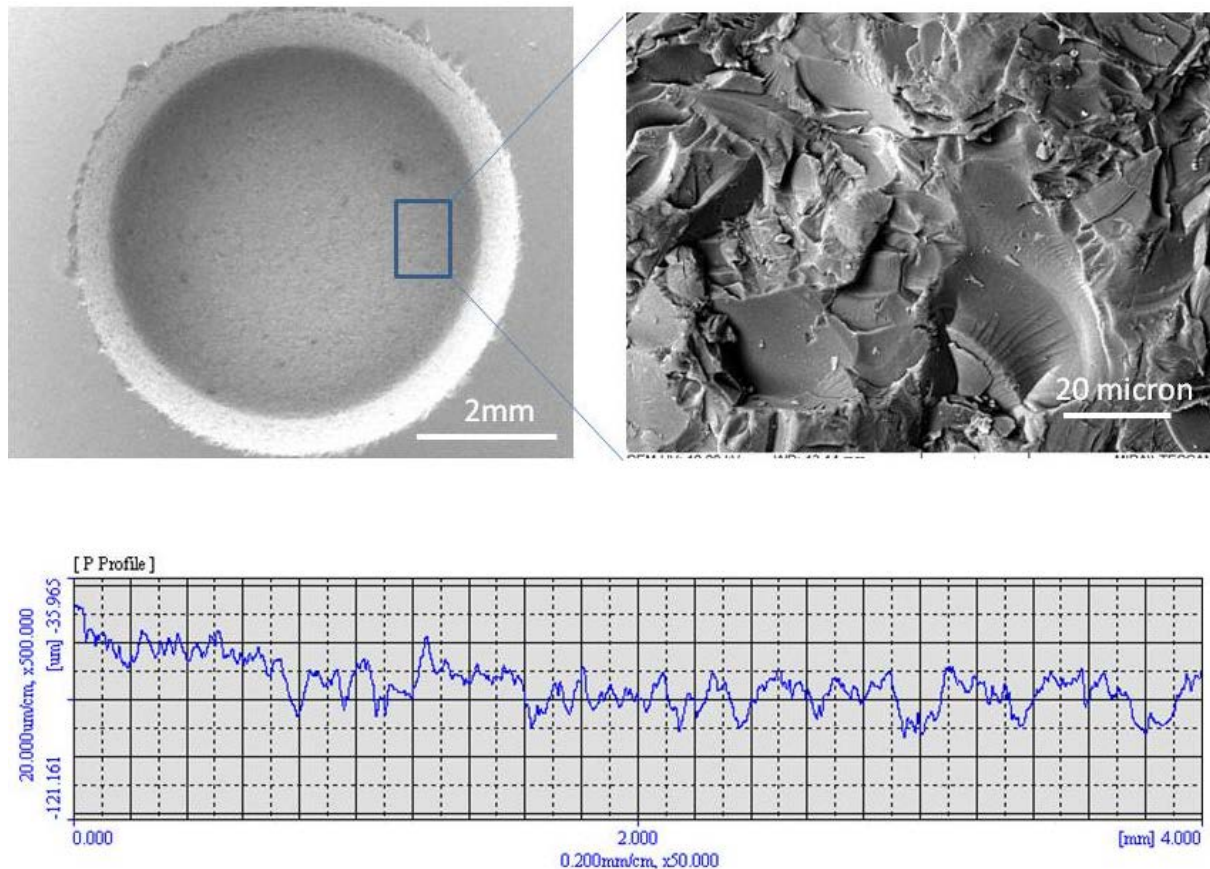


Figure 5-15: SEM and surface roughness of workpiece machined with new tool at 3mm/min and an amplitude of displacement of the tool being 0% - 75μm

A surface measurement of 4.22 Ra was also taken from the base of the hole of a workpiece machined at feed of 3mm/min and amplitude of displacement of 30% -118μm as seen in Figure 5-16. Also using a new tool the test indicates that the difference in amplitude of displacement only showed a slight increase when using the higher amplitude.

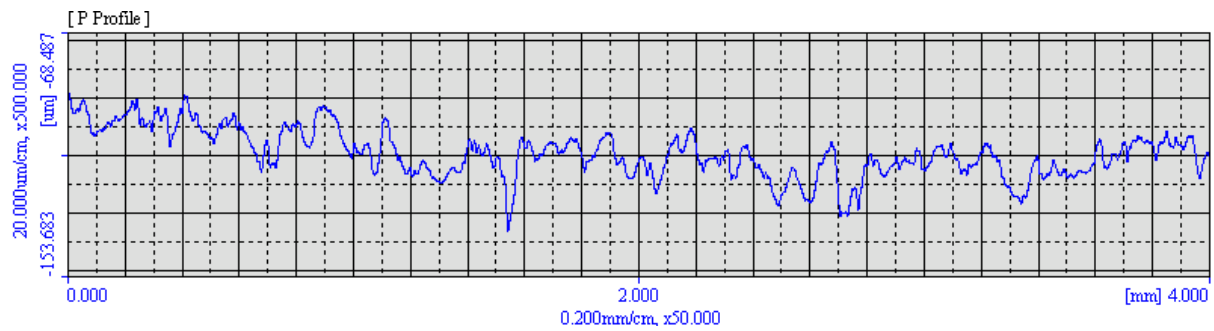


Figure 5-16: SEM and surface roughness of workpiece machined with new tool at 3mm/min and an amplitude of displacement of the tool being 30% - 118µm

The SEM images of periphery of the base of the holes were taken to highlight the effect of tool wear has on the machining accuracy. In Figure 5-17 it can be seen that the cross sectional image magnified to 184x of the base has a well-defined straight edge to the base of the hole.

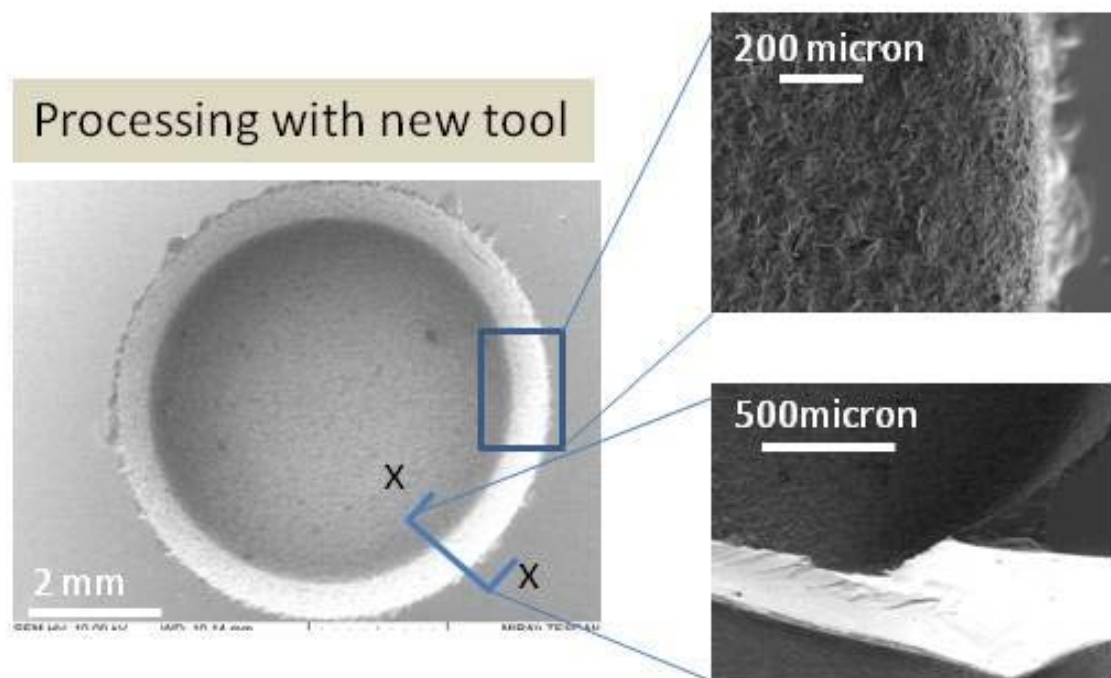


Figure 5-17: SEM examples of workpiece edge and base after machining with new tool

However, in the SEM image of the periphery of base of the hole in Figure 1.18 it can be seen that at a magnification of 129x, the used tool has machined a radius. This concurs with assessment made by Adithan [62] in the literature that when the slurry is fed externally with the point of feeding kept constant, rounding off at tool entry occurs during the ultrasonic impact grinding of holes.

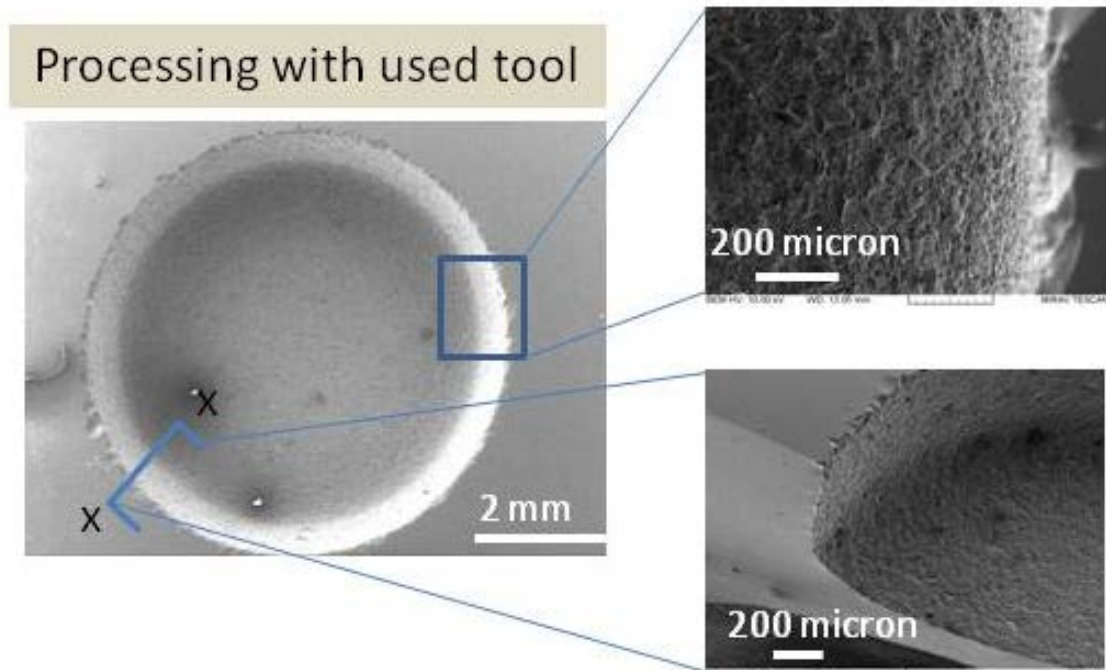


Figure 5-18: SEM examples of workpiece edge and base after machining with used tool

CONCLUSIONS

Ultrasonic Impact Grinding (UIG) is mechanical material removal process used to erode holes and cavities in hard and brittle materials such as glass, ceramics, silicon carbide, quartz and titanium as examples by using shaped tools, high frequency mechanical motion and an abrasive slurry. An old but relatively unknown technique in the micromechanical systems community, the process is effective whether the workpiece material is conducting or not. The machined workpiece has little or no subsurface damage and does not suffer thermal damage. The process has numerous advantages such as the ability to machine high tolerance through holes, to carry out micromachining, and to carry out cutting at high aspect ratios. Ultrasonic impact grinding is often preferred over conventional machining approaches as it can machine intricate features in advanced materials with hardness values of greater than 40 Rockwell Hardness (HRC). The use of CNC control to generate motion profiles for ultrasonic impact grinding is emerging as a new area of interest, as traditional approaches have focussed on sinking processes.

Machine development

The development of the ultrasonic impact grinding machine tool was based on a traditional 3 axes CNC controlled machining platform. A state of the art CNC control system was integrated to control the tool motion. An ultrasonic sonotrode with associated control was also integrated into the system. Finally an abrasive slurry handling system and workpiece clamping system were developed and integrated. The designed machine was shown to be fully capable of machining brittle materials such as glass. It was noted that the motion control in the z axes was the most critical as the main abrasive erosion action was taking place in this axis direction. Within this research work a modified z axes drive was integrated in order to provide more precise motion control in the z axis.

The performance of the ultrasonic sonotrode and tool were examined using a scanning laser vibrometer in the range from 0 to 40 kHz. It was noted that vibration amplitude measured by the laser vibrometer correlated with the % displacement set by the ultrasonic power supply, in a linear manner. The validation of this control functionality using the laser vibrometer has not been reported in the literature up to now.

The main conclusion that can be drawn from the design and development work is that traditional 3 axes machine tool platforms at bench top scale are a suitable platform for hosting an ultrasonic impact grinding sonotrode. The designed machine tool, provides the

potential for detailed process level analysis, and also offers a potential commercial solution for ultrasonic impact grinding.

Process parameters

The investigations were undertaken initially using a screening approach whereby 2 machining strategies namely pecking and plunging of the tool were chosen for investigation. Both strategies were tested using a wide range of machining parameters i.e. amplitude of displacement of the tool and feed rate, for the stable machining of glass using a Boron Carbide abrasive. It was concluded from the process parameter investigations that it was possible to bring together a combination of the various parameters for the successful machining of glass.

Force measurement

In order to be able to undertake a detailed analysis of the process characteristics, it was necessary to develop an in-process measurement system of process forces. The process forces were measured through the integration of a Kistler 9051A single axis force sensor and the development of a workpiece holding platform complete with a clamping system suitable for glass.

The process force measurement provided significant insight into the limiting factors of the machining process and also of the interaction of the process parameters. The in-process force measurements has shown that the machine feed rate and the amplitude of displacement of the tool and a combination of both are all critical factors for successful ultrasonic impact grinding operations. Through the use of the force measurement system process influencing characteristics of the workpiece material were also identified. A critical region when the tool was in close proximity to the surface was identified and it was noted that machining the initial layer of material on the surface of the workpiece required greater machining forces. It was observed that in the optimum parameter set, the force remained relatively constant in amplitude and the dynamic range was also consistent. At higher feed rates it was possible to randomly generate significant forces with potentially catastrophic implications for the workpiece. Similarly at high amplitudes it was noted that the abrasive slurry could be washed out of the interface zone leading to contact between the sonotrode and workpiece again leading to catastrophic damage. It can be concluded that through the integration of the force sensing system, the process can be characterised and a process parameter set for successful machining operations can be identified.

Wear measurement

The experience of the tool during extended machining was viewed as an important aspect based on the literature review; as it is known that the tool can change geometry due to wear. A vision based tool wear measurement technique was developed and integrated into the experimental set up to evaluate the effect of the process parameters on tool wear. An investigation tracking the evolution of tool wear using a combination of process parameters and machining strategies was undertaken from which influencing factors on tool wear were identified. It was noted that for the straightforward cylindrical geometry used in the investigations, that a change in height of the tool and rounding of the edges were the predominant wear mechanisms. For the range of parameters and duration of machining, it was observed that the height change and the peripheral volumetric wear was linear. It was also noted that the new tool geometry due to wear was replicated in the workpiece material. The outcome of this characterisation can be used to understand the impact of wear on the workpiece geometry and presents a foundation for further work on tool wear during ultrasonic impact grinding of glass.

Overall it can be concluded that a bench top ultrasonic impact grinding machine tool system with CNC control can be used for the machining of hard and brittle materials. The use of structured screening studies, process parameters and machining strategies can be identified. It can be concluded that the use of the developed process monitoring system for in-process measurement of forces and the quantification of tool wear can provide significant insight into the process mechanisms and the evolution of tool wear. The platform developed and technical and scientific work undertaken within this research provides a foundation for further study into the ultrasonic impact grinding process.

Future work

Future work in the area of ultrasonic impact grinding could follow a number of paths.

Development of the machine tool

The ability of the ultrasonic impact grinding machine tool in its format to undertake the machining of 2D or 3D freeform surfaces has to be explored. A further development may be the integration of an additional axis to be integrated between the machine tool headstock and the ultrasonic stack – the convertor, booster and sonotrode.

Development of process parameters

An investigation into the ultrasonic impact grinding of advanced materials used in the aerospace, automotive, energy and semi-conductor industries is another area of future work. In order to achieve this, a study on influence of a wider set of process parameter is necessary to cover the influence of parameters such as force, feed rates, abrasive material and grit sizes, workpiece properties and machining strategies would need to be undertaken.

Development of machining algorithms

In order to explore the ability to machine shapes, further work is required on machining strategies, and developing possible models of the process to allow for optimum tool path generation.

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APPENDIX A: MACHINE ACCURACY ASSESSMENT

The Z axis mechanism was calibrated using a zero setting height gauge model no WNT 85-900-018 with a displacement accuracy of 0.01mm. The controller settings were calibrated to the dial gauge. Therefore an accuracy of 0.01mm was realised on the Z axis mechanism.

Additionally to the output displacement the LVDT used in the machining tests was used to investigate the linearity and the backlash of the axis response. As the feed rates used were low, it was critical that the motor movement was smooth and the drive mechanism translated the motor rotation efficiently and in a linear manner. The LVDT tests demonstrated a stable linear response of the axis displacement with no backlash.

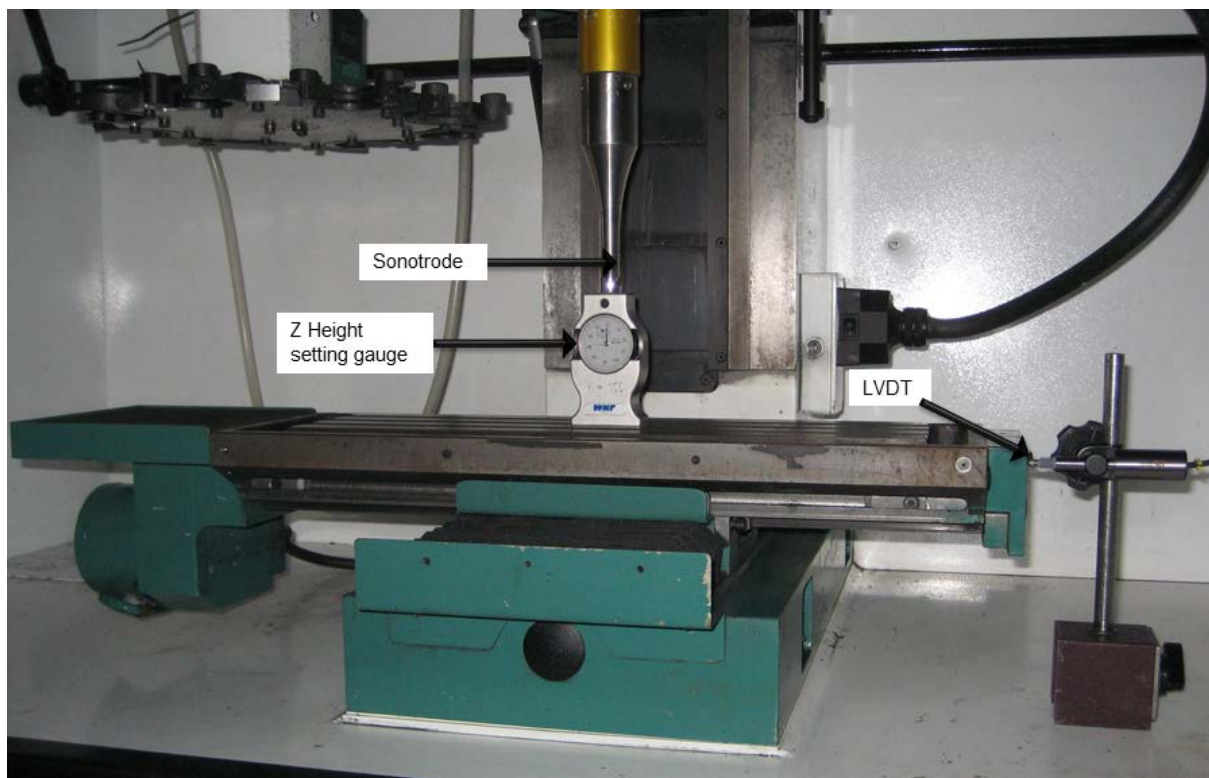


Figure A-1: XYZ axis calibration

APPENDIX B: CHARACTERISATION OF VIBRATION OF ULTRASONIC TOOL

The vibration oscillation of the ultrasonic tool was measured using a Polytec PSV 400 scanning laser vibrometer (SLV). The scanning laser vibrometer consists of a controller and workstation (for decoding, data recording and processing) and a scanning head, combining a laser and a video camera. The scanning laser vibrometer has a useful range from 0 to 40kHz (based on a maximum 0.25% variation in sensitivity) and can measure vibration oscillations up to 10m/s.

The core of the system is a laser Doppler vibrometer which uses the Doppler effect on a light wave to measure the velocity of a vibrating surface. A laser beam is split into a reference beam and an object beam within the scanner head. The reference beam is internally reflected and the object beam is focused onto the oscillating target (i.e. the ultrasonic tool) and is reflected back into the scanner head. The frequency of the reflected light is Doppler shifted. The magnitude of the shift is proportional to the instantaneous velocity of the object (along the axis of the laser beam). The reference beam and the Doppler shifted object beam interfere within the scanner head. A photodetector records the interfered light and provides a voltage proportional to the velocity of the vibration.

In this study we were interested in measuring a single position and in this instance the scanning laser vibrometer was used a single point laser. Figure 1 shows an image of the test setup. The laser from the SLV was orientated in the horizontal direction. However, the ultrasonic stack and tool was oriented so that vibration occurred in the vertical direction. A highly polished steel plate oriented at 45° to horizontal was used to position the laser on to tip of the ultrasonic stack tool with the laser beam orientated in the vertical direction. The polished steel was mounted on the machine bed which was isolated from the ultrasonic stack.

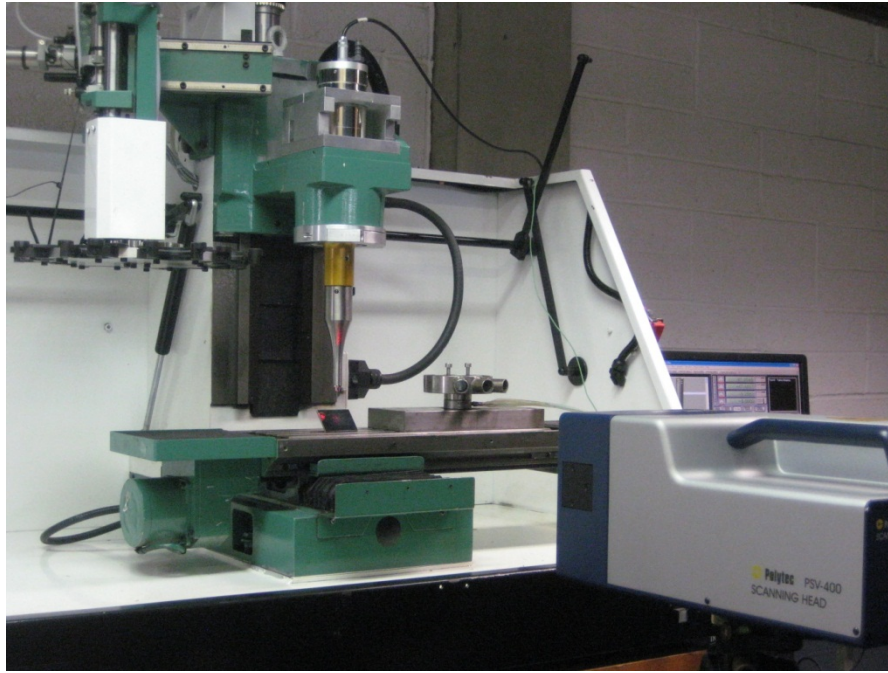


Figure B-1: Showing test setup

The video camera within the scanner head was used to monitor the surface under test. A virtual measurement grid (line in this instance) superimposed on an image the object was created. The SLV software enabled the laser to be positioned at anyone of the position on the virtual measurement grid. In this instance the SLV was used as a single point laser and measurements were recorded at single location on the tip of the tool.

The purpose of the vibration tests was to characterise the vibration behaviour of the ultrasonic stack. In this study we are primarily interested in the amplitude and frequency of oscillation. The measurement data was acquired at a sample frequency of 102.4kHz for a duration of 80ms. Vibration data was recorded for five input voltage settings (0, 1, 2, 3, and 4 volts). Note: measurements were restricted to a maximum input voltage of 4 volts due to exceeding of the dynamic range of the laser vibrometer (± 10 m/s) at input voltages above 4 volts. Tests were repeated three times and variation in vibration amplitude from test to test was within 5%.

Figure 2 presents the vibration oscillation at input voltage setting of 1 volts. The amplitude of oscillation appears relative constant over the 80ms test duration. However, upon closer inspection the amplitude varies as illustrated in Figure 3. It is proposed that the variation in amplitude is due to the auto tuning of the ultrasonic stack. This behaviour was observed for all tests and all input voltage settings under test. Although there is some variation in the peak to peak oscillating amplitudes the difference is less than 10% of the highest peak to peak

amplitude recorded. The slight variation in peak to peak amplitude is acceptable for the purpose of this study.

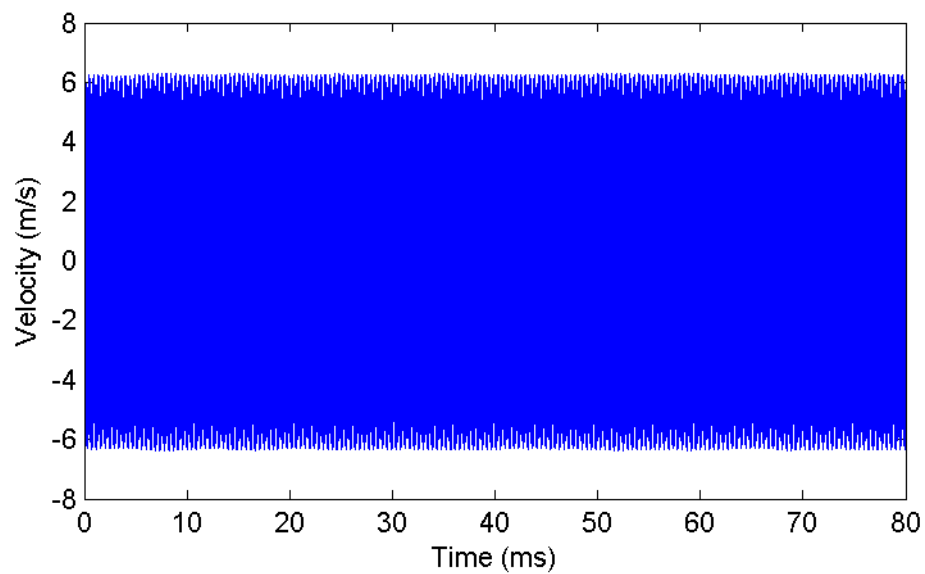


Figure B-2: Ultrasonic stack tool vibration oscillation (velocity) at input voltage setting of 1 volts

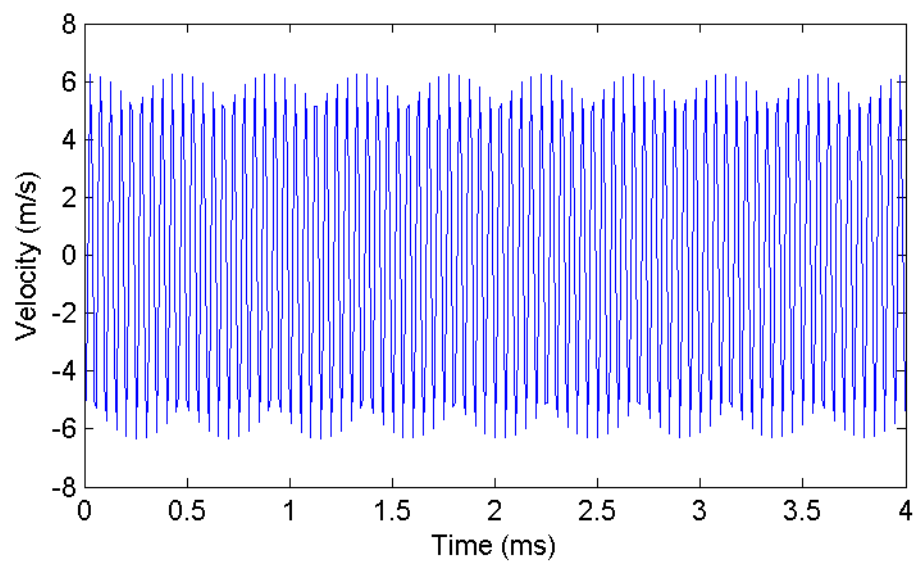


Figure B-3: Ultrasonic stack tool vibration oscillation (velocity) at input voltage setting of 1 Volt. Zoomed in section

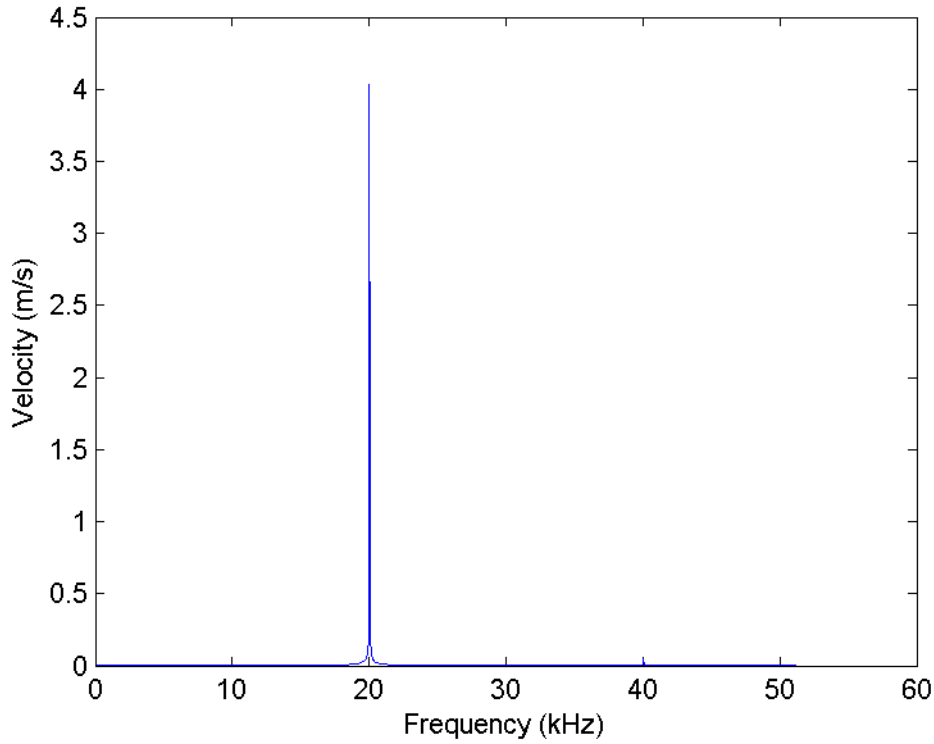


Figure B-4: Spectrum of Ultrasonic stack tool vibration oscillation (velocity) at input voltage setting of 1 Volt

From the velocity data, an estimate of the displacement of the ultrasonic tool was extracted. Dividing the ultrasonic tool velocity by the oscillating frequency in terms of radians yields an estimate of the ultrasonic tool displacement as shown in Equation 1:

$$x = \frac{\dot{x}}{\omega} \quad (1)$$

where x is displacement, $\dot{x}$ is velocity and ω is frequency in radians.

This approach is valid as the ultrasonic tool vibration was dominated by the excited oscillation frequency of 20kHz as shown in Figure 5. It is understood that vibration at lower frequencies with small velocity amplitudes could have comparable displacement amplitude as the relationship between velocity and displacement is frequency dependant as shown in Equation 1. However, no low frequency components were observed in the spectrum. For completeness the raw data was filtered to remove components other than those at the excited oscillation frequency of 20kHz and no other significant frequencies were observed. Using the analysis above the following peak to peak displacements were obtained. Figure 6 shows the displacement trace for the ultrasonic stack tool at an input voltage setting of 1 volt. A summary of all peak to peak displacements for the range of input voltages (0, 1, 2, 3 and 4 volts) are shown in Table B-1.

Table B-1: Approximate peak to peak velocity and displacement values for ultrasonic stack tool oscillation for a range of input voltages.

Input Voltage to Ultrasonic stack (volts)	Peak to Peak Values	
	Velocity	Displacement
0	10.5 m/s	84 μm
1	12.6 m/s	100 μm
2	14.3 m/s	114 μm
3	16.2 m/s	129 μm
4	18.1 m/s	144 μm

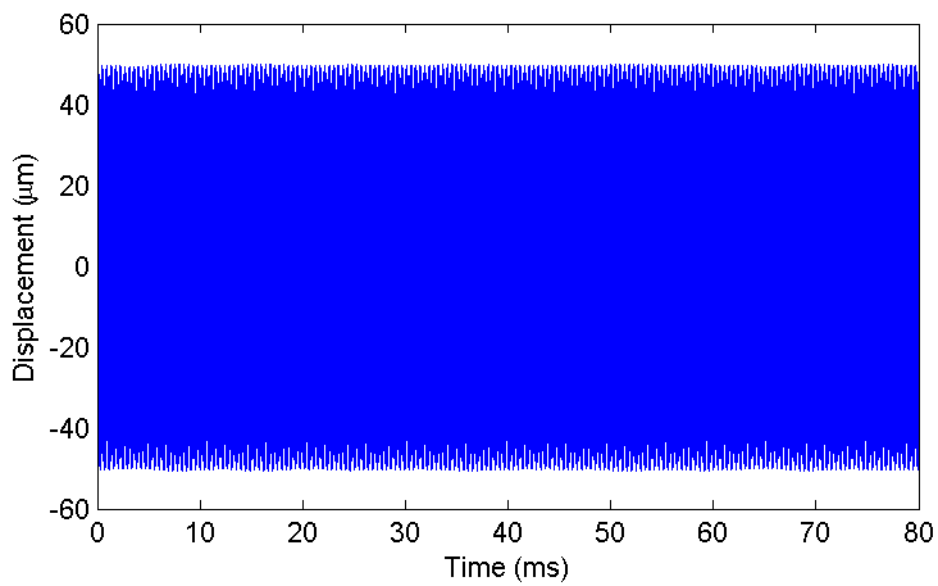


Figure B-5: Ultrasonic stack tool vibration oscillation (displacement) at input voltage setting of 1 Volt

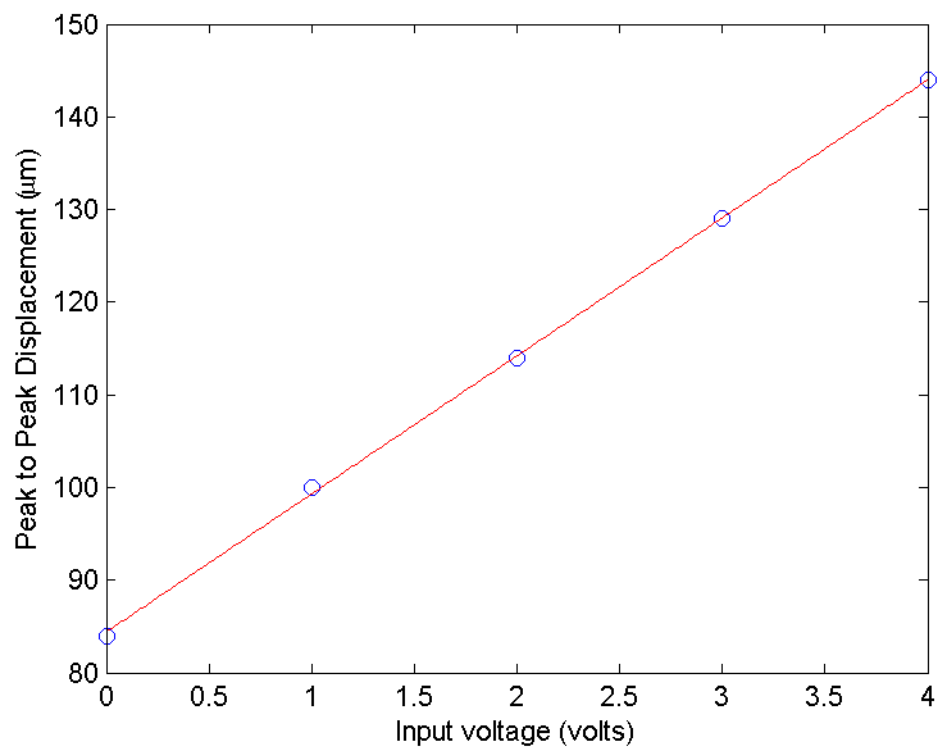


Figure B-6: Displacement trace for the ultrasonic stack tool at an input voltage setting of 1 Volt

APPENDIX C: MEASUREMENT TECHNIQUE FOR TOOLS

The measurement technique was based on analysis of images recorded using a USB camera. An example of the measurement setup is shown in the figure below.

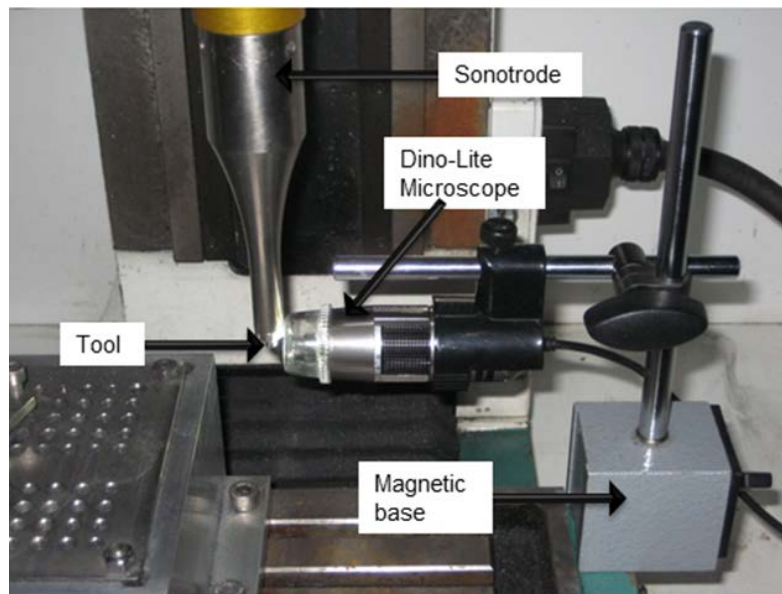


Figure C-1: USB microscope in situ for tool based inspection

It can be seen that the USB microscope was arranged to be able to be fixed with a magnetic stand in order to eliminate the need for the tool to be periodically removed from the sonotrode for inspection, and therefore reducing any risk of problems with remounting the tool. The analysis procedure initially involved the importing of the image files into Matlab. Key areas on the periphery of the tools are highlighted in the figure below.

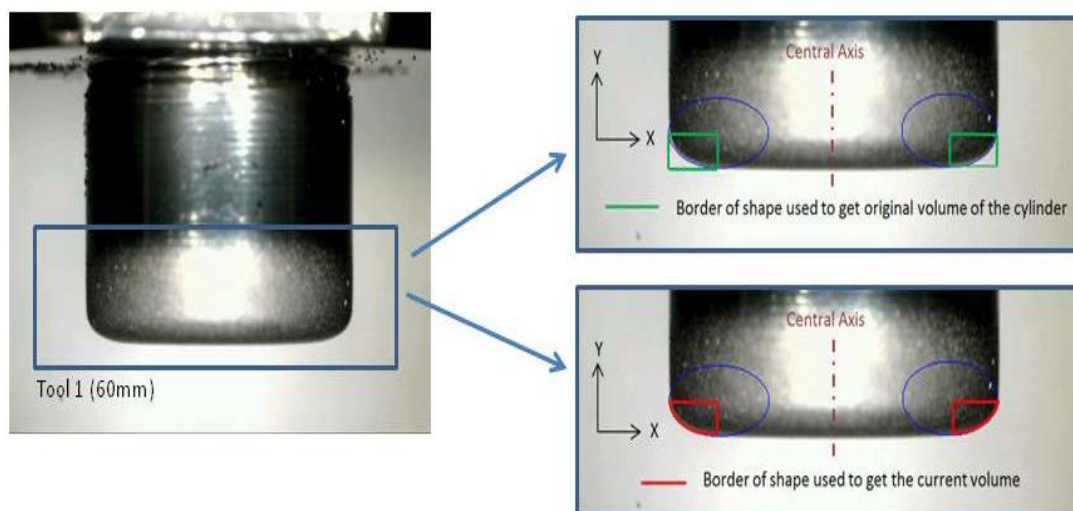


Figure C-2: Regions of interest for the tool wear analysis and calculation

It can be seen that the main region of interest were at the corner between the horizontal base of the tool and the vertical side walls of the tool. The algorithm was developed to calculate the peripheral volume loss due to wear in the region shown. The flowchart for the analysis procedure is shown in the figure below where the detail steps can be seen.

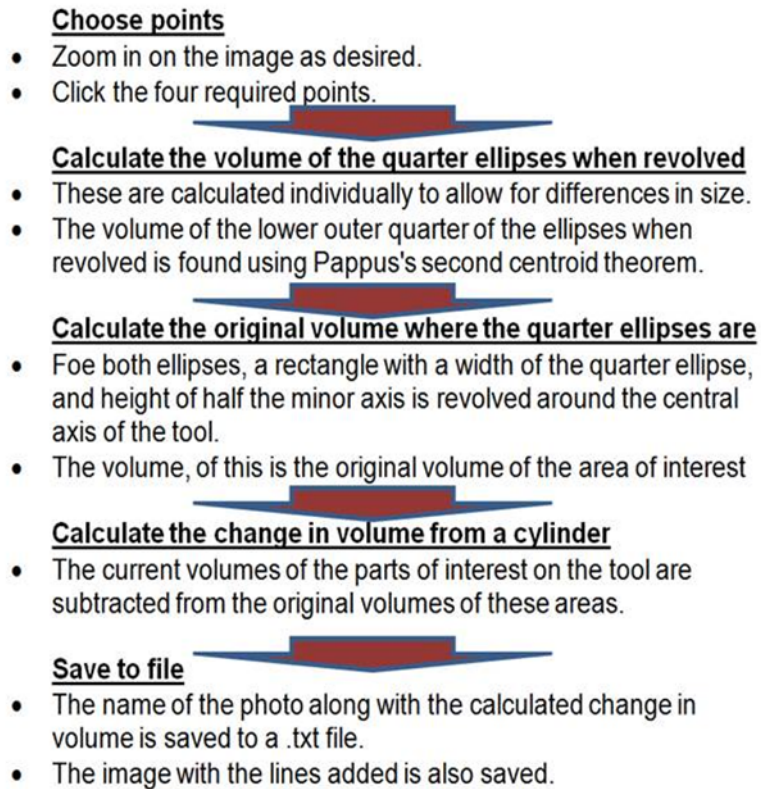


Figure C-3: Flowchart of the image based tool wear analysis

The peripheral volume loss was then plotted for a number of intervals over the machining distance up to 60mm of machining.