



GYTAUTAS BALEVIČIUS

**RESEARCH AND
APPLICATION
OF ULTRASONIC
VIBRATION GRINDING
IN DUCTILE MODE
OF HARD – BRITTLE
MATERIALS**

DOCTORAL DISSERTATION

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KAUNAS UNIVERSITY OF TECHNOLOGY

GYTAUTAS BALEVIČIUS

RESEARCH AND APPLICATION OF
ULTRASONIC VIBRATION GRINDING IN
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MATERIALS

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Technological Sciences, Mechanical Engineering (T 009)

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Scientific Supervisor:

Prof. dr. Habil. Vytautas OSTAŠEVIČIUS (Kaunas University of Technology, Technological Sciences, Mechanical Engineering – T 009).

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GYTAUTAS BALEVIČIUS

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LIST OF ABBREVIATIONS

DRM – Ductile regime machining
Lvl. – Level
HBM – Hard, brittle materials
HMP – Hybrid manufacturing processes
WC – Tungsten carbide
CMM – Conventional machining methods
VAM – Vibration-assisted machining
VAG – Vibration-assisted grinding
MRR – Material removal rate
XRD – X-ray diffraction
MD – Molecular dynamics
BRF – Brittle removal fraction
FEM – Finite element method
SPH – Smoothed particle hydrodynamics
SPDT – Single point diamond turning
CBN – Cubic boron nitride

INTRODUCTION

Relevance of the topic. The machining industry is the cornerstone of any well-functioning economy. Developments in this industry are the main driving forces behind humankind's major leaps and bounds of progress in scientific discoveries, the quality of human life, global mobility and other facets of our existence. At their very core, the performance, development and innovation of these facets depends directly on the tools and products employed by them that are manufactured by means enabled through the machining industry.

Branches of the machining industry are relevant only as long as they fulfill the needs of another interdependent machining branch, or another segment of the manufacturing industry to the best degree of suitability possible at the time. For this reason, most major discoveries and innovations throughout the history were followed by extinction or reduction of the role of long-standing, well-established industries and the emergence of new and more advanced industries. The degree of suitability of fulfillment can be perceived as a complex relation between the solution proposed by the machining industry branch and the needs and the landscape of the target industry as well as any relevant competing branches and industries. It cannot be determined or evaluated to the extent of a non-trivial answer. However, it can be objectively stated that the lower bound of the degree of suitability of fulfillment has been breached once the machining industry branch in question enters obsolescence for an extended period. It is possible, however, to summarize the performance of any machining industry branch based on its outputs.

Like all human activities, with measurable outcomes and observable performances, the machining activity outputs are governed by the iron triangle relation of evaluations in:

1. Quality;
2. Time;
3. Cost.

The *quality* evaluation can either refer to the degree of achievement of the required surface finish, geometric accuracy or even the performance of the final product, the latter of which could be related to any kind of physical properties, from optical characteristics to mechanical or even chemical properties. The two other evaluations are self-explanatory, the *time* refers to how long it takes to turn a raw material of a prefabricated blank into the final element, and the *cost* refers to the resource load required for the production of the said element, and both should be kept as low as possible. In practice, machining industries tend to perform a balancing act between the best available quality of the machined element, and the lowest time and cost in order to satisfy the target industry. It is rarely possible to improve all the three facets of this triangle to the maximum degree of satisfaction. However, it is possible to eventually reach the maximum possible (although unsatisfactory) degree of performance on all the three facets. Once this point has been reached, the development stalls and does not continue until the industry either has changed its requirements or a new material has been adopted.

The adoption of either already available or newly discovered materials has for a long time been a driving force of progress and innovation in the machining industry. The introduction of a new material changes the set of the physical characteristics parameters involved in the machining of the required element. This could either change the quality of the final product, alter the cost or influence the machining time in a significant way, thus resetting the progress positions of this golden triangle. The role of the way how the introduction of new materials can impact the technological development can be sufficiently appreciated even by briefly observing the human history. The ancient history is officially segmented by academics according to the dominant materials as the stone, bronze, iron age, etc. Even the periods of the modern history are sometimes unofficially dubbed by the media or the science community in the same fashion – the silicon age, the graphene age, etc.

One group of materials denoted by high industry transformation potential could be the group referred to in the academic literature as *hard, brittle materials*. This group is finding increasingly crucial applications in the fields of optics, medicine, aerospace, etc. Commonly exhibited desirable characteristics of these materials are thermal stability, rigidity, low wear, chemical inertness, etc. However, the hardness and brittleness of these materials tend to negatively impact the machinability of these materials. The brittleness (quantified by low fracture toughness) results in brittle deformation when the workpiece is exposed to an excessively high impact of the machining scale. This negatively influences the machining quality by introducing cracks and subsurface damage into the final product. Hardness, on the other hand, despite being a desirable property in some applications, also negatively influences machining by increasing the tool wear.

In order to machine a HBM in the ductile mode while using conventional methods, it is necessary to limit the material removal rate. However, such an approach is costly, with regards to both time and machining resources (tools, energy etc.). Therefore, a new category of machining processes, referred to as hybrid manufacturing processes (HMP), has been gaining prominence in the recent years. These processes are based on simultaneous control and interaction of more than one machining process with a significant effect on the process performance and machinability. Among these processes, a process group – vibration assisted machining (VAM), and, namely vibration assisted grinding (VAG) – have been found to be the most readily applicable and flexible approaches towards improving the machinability of HBM. However, the current research on VAM applications tends to focus on the auxiliary effects of VAM in HBM grinding (improved cooling, extended tool lifetime, etc.) instead of improving the ductile mode grinding parameters (the critical depth, material removal rate, etc.).

The **aim** of this research is to analyze and develop ultrasonic vibration assisted grinding methods and devices for machining HBM. To achieve this, the following **objectives** were formulated:

1. Conduct literature analysis on the subject of hard, brittle material grinding and specify the research goals;

2. Design and test a cylindrical grinding technology enabling high frequency excitation of a massive rotating workpiece.
3. Design and produce an actuator for the ultrasonic excitation of a rotary tool in the back grinding of hard, brittle materials.
4. Establish conditions for the brittle-ductile transition in machining, propose, produce and patent a device for ultrasonic excitation of a workpiece and conduct the related experiments.

Research Methods

Both theoretical and experimental studies were conducted in the course of the research work presented in this dissertation. Theories of vibrations were applied in our numerical modeling which was carried out by means of the finite element method within open source software Salome Meca/Code_aster and commercial ANSYS solvers. Methods of ultrasonic excitation were applied for experimental data generation. For the validation of computational models, several experiments with different setups were conducted. These surfaces were characterized by scanning electron microscopy, white light interferometry, and contact profilometry. The grinding chip morphology was analyzed by using optical microscopy and X-Ray diffraction analysis. The process performance was monitored by force measurements.

The research was conducted at *Kaunas University of Technology Institute of Mechatronics*, *Fraunhofer Institute of Production Technology*, and *JSC Stevila*, Lithuania.

Scientific novelty

1. Vibratory excitation equipment was developed and designed by using the finite element method.
2. A novel excitation method employing higher vibration modes for achieving higher excitation frequencies of the workpiece was proposed and tested.
3. Surface characterization methods were used to determine ductile and brittle site distribution throughout sample surfaces.

Defended statements

1. Machined surfaces can be noticeably improved through the introduction of vibrational assistance during the machining of hard, brittle materials;
2. Machined surface improvement is not a result of changes to the kinematics of the tool, but rather a result of changes to the dynamics of the tool-workpiece interaction;
3. Vibration assisted machining method performance can be improved with an increase of the operating frequency.

Practical value

1. A novel method for rotating workpiece excitation in cylindrical grinding has been developed.
2. A novel method for static workpiece excitation in cylindrical grinding has been developed and patented.

3. The experimentally observed, but yet unexplored, dependence between surface roughness and the relation of the tool engagement depth to the excitation amplitude can be used for further research on improving back grinding through the static workpiece excitation technique.

Research approbation

Vibration assisted grinding study of tool excitation was conducted at Fraunhofer Institute of Production Technology (IPT) during a traineeship financed through *Erasmus+* programme during the period of September 01, 2015– October 31, 2015.

The results of this dissertation were published in 6 scientific papers: 5 in journals with the impact factor indexed in the *Web of Science* database, and 1 in conference proceedings.

The research results were also presented at 5 international scientific conferences: *Mechatronic Systems and Materials 2015* (Kaunas, Lithuania), *Mechanika 20* (Kaunas, Lithuania), *Mechanika 21* (Kaunas, Lithuania), *Mechanika 24* (Kaunas, Lithuania), *2nd International Conference and Expo on Ceramics and Composite Materials* (Berlin, Germany).

The results were also presented at the Lithuanian Science Academy's 7th *Young Scientist Conference* and received recognition by claiming the award for the best report in the physical and interdisciplinary research category.

Structure and Volume of this Dissertation. The dissertation consists of an introduction, nomenclature, four chapters, conclusions, references, and the list of author's publications. The total volume of the dissertation is 120 pages, 92 figures and 18 tables.

The first chapter is intended to determine the key research objectives. In addition to the historical analysis on brittle – ductile transition and hard, brittle material applications, systemic analysis of the material is performed in order to specify the definition of hard, brittle materials, as well as to establish the relevance of the topic. The historical retrospective, on the other hand, gives the reader an insight into the main research trends into the mechanisms of brittle – ductile transition as well as solutions to the hard, brittle material machining problem.

The second chapter outlines the development of excitation equipment. It is initiated with the concept outline for three of the excitation configurations investigated in this work. The concept of each subsequent design is intended to address the shortcomings of the previous one. Further, the analytical design as well as the numerical and experimental validation procedures for each design are outlined.

The third chapter introduces the experimental equipment and means used for process performance evaluation in this work. The chapter introduces force measurement, as well as surface and chip morphology evaluation techniques.

The fourth chapter provides analysis of the obtained results. The results are compared and discussed. The best-performing method is determined, and future research directions are discussed.

1. LITERATURE ANALYSIS

The areas of research in the branch of machining technologies are extremely vast and highly diverse. While a specific technology might have been researched by a significant number of scientists, it may turn out to be completely irrelevant when compared to the sheer number of other publications on other technologies in the same field. Therefore, in order to gauge the current degree of research into the problem, as well as its relevance in the academia, analysis of keyword combination results and their distribution with regard to the master keywords was performed. All the searches concerning keywords that are common in both plural and singular forms (in this case – ‘machining’ and ‘hard brittle material’ (HBM)) include the search results for both. The search results for both keywords are provided below (Table 1):

Table 1. Keyword search results for master keywords – *Machining* and *Hard brittle materials*

Master Keyword	Instances in 2014	Instances in 2015	Instances in 2016	Instances in 2017	Instances in 2018	Instances in 2019
Machining	37,000	35,400	35,300	33,500	30,400	22,600
Hard, brittle materials	185	146	197	227	209	150

The next logical step of analysis is to identify the significance of machining in the context of HBM. Machining is a process, hence, many other processes can be prevalent within the topic, such as processing, manufacture, investigation, recycling etc. Hence, the knowledge of the percentage of instances within the ‘hard brittle materials’ keyword search that include the keyword ‘machining’ allows gauging of the importance of machining to the area of HBM. Provided below (Table 2) are the search results for a combination of ‘hard brittle materials’ and ‘machining’ keywords:

Table 2. Analysis of significance of machining in HBM

Keyword rank	Keyword	Instances in 2014	Instances in 2015	Instances in 2016	Instances in 2017	Instances in 2018	Instances in 2019
Master	Hard, brittle materials	134	97	142	174	156	119
Slave Lvl.1	Machining						
Percentage of master keyword instances		72.43%	66.44%	72.08%	76.65%	74.64%	79.33%

In order to carry out the studies on the effect of vibration assistance on the brittle – ductile transition, it is necessary to first establish the initial study parameters. These parameters are obtainable through literature analysis.

The first parameter is the material used for studies. The two main requirements for this parameter are the relevance and the degree of representation of the hard, brittle material range. Before any of these parameters can be determined, it is first imperative to clearly state what qualifies a material as *hard, brittle*. Therefore, the first section in this chapter deals with the materials encountered in the literature that are referred to as *hard, brittle*. The frequency of encounters in the literature is used to qualify suitable materials first, then the common characteristics are outlined which serve to determine the qualifiers for hard, brittle materials. Out of the list of materials that fit within the determined qualifier limit, a sample study material is determined based on several subjective as well as objective criteria, such as popularity, availability, and relevance.

The second parameter is the brittle-ductile transition initiation mechanism to be investigated. Therefore, in the second section of this chapter, the brittle-ductile transition is defined, and an overview of the initiation mechanisms is conducted. The most suitable mechanism is chosen based on the ability to best leverage the ultrasonic assistance to initiate the brittle-ductile transition.

The third parameter is the set of vibration-assisted machining configurations and methods to be used for the investigation and equipment design. Therefore, in the third section of this chapter, a literature review of vibration assisted machining configurations is conducted. The suitable configurations are determined based on several subjective as well as objective criteria, such as popularity, availability, and relevance.

1.1. Hard, brittle materials and their applications

As demonstrated in the analysis at the introduction of this chapter, the term ‘hard, brittle materials’ is used in a sizeable amount of publications. At the first glance, establishing the definition of hard, brittle materials is supposed to be a straightforward task. *Hard, brittle materials* are materials possessing high hardness and low fracture toughness. The commonly encountered hard, brittle materials as well as the ones of interest to this investigation are denoted by high hardness and low fracture toughness, ergo the straightforward definition.

Yet, it is unclear as to how high the hardness, how low the fracture toughness, and how correlated the relation between the two should be to qualify the material as *hard, brittle*. In addition, the range of materials that are referred to as hard and brittle in the publications is broad and varied. While some publications refer to materials, such as engineering ceramics (Alkhalefah, 2020), (Elhami & Razfar, 2020), (Guojun, *et al.*, 2020), metals, their alloys and compounds (Alisir & Cevik, 2019), (Yu, *et al.*, 2019), others mention plastics, minerals, etc. The machining challenges, their solutions as well as applications of the materials will greatly differ between the two groups. It is therefore clear that a superficial definition of the hard, brittle

material group as materials possessing high hardness and low fracture toughness is insufficient when choosing a sample material for investigation.

To build up a proper definition or a qualification criterion, it is first necessary to filter out hard, brittle materials that are either irrelevant, or that have been falsely attributed as hard, brittle materials in the literature. To achieve this, the frequency of the appearance of materials in publications is evaluated.

Commonly encountered materials can be classified into four categories: ceramics, metals, composites and plastics. These categories were chosen as the variation values for the ‘material’ component in the ‘hard brittle materials’ keyword. Hence, further analysis will be used to determine the occurrence of instances of the following keywords: ‘hard brittle metals’, ‘hard brittle composites’, ‘hard brittle ceramics’ and ‘hard brittle polymers’ (Table 3).

Table 3. Keyword analysis for keywords ‘hard brittle metals’, ‘hard brittle composites’, ‘hard brittle ceramics’ and ‘hard brittle polymers’

Master Keyword	Instances in 2014	Instances in 2015	Instances in 2016	Instances in 2017	Instances in 2018	Instances in 2019
Hard brittle metals	5	3	1	3	4	2
Hard brittle polymers	0	1	5	5	1	2
Hard brittle ceramics	16	20	19	16	16	11
Hard brittle composites	0	0	0	0	1	0

Brittle materials, such as single crystals (Si, Ge), ceramics (alumina, SiC), and glass, are currently being utilized in semiconductors, optical instruments, microelectronics, and various other fields. Among the brittle materials, silicon (Si) is the material that drives the semiconductor industry, whereas the semiconductor is the building block for the information technology (IT) industry. The semiconductor industry is worth US\$ 213 billion a year and is the backbone of other fields, such as telecommunications, Internet, etc.

The results that our search yielded show that ceramics is more commonly referred to as hard and brittle, followed by metals, then polymers, and, finally, composites. The low number of instances suggests that researchers rarely identify hard, brittle materials by their category. This assumption is further confirmed after studying the literature obtained from the ‘hard brittle material’ keyword search. However, since the number of instances is so small, the sources are easier to manage, and, therefore, can be manually reviewed to identify the exact materials that were referred to as hard and

brittle for further analysis. The materials mentioned in these instances are outlined below (Table 4).

Table 4. Materials occurring in keyword searches for ‘hard brittle metals’, ‘hard brittle ceramics’, ‘hard brittle composites’ and ‘hard brittle polymers’

Keyword	Hard brittle metals	Hard brittle polymers	Hard brittle ceramics	Hard brittle composites
MATERIALS	Cast iron	Chitosan	Calcium phosphate glass ceramics	Tungsten carbide
	Titanium alloy	Methyl meta-acrylate	hydroxyapatite	
	Chromium	Polystyrene	Silicon nitride	
	Antimony		Alumina ceramics	
	Manganese		Silicon carbide	
	Bismuth		Barium titanate	
			Lead zirconate titanate	
			Quartz	

The number of the obtained materials is in relative agreement with the number of the obtained instances per category in Table 3. Some discrepancies among the search results showed misidentification of tungsten carbide (WC) as a ceramic, while it is a metal composite, as well as misidentification of bismuth as a composite, while it actually is a metal. The discrepancies were addressed, and our further analysis shall aim to provide additional HBM instances by performing a keyword search for ‘hard brittle materials’ with the keywords representing the material set obtained in

Table 4 excluded from the search. The material keywords used to narrow down the search results within the ‘hard brittle material’ keyword search results are further referred to as the exclusion set. The additionally obtained materials are outlined below (Table 5).

Table 5. Materials obtained upon applying the exclusion set to the keyword search

Category	Polymers	Ceramics	Other
	Poly(L-lactide)	Crown glass	Silicon
	Methyl cyanoacrylate		

The keyword search for ‘hard brittle materials’ with the applied exclusion set yielded 4 additional materials. It is possible that the application of the exclusion set also removed other material instances that are not present here which would have shown up on the same entry as parts of the exclusion set. However, this is not a crucial issue as those materials would have likely possessed similar mechanical characteristics as the exclusion set material. Therefore, the missing materials should eventually enter the list. The significance of each material in the area of HBM was analyzed in the further segment. Consequently, the results from our keyword search over each material keyword in the obtained HBM set in combination with the ‘hard brittle materials keyword’ are presented below (Table 6).

Table 6. Analysis of significance of obtained HBM set materials in the area of HBM

Keyword	Total instances	% of HBM
BK7	147	6.07
SiO ₂	208	8.58
PZT	46	1.89
BaTiO ₃	4	0.17
SiC	492	20.31
Al ₂ O ₃	59	2.44
Si ₃ N ₄	145	5.98
Ca ₅ (PO ₄) ₃ (OH)	36	1.49
Bi	111	4.58
Mn	39	1.61
Sb	118	4.87
Cr	225	9.29
TiAlV	97	4
Fe	78	3.22
C ₅ H ₅ NO ₂	1	0.04
PLA	2	0.08
(C ₈ H ₈) _n	29	1.2
PMMA	59	2.44
Chitosan	23	0.95
WC	306	12.63

Si	197	8.13
Total:	2423	

The materials whose relative frequency of occurrence along the ‘hard, brittle materials’ keyword was below 5% were considered to be either false attributions or irrelevant. Therefore, further on, only Si, WC, Cr, Si₃N₄, SiC, SiO₂ and BK7 are considered as hard, brittle materials. The hardness and fracture toughness of these materials is listed in the table below (Table 7).

Table 7. Strength properties of common HBM’s

Material	Hardness	Fracture toughness	Instances in publications
Si	7	0.68	197
WC	9	6.9	306
Cr	8.5	120	225
Si ₃ N ₄	8.5	1.8	145
SiC	9.5	4.6	492
SiO ₂	7	0.62	208
BK7	6.5	0.82	147

Young’s modulus for 4H-SiC was reported to be 444 GPa (Nuruzzaman, *et al.*, 2015). The structural, five different elastic constants and electronic properties of 2H- and 4H-Silicon carbide (SiC) are investigated by using the density functional theory. However, the polytypes are more common for thin film applications. In the case of ceramics, the polytype proportion is not controlled as easily; in addition, the mechanical properties can be influenced by sintering and binding agents. SiC possesses great properties for application in harsh environments. In the previous research, applications of a strengthened variety of SiC in a substrate of a 650 mm diameter optical space mirror were reported (Tsuno, *et al.*, 2005).

Overall, it is demonstrated in the table that, in the literature, hard, brittle materials are considered to be the materials whose Moh’s hardness exceeds 6.5 and fracture toughness is below 6.9 (except for chromium). The most prominently occurring of all given materials are tungsten carbide (WC) and silicon carbide (SiC). Both of them feature Moh’s hardness above 9 and fracture toughness about an order of magnitude higher than most other less prominently occurring materials (except for chromium). Therefore, WC and SiC are taken for further consideration as sample investigation materials in this work. Further research could consider the application of technologies proposed in this thesis on materials that are more challenging due to their low fracture toughness, such as crown glasses, SiO₂, Si, and Si₃N₄.

Tungsten carbide, apart from being machined itself for different applications, is one of the most common machining tool materials as well (Rizzo, *et al.*, 2020). However, it has also found applications as a dye material, and in optics molding processes. High-volume optical component production by glass molding is an

economically viable replication technology using high-precision molds, with which, glass components are deformed above the transition temperature (He, *et al.*, 2011). Such properties as hardness and thermal stability of tungsten carbide in this case lend themselves to withstand the high pressures and temperatures involved in the process. However, the issue of machinability is still an unsolved problem.

Both of these materials possess high application prospects; however, tungsten carbide is less researched of the two. Therefore, WC was chosen as the sample material for the study.

1.2. Brittle – ductile transition

The applications of hard and brittle materials, typically represented by advanced ceramics, for a number of high-performance components have recently generated high interest. To meet this increasing demand, high efficiency machining technologies are needed. Brittle material breaks are characterized by absorption of little-to-no energy during stress (Redwing, 2017). This suggests that the material fractures with no plastic deformation. The material in the figure below (Fig. 1) marked with (a) shows what a brittle material looks like after pulling on a cylinder of that material. Typically, there will be a large audible snap sound when a brittle material breaks. A brittle material is also known as a material denoted by low ductility.

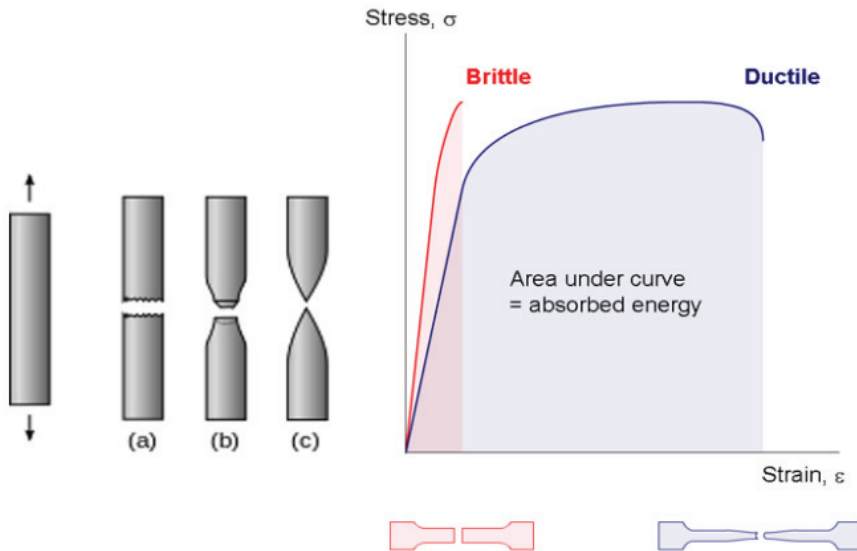


Fig. 1. Stress-strain curve for brittle and ductile materials (Redwing, 2017)

Ceramics features a much higher brittleness level than metals. The main reason for this is the difference in the bond type. Due to metallic bonds between atoms making up metals, it is possible for metal atoms to easily slide past each other. Meanwhile, ceramics is held together by the ionic bond which provides resistance to

the sliding deformation. Due to the alternating nature of the charge in ionic bonding, any attempts of rows of atoms to slide past each other results in negative atoms encountering negative atoms, and positive atoms encountering positive atoms. The resulting electrodynamic repulsion inhibits the sliding behavior between the rows. On the other hand, in metals, as the rows slide past each other, slip is exhibited, which allows the metal to be deformed in a plastic manner by preventing any fracture. Due to the inability of ceramics to exhibit sliding and subsequent slipping deformations, ceramics cannot be deformed plastically. Instead of deforming plastically, fracture is exhibited by ceramics when stressed, which results in brittle deformation (Redwing, 2017).

Brittle-ductile transition (BDT) is the main driving phenomenon enabling ductile regime machining of HBM. BDT is usually characterized by a change in the material deformation behavior, whereby a transition occurs changing from the material removal mode mainly dominated by the severing of interatomic bonds within the material (brittle) to the removal mode dominated by shear deformation, slipping or twinning along crystalline planes (ductile). In practice, the former mode generally fragments the material, either into large sharp-edged chunks, or into fine powder along cracks that then propagate into the material thus causing chipping, sub-surface damage, etc. In the latter mode, material is deformed plastically and pushed off the workpiece surface thus forming longer, more continuous chips of varying sizes (in the case of higher temperatures, sphere-shaped chips) and mirror-like surfaces. BDT is a machining scale-dependent phenomenon. In the literature, BDT has mostly been attributed to the increased pressure at the material removal zone. The large pressure at the deformation zone could elicit a change of the lattice structure within the cutting region. BDT was first observed by King and Tabor in 1954 (King & Tabor, 1954). It was observed that, although, after frictional wear, rock salt crystals exhibited brittle cracks on the surface, high hydrostatic pressure induced plastic deformation sites on the surface as well. Bridgman and Šimon observed similar results with glass (Bridgman & Šimon, 1953). Since 1973, Lawn and colleagues conducted a series of indentation experiments on glass and observed similar results. Lawn's and Wilshaw's indentation experiments in 1975 (Lawn & Wilshaw, 1975) led to the identification of the elastic plastic transition. It was determined that, when a material exhibits ductile behavior, it expands in a radial core which exerts uniform hydrostatic pressure on the material surrounding the core. This radial core is encased in two deformation zone layers – first, the plastic region, and then, the elastic matrix (Fig. 2).

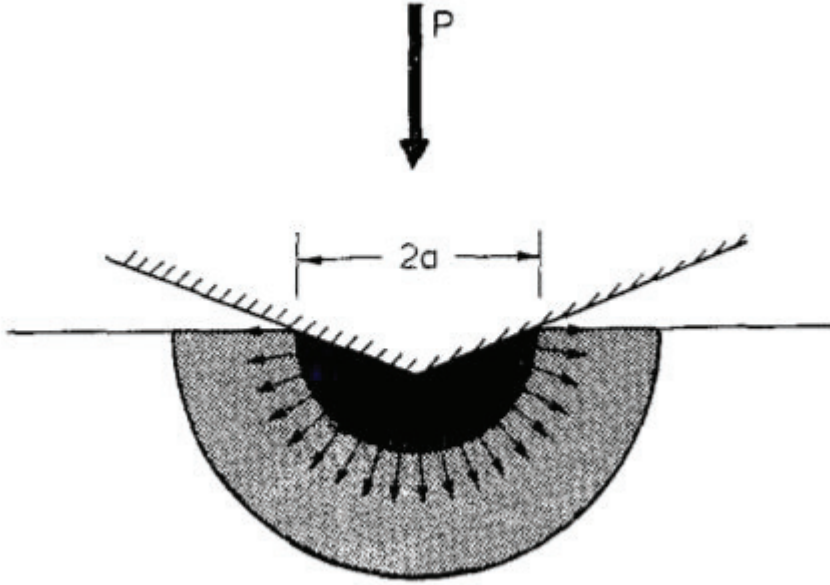


Fig. 2. Elastic-plastic indentation model: black region – the hydrostatic core, shaded region – the plastic zone, everything else – the elastic matrix (Lawn & Wilshaw 1975)

Hence, in 1975, the elastic plastic response was established (Lawn & Wilshaw, 1975), which suggested that, under sufficient hydrostatic pressure, any material can be plastically deformed. Later on, Lawn & Marshall proposed a relation for determining the lower limit of the critical load P and the subsequent critical crack length c which correlated with the hardness and fracture toughness of the affected material (Lawn & Marshall, 1979):

$$P = \lambda_0 \frac{K_C^4}{H^2} \quad (1.1)$$

$$c = \mu_0 \frac{K_C^2}{H^2} \quad (1.2)$$

where λ_0 and μ_0 are geometric constants which depend on the material, H is the hardness of the material which is the resistance of the material to the plastic flow, K_C is the fracture toughness which is the resistance to fracture. Upon further development, the critical indent size was identified (Marshall & Lawn, 1986):

$$CIS = \mu \left[\frac{K_C}{H} \right]^2 \quad (1.3)$$

where $\mu \propto E/H$, E refer to the elastic modulus of the material.

It was subsequently proposed by Bifano *et al.* (Bifano, *et al.*, 1991) that every material can undergo the brittle-ductile transition when the infeed rate is maintained sufficiently small. Due to the energy required to propagate the crack at this rate being higher than the one required for plastic deformation, deformation becomes dominated by the plastic mode. Simultaneously, and in a similar fashion, Scattergood and Blake (Scattergood & Blake, 1990) identified that a critical chip thickness d_c separates the plastic deformation portion from brittle removal. As a result, they developed the critical depth model for ductile regime machining:

$$d = d_c \propto \left[\frac{K_c}{H} \right]^2 \quad (1.4)$$

According to Arif *et al.*, BDT should be treated as the intersection point of the specific energy curves for ductile and brittle behavior (Arif, *et al.*, 2012), and an increase of the machining scale beyond this point would elicit brittle deformation, while reduction would transition the deformation into the ductile mode.

According to a number of researchers (Kailer, *et al.*, 1997), (Zhang & Tanaka, 1999), and (Zhang & Zarudi, 2001), monocrystalline silicon can experience phase transformations as the pressure at the affected zone approaches at 10–13 GPa. This was confirmed through molecular dynamics studies by (Cheong & Zhang, 2000).

These transformations could induce ductile deformation. It was suggested that, in the course of machining, provided sufficient hydrostatic pressure is achieved in the compressive region in the tool vicinity, a plastic, metallic phase transition could occur (Yan, *et al.*, 2009), (Lai, *et al.*, 2012) (Fig. 3).

However, even in the ductile mode, subsurface damage may still occur. Fast unloading may form a superficial amorphous layer resulting in the initiation of dislocations that could serve as cores for micro-cracks. In addition to inducing plastic phase deformation, compressive stress could serve as a crack propagation retaining force preventing the deformation from evolving into the brittle mode (Liu, *et al.*, 2007).

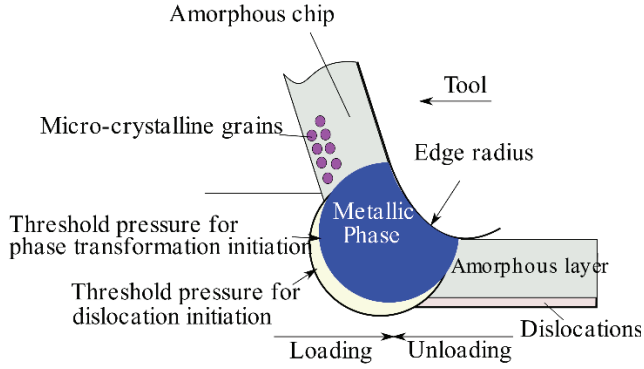


Fig. 3. Subsurface damage in ductile deformation

Lateral and median cracks form outside of the plastic zone during the loading even, when plastic deformation is exhibited. Fig. 4 shows the typical crack systems in a brittle material during the scratch process. We can see that there is a plastic deformation zone with a depth h_{pi} generated below the contact site at any time (Chen, *et al.*, 2015).

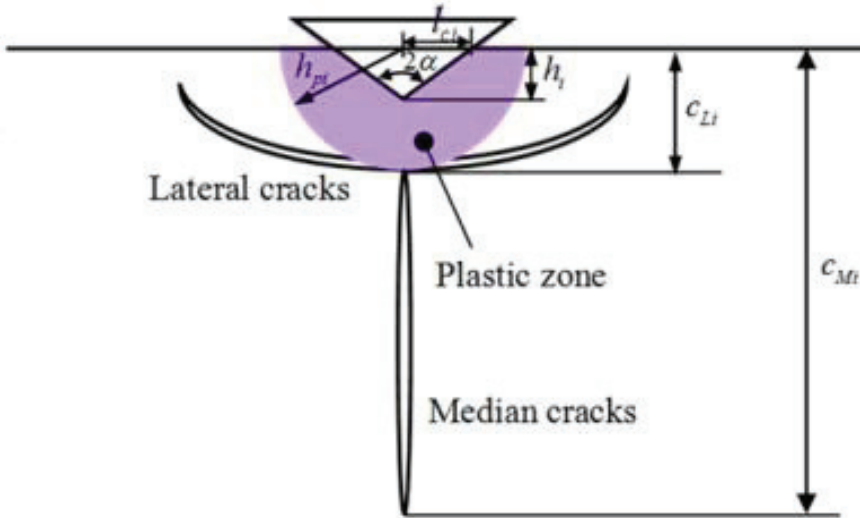


Fig. 4. Typical crack systems in scratching brittle materials (Chen *et al.* 2015)

Experimental analysis of the scratch process suggests that a lateral crack initiates at or close to the boundary of the plastically deformed zone and spreads out laterally on a plane closely parallel to the scratched surface. That is to say that the depth of the lateral crack c_{Li} is usually approximated as the plastic zone size. As a result, the lateral crack depth can be expressed as a function of material properties, the geometry of the grain, and the penetration depth. The median crack which is considered as the main type of the subsurface crack, nucleates on the boundary of

the inelastic zone as well, but it extends perpendicularly to the surface to a final distance c_{Mi} .

Deformation modes are best characterized by nano-indentation and nano-scratching experiments. When a material is affected by vertically moving localized compressive stress, during indentation, a plastic deformation zone of indeterminate volume would form as the indenter enters depth h_i ; then, a lateral crack initiates at or in close proximity of the boundary of a plastically deformed zone, it then propagates upward to the workpiece's surface at a trajectory offset to the contour of the plastic zone (Fig. 5). Here, depth C_L is therefore useful in approximating the depth of plastic deformation. From depth C_L , a median crack would propagate perpendicularly to the workpiece surface, away from the indenter and would terminate at depth C_M causing subsurface damage (Chen, *et al.*, 2015). During scratching, which is more representative of cutting processes, the crack system remains the same, except it is supplemented with radial cracks (Duan, *et al.*, 2017) that occur as a result of tangential motion (Fig. 6).

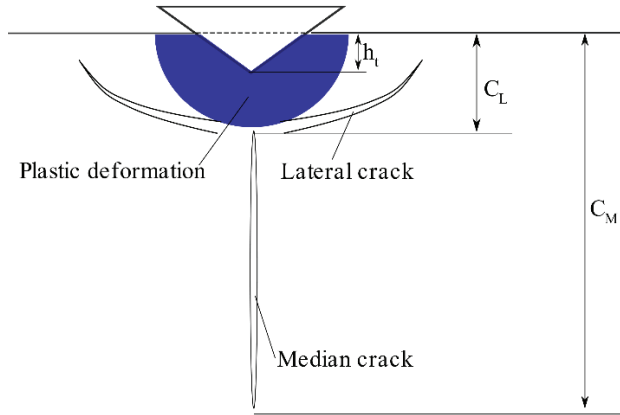


Fig. 5. Crack propagation system in the indentation of HBM

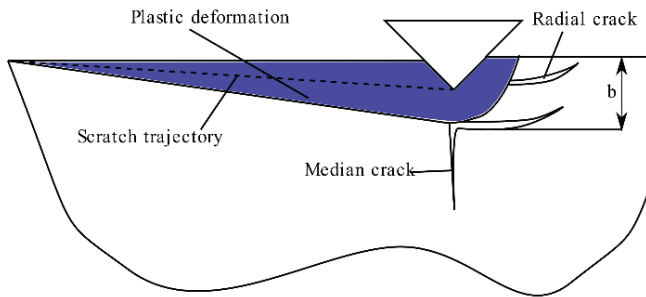


Fig. 6. Crack system in nano-scratching

In the paper by (Li, *et al.*, 2017), a varied-depth nano-scratch test of a single grain was carried out on a nano-indentation system. As shown in Fig. 7, to explore

the material removal mechanism of SiC ceramics, a varied-depth nano-scratch test of a single grain was carried out on the nano-indentation system. The nose radius of the indenter was approximately 300 nm.

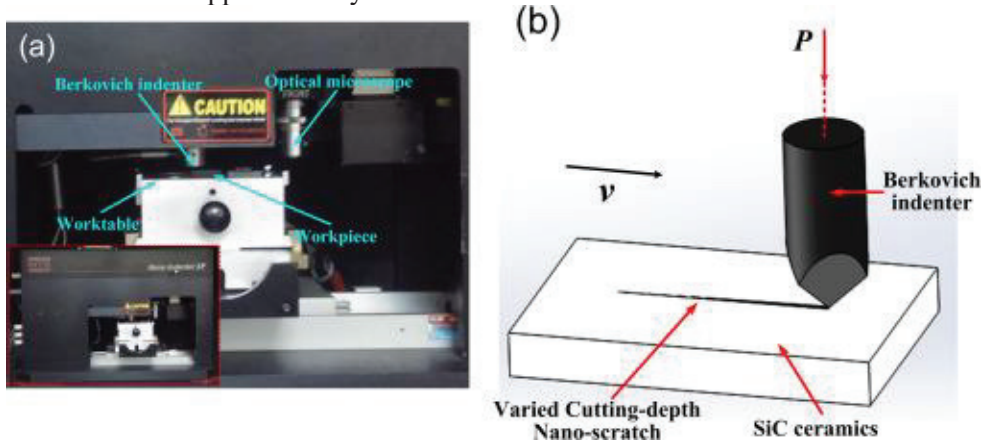


Fig. 7. Experiment device and schematic diagram of nano-scratch (Li, *et al.*, 2017)

There have been a fair number of creative attempts to combat the crack propagation in HBM machining. For instance, a study by (Cheng, *et al.*, 2014) presents a fracture restraining technique employing resin bonding of the surface in micro-grinding of glass and the micro-fracture behavior in the micro-grinding of glass (Fig. 8).

However, vibration assisted grinding is by far the easiest to apply and the most promising technique for brittle material machining. For instance, a method of adding ultrasonic vibrations to the cutting process of hard, brittle material was developed to increase the surface quality and the tool life (Zhang, *et al.*, 2014) while realizing defect-free ductile mode machining of sintered tungsten carbide by the tool ultrasonic elliptical vibration. Fig. 9 demonstrates a groove surface of BL4 which was machined with circular vibration ($2 \mu\text{m}_{\text{p-p}}$) at a nominal cutting speed of 150 mm/min. The depth of the cut is gradually increased from $0 \mu\text{m}$ to $2 \mu\text{m}$. The surface quality changes depending on the depth of the cut where brittle cracks can be generated at a large depth of the cut even in the elliptical vibration cutting. The transition border from ductile to brittle modes is observed at the depth of the cut of about $1.5 \mu\text{m}$ (Fig. 9). Therefore, various types of vibration-assisted machining will be investigated in the next section.

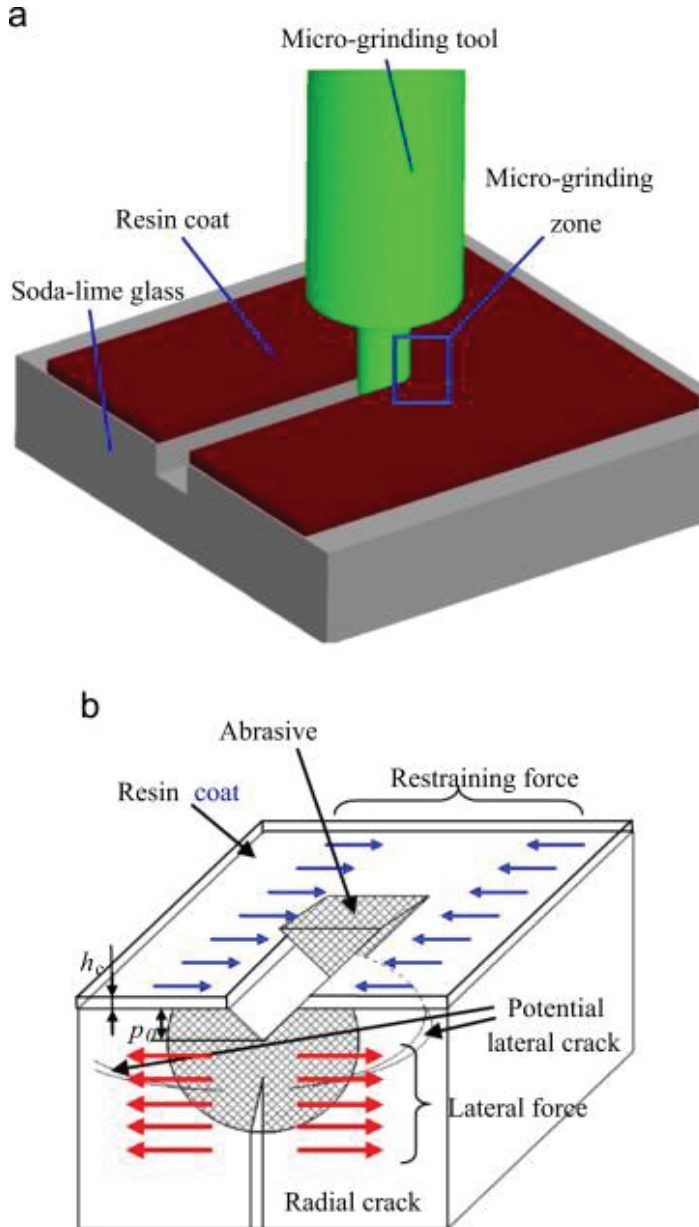


Fig. 8. Micro-fracture restraining technology in glass micro-grinding. (a) Micro-grinding with a resin coat. (b) Single abrasive interaction under restraining force (Cheng, *et al.*, 2014)

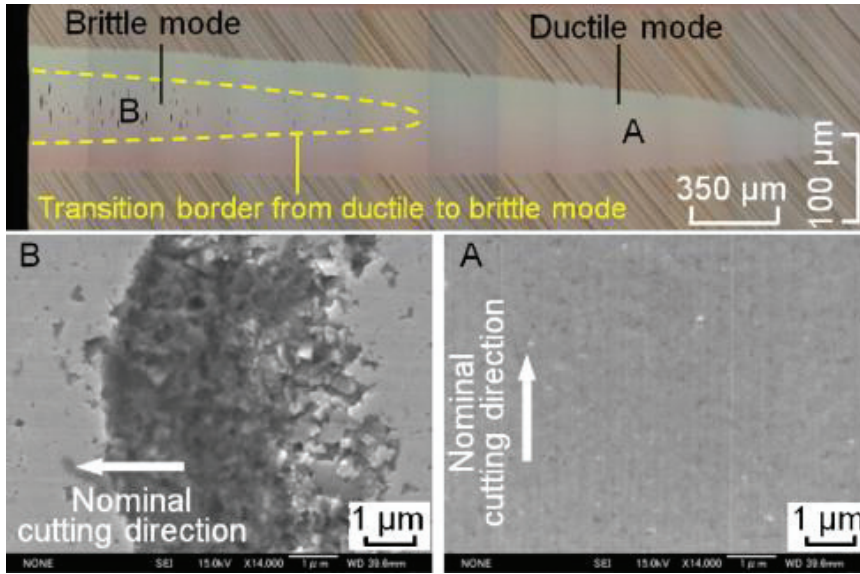


Fig. 9. Machined groove with an increase of the depth of cut (workpiece: BL4, amplitudes: 2–2 $\mu\text{m-p-p}$, nominal cutting speed: 150 mm/min) (Zhang *et al.* 2014).

1.3. Brittle ductile transition in vibration assisted grinding

From the overview in the previous section, it is apparent that, in order to induce the brittle-ductile transition, it is necessary to produce a momentary increase of hydrostatic pressure at the tool – workpiece interface. Vibration assisted machining is a set of processes that has a potential to deliver this effect and to do it in a rapidly intermittent and incremental manner while preventing previously described unloading-induced defects. The vibration assisted machining process group combines vibratory motion with the conventional machining processes. Vibratory motion can be induced either onto the workpiece, on the tool, or on both. The most popular methods to include vibration assistance are drilling, grinding, and turning.

Vibration assisted machining has been shown to benefit the conventional processes in a myriad of ways, yet not all of them are related with the deformation mechanism of the work material. For instance, it was observed in a study by (Gaidys, *et al.*, 2017) that vibration assistance in the 100 kHz range induced intermittence of the tool workpiece contact reduced the tool wear in the single point diamond turning of ferrous materials. Other improvements to the surface quality had to do more with the tool path kinematics rather than with the tool-workpiece dynamics, for instance, in (Wang, *et al.*, 2014), it was established that, at a sufficiently high frequency, the path of the grain in the grinding process overlaps thus reducing the cutting force on the subsequent pass.

Since, at its core, vibration assisted grinding is a basic grinding process supplemented with vibratory assistance, common grinding process studies are

presented first. In (Chen & Jiang, 2015), the quartz-glass micro grinding technique was developed, and it was shown that it was necessary to provide a proper machining force for preventing brittle fracturing. Fig. 10(a) illustrates the removal mechanism of a hard, brittle material under ductile machining. The effective critical cutting depth propagated to a surface damage depth of y_c as shown in Fig. 10(b). Under the ductile grinding regime, this type of machining can be implemented as micro-fracturing and does not extend below the cut surface plane.

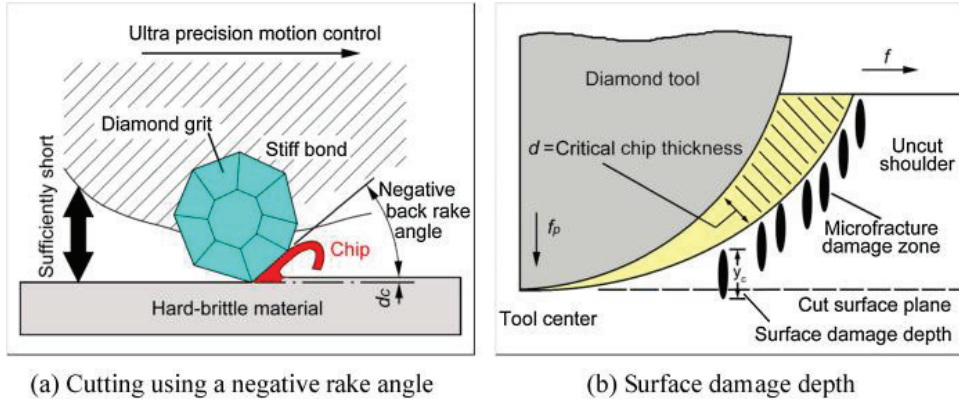


Fig. 10. Ductile regime machining on hard, brittle material (Chen and Jiang 2015)

In (Yin, *et al.*, 2005) nano-grinding of fine-grain WC-Co composite was designed to achieve the optimum surface quality without further polishing. The flat ground surfaces were tested by using the scanning electron and atomic force microscopy as well as optical and laser interferometry in order to measure the surface roughness, flatness, and surface integrity as a function of the grinding conditions. The results obtained in (Zhong & Peng, 2007) show that precisely processed WC-Co and Inconel-625 surfaces could be identified as independent fractals.

Ductile cutting of brittle materials can replace the traditional manufacturing technologies. Ductile cutting should decrease the time and cost of processing brittle materials and accordingly improve the process performance. Ductile cutting is possible if the undeformed chip thickness is smaller than the tool's cutting edge radius which should be at the sub- μm level (Arif, *et al.*, 2012). This reduces the surface damage, which is a serious problem of the traditional brittle material machining. Ductile cutting also eliminates the requirement for the secondary finishing process related to the traditional brittle material processes and therefore improves the overall process performance. The treated surface is finished at a high quality, which is an essential requirement for optoelectronic devices. Yet, one of the the problems facing this industry is the tool wear (Li, *et al.*, 2005), whereas the cutting edge sub- μm level maintenance is the main problem affecting the time and cost of the machining process.

Grinding is one of the most common and suitable methods in the machining of HBM. The cutting edge of a grinding tool is never fully defined. Instead of a known set of edges oriented along specific axes, grinding tools possess an unknown set of miniature edges in the form of abrasive grains (Anderson, *et al.*, 2011). Each abrasive grain engages with the workpiece, much in the same way as a nano-indenter engages with the material during the nano-scratching experiment (Fig. 11).

Because of their low size, grains can work in the ductile mode when abrading the workpiece. Unlike in other multi-edge machining methods (e.g., milling), the cutting edges are not aligned with each other, nor do they have any specific orientation. Therefore, the grain trajectories tend to overlap but are rarely identical. Because of this, the MRR per grain is even more greatly reduced, which allows for higher feed rates. Due to differing grain trajectories, grains will interact differently, depending on the penetration depth of the grain into the material, at a certain point in their trajectory. A grain can interact with the workpiece in three ways. In-depth analysis of these modes was outlined by (Anderson, *et al.*, 2011); it is presented below (Fig. 11).

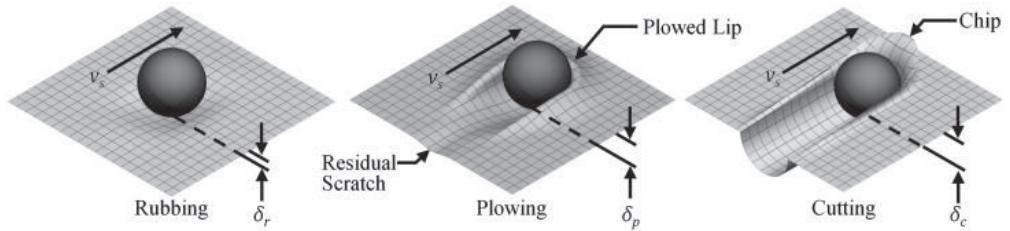


Fig. 11. Three modes of grain interaction with material (Anderson *et al.* 2011)

A grain interacts with the material at a certain penetration depth h . The modes proceed to change as the depth increases. The initial mode occurs when the penetration depth h is between 0 and some value δ_r . In this mode, no material removal takes place – all the deformation is elastic, and the mode is referred to as rubbing. The second mode is called plowing, and it occurs when h is between δ_r and δ_p . In this mode, the material removal is plastic, although some elastic deformation still occurs at the scratching site – the resulting mark from the tool tends to recover a little bit from the deformation. The material in this case is not as much cut as it is actually pushed away. When h is between δ_p and δ_c , then, the cutting mode occurs. Deformation in this mode is mostly plastic, and the material is removed through chipping.

Additional research into the grain interaction with the workpiece (Liu, *et al.*, 2018) yielded three modes based on the degree of brittleness/ductility which further detail the cutting mode as outlined previously. The crack induced surface/subsurface damage in SiC ceramic grinding limits the industrial application. A single-grain scratching simulation based on the smoothed particle hydrodynamics (SPH) has been used to analyze the SiC grinding mechanism including the material removal process, the scratching speed effect on the crack propagation, the ground surface

roughness, and the scratching force. As well as the previously outlined modes, these modes also depend on the depth of the cut (Fig. 12).

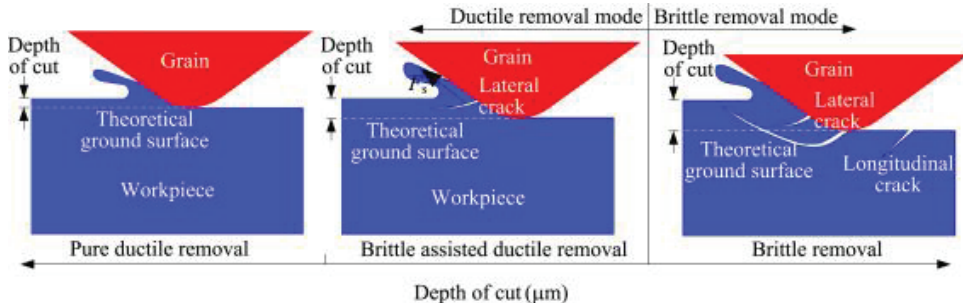


Fig. 12. Degrees of brittleness in abrasive grain interaction with SiC (Liu *et al.* 2018)

As the depth of the cut increases beyond the ploughing depth, the grain first starts to interact with the workpiece in the purely ductile mode. In this mode, the material removal is dominated by the plastic flow, cracks are not initiated, and the ground surface is smooth. Beyond a certain value of the cutting depth, brittle assisted ductile removal is initiated, and a lateral crack is induced in the vicinity of an undeformed chip; however, it does not extend into the workpiece. As a result of the lateral crack formation in the chip, the undeformed chip's thickness (UCT) is effectively reduced, which results in material removal in the ductile mode just as in the purely ductile mode. Upon the increase of the cutting depth, beyond the critical value, the crack propagates into the workpiece, beyond the grain front and the undeformed chip. This yields purely brittle deformation which leaves behind a crack surface in poor conformance to the theoretical ground surface.

Three types of material removal modes – the pure ductile mode, the brittle assisted ductile mode, and the brittle mode – were defined in the SiC scratching process, as shown in Fig. 12:

1. Pure ductile mode: when the depth of the cut is small, the chip formation is dominated by the plastic flow. No crack occurs, and the ground surface is smooth;
2. Brittle assisted ductile mode: as the depth of the cut increases, the Mode I lateral crack develops in the material above the theoretical ground surface due to the plastic chip flowing shear force. This lateral crack propagates along the workpiece's surface and creates the brittle chip so that to remove part of the material. The remaining material is removed in the ductile mode due to the reduced depth of the cut after the brittle chip formation, and a crack-free ductile ground surface is generated conforming to the theoretical ground surface;
3. Brittle removal mode: with the depth of the cut increasing further beyond the critical value, the Model II type lateral crack initiates and propagates

into the material below the theoretical ground surface due to the grain-chip friction force while leaving crack marks on the surface/subsurface.

Fig. 13 illustrates the scratching process while grinding a brittle material with a single abrasive grain (Duan, *et al.*, 2017). The abrasive grain is rotating around the grinding wheel axis at a constant speed (V_s), and the workpiece is fixed. Scratching is performed at the intermittent mode.

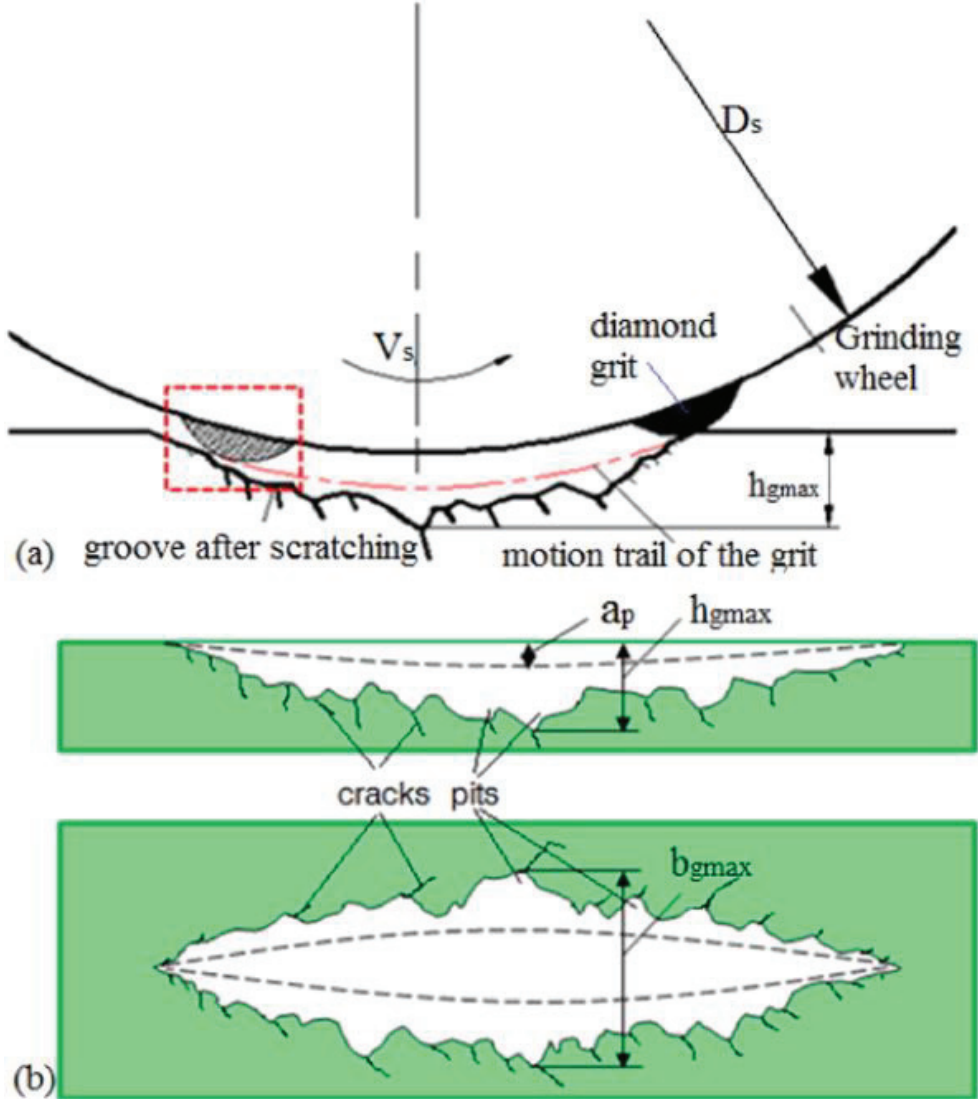


Fig. 13. Illustration of scratching a brittle material by single grit: (a) the motion of scratching, (b) the groove on the workpiece produced by scratching (Duan *et al.* 2017)

A three-dimensional molecular dynamics model was proposed to study the influences of the scratch feed, depth and crystal orientation on the shape and surface quality of the scratched groove during the nano-scratching process. In the paper by (Zhang, *et al.*, 2013), comparisons were made between the results of double tips simultaneously scratching the surface and those of single tip successively scratching the surface with the same scratch feed, depth, and crystal orientation. The molecular dynamics simulation model consists of two parts, a mono-crystalline copper specimen, and a diamond tip, as shown in Fig. 14. The AFM diamond tip used in the current simulation has a configuration of the cone shape with a tip angle of 30° , which is constructed with the perfect diamond atomic lattice consisting of 4944 carbon atoms. The apex of the cone is truncated by one atom. Due to the evidently higher hardness of diamond than copper, the diamond tip is treated as a rigid body during the process of scratching the specimen's surface.

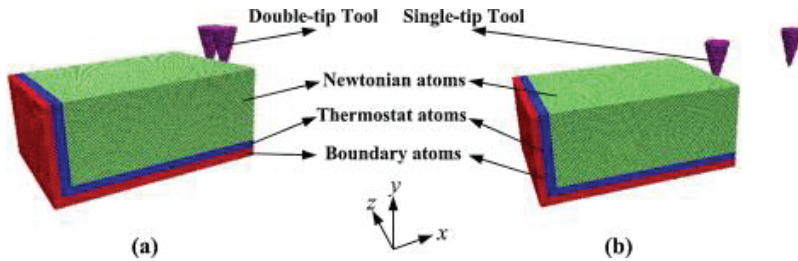
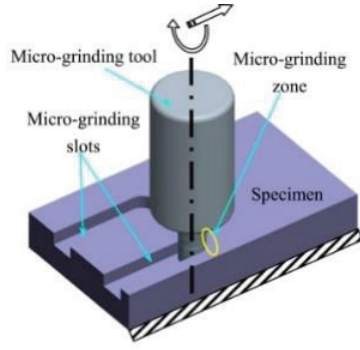


Fig. 14. (a) Molecular dynamics simulation model with a double tip simultaneously scratching the specimen's surface; (b) Molecular dynamics simulation model with a single tip successively scratching the specimen's surface (Zhang *et al.* 2013)

In the paper by (Cheng, *et al.*, 2017), a predictive model was developed for the grinding force in micro slot-grinding in three different orientations of a single crystal sapphire. A geometric model of the micro slot-grinding process is shown as Fig. 15(a) with a tool diameter d_s of 0.5 mm. The sapphire specimen is held on the workbench, and the micro-slots on the surface are fabricated by using the feeding motion with a diamond micro-grinding tool. Fig. 15 (b) shows the motion path of two grains (g_1 and g_2) during MSG, where θ is the rotation angle, h_m is the undeformed chip's thickness, f is the feed per circle, ϕ is the tangential angle of the grit instantaneous velocity, x is the width direction of the slot, and y is the feed direction. The variations in h_m (g_1 and g_2) for different feed velocities v_f are calculated and are shown in Fig. 15 (c).



(a) Geometric model of the MSG process

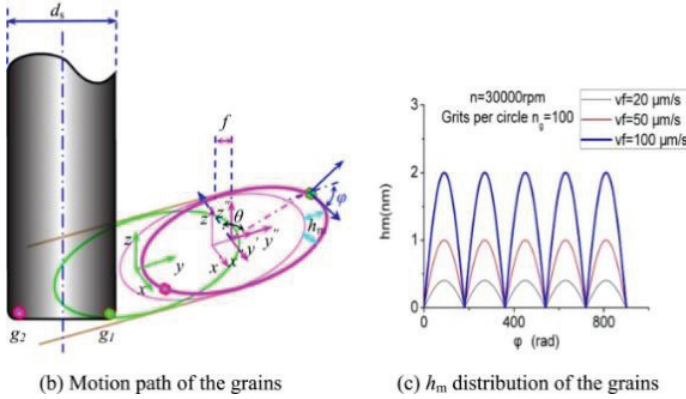


Fig. 15. Processing principle of micro slot-grinding (Cheng *et al.*, 2017)

The combined effect of material removal and plastic stacking on the grinding force model was investigated in (Zhang, *et al.*, 2017). As shown in Fig. 16, the cutting depth a_g increases gradually from zero to the maximum (the maximum undeformed chip thickness is noted as a_{gmax}). The critical cutting depth a_{gc} is used to distinguish between the ploughing stage and the cutting stage. The ploughing stage is reached when the cutting depth a_g is less than the critical cutting depth a_{gc} , while the cutting stage is reached when the cutting depth a_g is greater than the critical cutting depth a_{gc} . The critical cutting depth of the ploughing-to-cutting transition a_{gc} can be obtained by the scratch test.

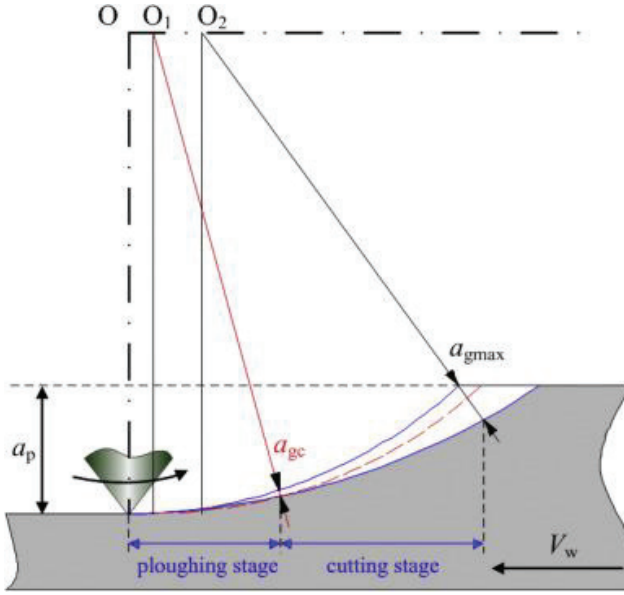


Fig. 16. Cutting depth of a single grain (Zhang *et al.*, 2017)

When $a_g \leq a_{gc}$, the grain is in the ploughing stage, as shown in Fig. 17. Owing to the small cutting depth of the grain, the stress between material units has not reached the fracture stress. Thus, the workpiece material flows upheaved and stacked at the two sides of the furrows.

When $a_g > a_{gc}$, the grain is in the cutting stage. As shown in Fig. 17 (b), the stress between the pink-colored material units has not reached the fracture stress. Thus, the workpiece material flows upheaved and stacked at the two sides of the furrows. On the contrary, considering that the blue-colored material units have a longer flow distance in the unit time with the action of the grain, a boundary exists between the blue- and pink-colored material units. At this boundary, the stress component at the grain movement direction reaches the fracture stress level. Therefore, the blue- and pink-colored material units are cut out as debris.

In order to improve the mechanical models of ceramics, surface grinding experiments on crystalline ceramics and non-crystalline ceramics were conducted in (Zhang, *et al.*, 2015). The normal and tangential grinding forces were measured to calculate the single grit force and the specific grinding energy. In the paper by (Tian, *et al.*, 2015), the effect of the speed on the material removal was investigated by single grit grinding of the GH4169 super alloy which is difficult to machine while employing the new test method. During the tests, the whole material removal process was observed, and then, the critical thickness of the chip formation was quantitatively analyzed.

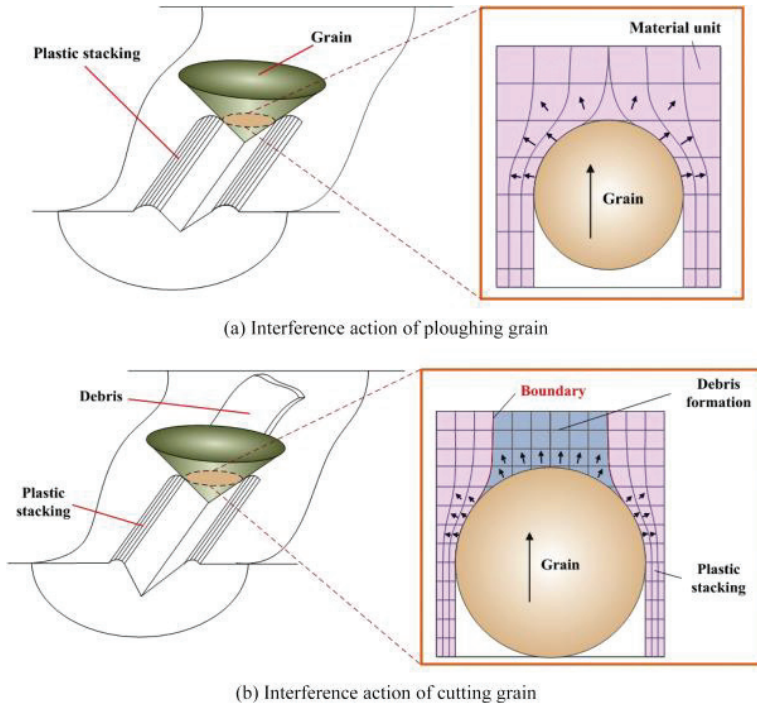


Fig. 17. Interference action of grains in surface grinding (Zhang *et al.*, 2017)

Vibration assisted machining is generally observed in two forms regardless of the conventional machining method being supplemented. The two groups can be distinguished by the nature of the cutting-edge movement as illustrated below (Fig. 18):

- 1-dimensional, whereby the linear motion is produced by vibration as it is applied in line with the cutting-edge movement direction;
- 2-dimensional, whereby the cutting edge moves along a plane formed by the excitation direction and the cutting direction.

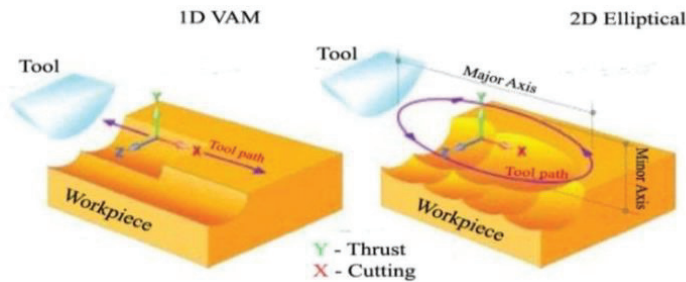


Fig. 18. Types of VAM based on the modes of vibration (a) 1-Dimensional VAM, (b) 2-Dimensional VAM (Cerniway, 2001)

The article by (Zhong & Rui, 2005) presents the experimental results of single crystal silicon grinding while using a diamond grinding wheel and a micro vibration device. The best surface finish was achieved when silicon was being ground at 70 Hz and 6 μ m amplitude horizontal vibrations perpendicular to the grinding direction, thus making it a 2-dimensional vibration-assisted grinding setup. However, the desired efficiency of the machining processes is proportional to the ultrasonic excitation frequency which often exceeds 100 kHz. Obviously, therefore, we have no data on the applications of the ultrasonic back grinding process for the hard, brittle material manufacturing.

A study by (Guo & Zhao, 2017) presents a one-dimensional vibration-assisted grinding case. Fig. 19 presents the experimental setup of ultrasonic vibration-assisted grinding. The left part is the on-machine dry electric discharge truing (EDT) subsystem used to precision condition the diamond wheel with a designed profile. The EDT is composed of an electrode wheel, a precision spindle, a pulsed power source, and an air compressor. The right part of Fig. 19 shows the ultrasonic vibration assisted grinding subsystem consisting of a workpiece, an ultrasonic vibration table, and a universal angle table. The ultrasonic vibration table is used to actuate the workpiece's vibration. The vibration direction of the workpiece is precisely adjustable by using the universal angle table in order to avoid interference between the micro-structures and the vibration trace. Additionally, the rotation of the workpiece around the X axis could be controlled in order to increase the tilt angle θ .

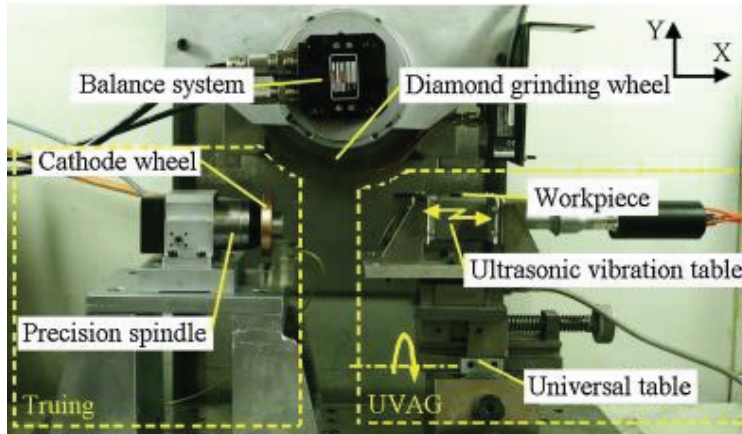


Fig. 19. Experimental setup of ultrasonic vibration assisted grinding (Guo & Zhao, 2017)

Vibration assisted grinding has found applications in the production of high-precision casting molds that are manufactured for back finishing of hard materials. One study of such an application (Chen, *et al.*, 2015) established the surface waviness correlation with the excitation amplitude. Fig. 20 shows the surface waviness under different grinding tool vibration amplitudes. The surface height increases as the grinding tool's amplitude increases, and varies periodically.

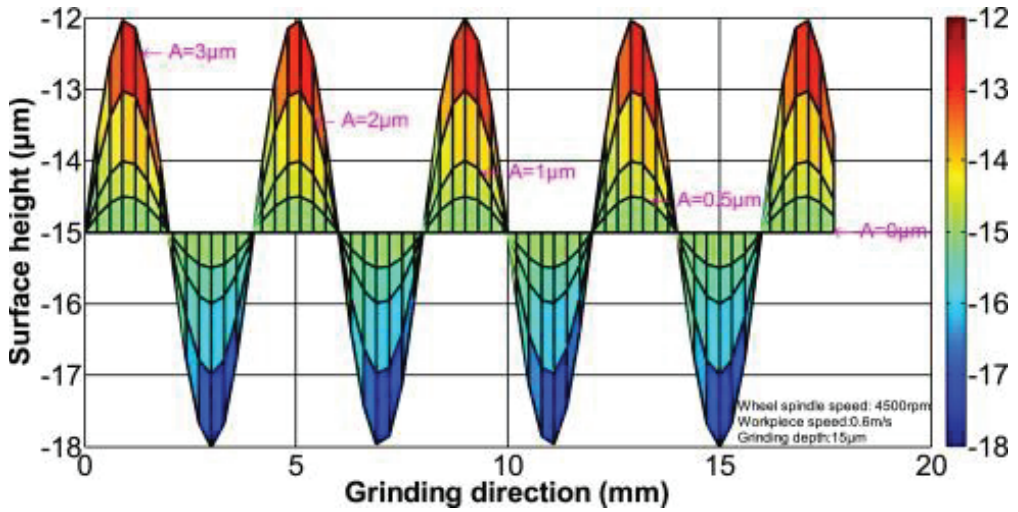


Fig. 20. Influence of the grinding tool vibration amplitude on the surface waviness (Chen, *et al.*, 2015)

In (Cao, *et al.*, 2014), the material removal behavior of the one-dimensional ultrasonic SiC grinding setup is presented. The critical cutting depth, the scratch strength, and the cutting efficiency were analyzed in detail as well as two scratching modes (continuous and interrupted) depending on the actual cutting depth. A schematic diagram of the experimental SiC grinding setup is presented in Fig. 21 (Cao, *et al.*, 2014). An in-house-produced ultrasonic unit which featured a cone-shaped single diamond tool with a vertical angle of 80° and a nose radius of $15\text{ }\mu\text{m}$ attached to its lower end face was installed on the wheel head of an existing Numerical Control surface grinder (*SGT-315RPA* by *Nagase Integrex Co., Ltd.*). A disc-shaped SiC ceramic workpiece ($\varnothing 30\text{ mm} \times 5\text{ mm}$) with a surface roughness of 10 nm Ra and an elevation angle of $\alpha=0.018$ was held on the worktable via a 3D dynamometer (*9256A* by *Kistler Co., Ltd.*). The ultrasonic unit was constructed by bonding a PZT (piezoelectric ceramic) device onto a metal (SUS304) elastic body. A wave function generator (*WF1944* by *NF Corporation*) and two power amplifiers (*4010* by *NF Corporation*) were employed to generate two AC voltage phases that were applied to the PZT to make the diamond tool ultrasonically vibrate in two directions, i.e., along the y- and z-axes, simultaneously. The vibration amplitudes of the tool were measured with two laser Doppler vibrometers (*LV-1610* by *Ono Sokki Co., Ltd.*) for the respective UVs in the Y and Z axes; the UV amplitudes (peak-valley) were $1.2\text{ }\mu\text{m}$ in the Z axis and $0.25\text{ }\mu\text{m}$ in the y-axis under an AC voltage with a frequency of $f=14.3\text{ kHz}$ and an amplitude of $V_{p-p}=50\text{ V}$.

SUS304). When two alternating current (AC) signals (over 20 kHz) with a phase difference of ψ generated by a wave function generator are applied to the PZT after being amplified by means of power amplifiers, bending and longitudinal ultrasonic vibrations with amplitudes of several μm are excited simultaneously. The synthesis of vibration displacements in the two directions creates an elliptical motion on the end face of the metal elastic body.

In the paper by (Patnaik Durgumahanti, *et al.*, 2010), a new grinding force model was developed by incorporating the effects of a variable coefficient of the friction and ploughing force. This is based on the fact that chip formation during grinding consists of three stages: ploughing, cutting, and rubbing.

In the work by (Jiang, *et al.*, 2013), 2D and 3D ground surface topography models were established based on the microscopic interaction mechanism model between the grains and the workpiece in the grinding contact zone. In this study, beside the grinding parameters, the wheel dressing and wear effects were taken into consideration, including the dressing depth, the dressing lead, the geometry of the diamond dressing tool, and the wear effects of both the wheel and the diamond dressing tool.

In the study by (Li, *et al.*, 2017), a new analytical surface roughness model was developed on the basis of the stochastic nature of the grinding process governed mainly by the random geometry and the random distribution of the cutting edges on the wheel surface featuring random grain protrusion heights. A simple relationship between the surface roughness and the chip thickness was obtained which was validated by the experimental results of AISI 4340 steel in surface grinding.

In the study by (Li, *et al.*, 2017), a detailed modeling methodology of the grinding forces was analytically established, experimentally validated, and utilized to study a specific issue. As illustrated in Fig. 23(a), hundreds of discrete moving grains would simultaneously interact with the workpiece's surface. Thus, the normal grinding force at a certain moment should be the vector superposition of all the normal force components induced by all the cutting grains at that moment.

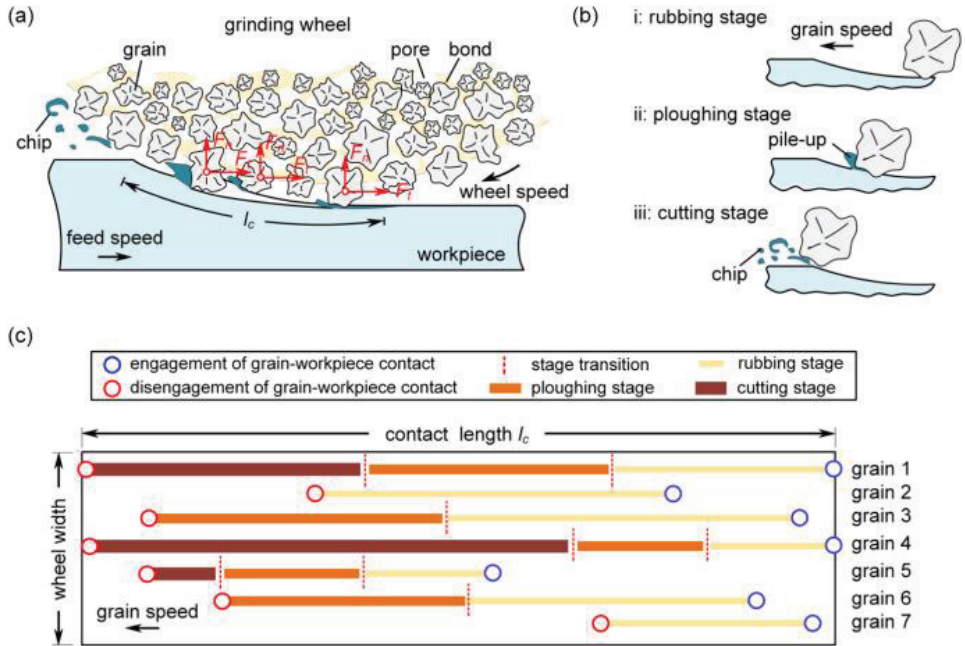


Fig. 23 (a). Schematics of the grinding process where hundreds of grains simultaneously interact with the workpiece's surface and thousands of grains continuously, (b) three possible grain-workpiece contact stages including (i) rubbing (Li *et al.*, 2017)

Tangential forces are usually determined by both the normal forces and the friction coefficients. However, the friction coefficients would be varied for different grains depending on the different grain-workpiece contact stages, including (i) rubbing, when elastic or plastic deformations happen on the workpiece's surface, (ii) plowing, when pile-ups are formed, and (iii) cutting, when the workpiece's material is removed (see Fig. 23b). The bigger issue is that each grain's protrusion height is also different due to the varied grain sizes and distributions, which would further result in diverse grain trajectories and different grain penetration depths. Different grains therefore would have different grain engagement, disengagement and stage transition points when they pass the workpiece's surface (Fig. 23c).

The grinding process of monocrystalline silicon easily leads to fractured surfaces; therefore, an analytical model of the ground silicon surface is presented (Li, *et al.*, 2017). The experimental measurements of CBN grains showed that the grain shapes, to a large extent, were random, but they can be approximately simplified as a round-tipped cone with the 60° included angle and the chord length of 20% of the cone height (Li, *et al.*, 2017) (Fig. 24 a).

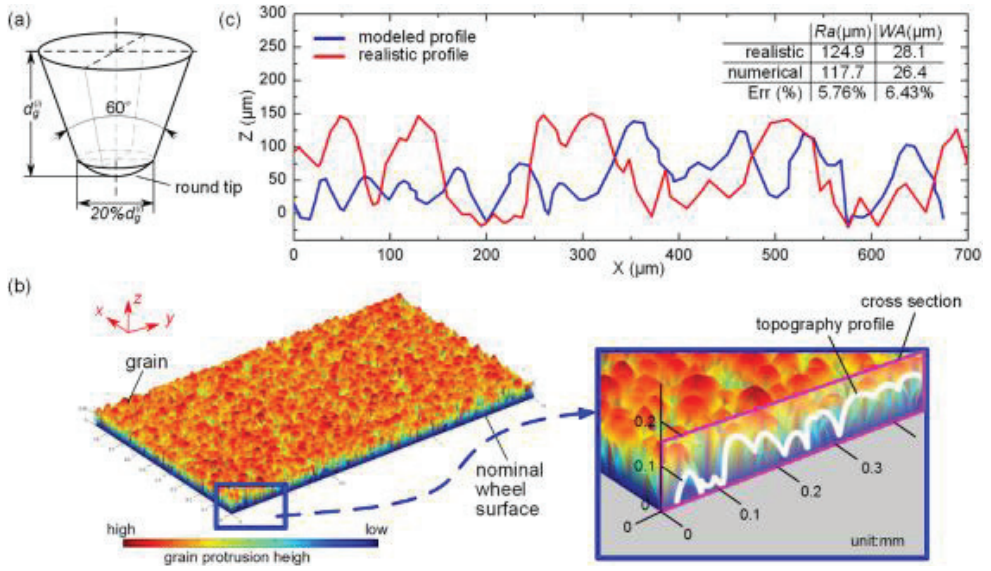


Fig. 24 (a). Illustration of the employed abrasive shape, (b) the obtained grinding wheel topography, (c) the 2D profile comparison between the realistic and the modeled grinding wheel topography (Li *et al.*, 2017b)

Fig. 24 (b) and (c) separately shows examples of the modeled wheel topography and the 2D profile comparison. Single-grit simulation was employed to investigate the initiation and propagation of individual cracks in SiC grinding under controllable maximum undeformed chip thickness (Li, *et al.*, 2017).

The work of (Zhu, *et al.*, 2014) relies on smooth particle hydrodynamics (SPH) for overcoming this issue. SPH approximates a continuous field by using a set of kernel functions centered about the so-called particles. These particles carry the physical properties of the system, e.g., its mass, internal energy, or velocity, thus discretizing the set of underlying partial equations. By using a discrete method, material detachment is intrinsically taken into account.

The paper by (Varga, *et al.*, 2017) presents a numerical model that simulates the contact between the grinding wheel and the workpiece in surface grinding. The model reproduces the granular structure of the grinding wheel by means of the discrete element method. The papers by (Osa *et al.*, 2016) and (Jiang, *et al.*, 2016) are based on the microscopic interaction mechanism model between grains and the workpiece material in the grinding contact zone, which will describe the interaction situation of a grain with any size, protrusion height and location; as a result of this research, the distributions of each type of grains were obtained. Single plowing and cutting grain force models were developed, which led to the grinding tool aggregate force expression based on grain distribution.

An analytical model for the elastic stress field in isotropic hard and brittle materials during scratching is presented (Wang, *et al.*, 2017). The model considers the entire elastic stress field and the effect of material densification that was ignored

in the past studies and is developed under the cylindrical coordinate system in order to make the modeling process simpler. Based on the model's predictions, the location and sequence of crack nucleation are estimated, and the associated mechanisms are discussed. In the article by (Sun, *et al.*, 2016), a theoretical model is established based on the removal behavior of silicon, including cutting and sliding. For the first time, the effects of the processing parameters, the wafer radial distance and the crystal orientation on the grinding force are quantitatively described in a theoretical model. Excess grinding force causes local damage of the wafer in the form of subsurface cracks as a determinant factor on the quality of the wafer. The paper by (McDonald, *et al.*, 2017) combined experimentally-measured grinding wheel topography data taken around the entire circumference of the grinding wheel with a kinematic simulation of the grinding process. A method was developed by (Setti, *et al.*, 2017) to predict the active grits count by assuming a stochastic distribution of abrasive grits and their physical interaction with the workpiece based on a presumed abrasive wear mechanism. In addition, the count of the active cutting edges was included by using dressing kinematics.

Further, throughout this research, both one-dimensional and 2-dimensional vibration assisted grinding cases will be considered. The one-dimensional case is considered in cylindrical grinding, while the 2-dimensional case is researched in rotary back grinding.

1.4. Chapter conclusions

Upon conclusion of this chapter, a historical retrospective on brittle-ductile transition and ductile mode machining was conducted. Also, the following points were established:

1. Spectrum of hard, brittle materials: it was observed that a lot of HBM machining cases in the literature were actually a result of false attributions. Based on the amount of publications for each case, the majority of false attributions were eliminated, thus yielding a smaller list of universally accepted HBM's.
2. The mechanical property range: based on the mechanical property range within the established hard, brittle materials, it was determined, that a material is likely to be considered hard and brittle if its fracture toughness is below 6.5 and hardness on the Moh's scale exceeds 6.9.
3. Sample material for research: the most prominently researched hard, brittle materials in the literature were WC and SiC. Due to their availability as well as the fact that it was less researched than SiC, WC was chosen as a sample material for research within this thesis.
4. Brittle ductile transition mechanics: our literature review yielded a conclusion that brittle, ductile transition can not only be achieved through the reduction and variation of the undeformed chip thickness, but also through the increased pressure at the tool-workpiece interface.

5. Investigated machining method: following immediately from the previous conclusion, it was decided, that, for pressure increase induction, at the tool-workpiece interface, vibration assisted methods should be developed, namely, vibration assisted grinding, due to its conventional counterparts already being denoted by success in dealing with hard, brittle materials.

2. METHODOLOGY

Based on the analysis conducted in the previous chapter, the object of our experimental investigation can be outlined as brittle ductile transition initiated by rapid hydrostatic pressure fluctuation in vibration assisted grinding of tungsten carbide. To further establish the parameters necessary to experimentally analyze it, theoretical analysis of the vibration assisted grinding process seeking to identify the brittle-ductile model setup is carried out. Upon determination of the model setup, numerical analysis of the process is conducted in order to determine design specifications for the machining equipment. This equipment is then designed and developed in the final section of this chapter.

2.1. Theoretical analysis of ductile regime machining in vibration assisted grinding

On the fundamental level, grinding can be defined as cutting in absence of a deterministically defined cutting edge. Outside of heavily controlled scientific trials, the cutting edge of a grinding tool is distributed stochastically owing to the randomness of abrasive grain shapes, sizes, orientations, and the chaotic nature of the bonding to the substrate, as well as individual wear rates, defects and other complex interactions.

It is, therefore, only natural to consider every grinding process from the standpoint of its most fundamental constituent – the grain – and only then to employ broader approximations in order to determine the overall performance of the process. Due to the commonly encountered sizes of grains, the analysis of the grain-workpiece interaction is best performed on the microscopic level.

Initially, the grain can be represented either as a sphere-shaped particle or a sharp pyramid-sized to the average observed dimensions of abrasive grains, while ignoring the orientation, wear and defect factors. Unless a micro grinding tool is employed, the curvature effects of the tool-workpiece interface can be neglected. It can therefore be assumed that, in all the commonly encountered cases, the grain-workpiece interaction interface is essentially the same and is defined as a spherical grain interacting with a flat plane under parameters predetermined by the process configuration. The only influence the curvature has on the approximation of the grain behavior is the determination of the effective engagement diameter between the tool and the workpiece.

The basic premise of the grinding process relies on the high speed (V_s in Fig. 25) rotation of an abrasive wheel and a uniform feed rate (V_w in Fig. 25) of the workpiece or the tool at a predefined tool engagement depth (a_f in Fig. 25) to bring randomly distributed grinding grains into a momentary contact with the workpiece's surface and to remove small portions of the material. Further, throughout this analysis, the ground surface (the contour marked by letter 'p' in Fig. 25) will be referred to as the passive surface, while the points of the active grains (any grain

points that fall into the circumference marked by ‘a’ in Fig. 25) will be referred to as the active surface.

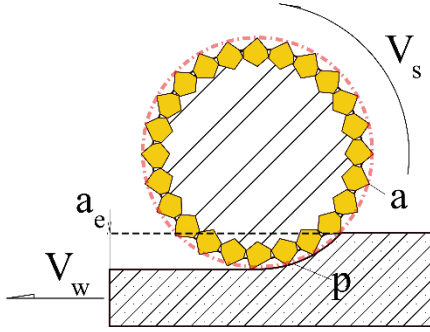


Fig. 25. Basic schematic of the tool-workpiece interaction during grinding: a_e – engagement depth, V_w – feed rate, V_s – cutting speed, a – active surface, p – passive surface

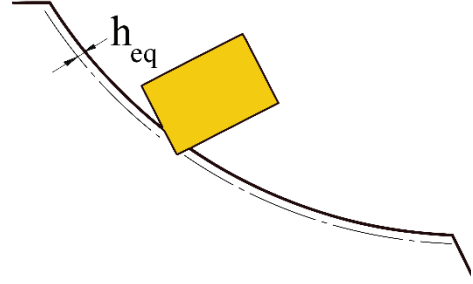


Fig. 26. Schematic representation of abrasive particle penetration of passive surface at effective depth h_{eq}

The shared interface between the active and passive surfaces constantly changes throughout the process. As the tool wears and the grains eventually fracture and break away, the active surface geometry changes accordingly. Meanwhile, the material removal process itself results in a constantly changing interface of the active and passive surfaces. If it were assumed that the tool has a no-wear condition and is perfectly rigid, the abrasive grains would still need to penetrate the material to some effective depth (denoted as h_{eq} in Fig. 26) to remove chips from the said material. Thickness h_{eq} is better known as the equivalent chip thickness and is a function (Eq. 2.1) of the feed rate (V_w), the grain velocity (V_s), and the tool engagement depth (a_e) (Ilio, *et al.*, 2009):

$$h_{eq} = a_e \frac{V_w}{V_s} \quad (2.1)$$

However, this quantity is only useful when considering a single grain, and when assuming the perfect contact. The grains are distributed and orientated randomly, at different heights. This results in different grain engagement and variation of the cutting modes along the grain path – some grains will only rub or plow along the surface while others will cut or cut and scratch intermittently.

The center axis of the rotary grinding tools generally has two support configurations – the supported on both ends of cantilever support (**Fig. 27**). The two-axis support is indicative of most large grinding disc applications, and the majority of the smaller grinding tools, such as grinding stems, are encountered in the cantilever axis support category.

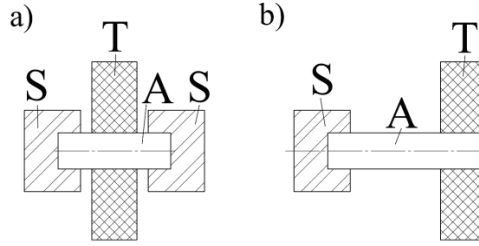


Fig. 27. Various grinding tool configurations a) fixed – fixed support b) cantilever support. Here, A – tool axis, T – abrasive tool, S – axis support

In a typical grinding disk application, the grains will engage the workpiece in a similar manner to the one outlined in Fig. 25 and Fig. 26. However, such applications as back-grinding employ grinding tools which are in the cantilever axis support configuration. In such an application, grains on the cylindrical surface of the tool will engage the workpiece much in the same way as shown previously (Fig. 25 and Fig. 26) (except that, here, the surface being ground by these grains is the side surface of the grinding path); however, the grains at the bottom of the tool will also engage the workpiece. Here, however, the contact with the workpiece can be defined either by the normal force applied to the tool – in the case of a single vertical axis movement (here, the cylindrical grains do not engage the workpiece), or by a resultant force caused by the grinding torque defined by the interaction of the side face of the grinding path and grains on the cylindrical surface of the tool. The resultant force deflects the tool by an angle, thus forcing the grains on the bottom surface of the tool into contact with the bottom surface of the grinding path. The degree of deflection of the tool, in turn, defines the grain engagement mode with the surface – whether it is sliding, plowing, or cutting, which, in turn, influences the surface quality of the bottom surface of the grinding path.

Virtual deflection of the tool can be determined analytically, by assuming a deflection case for a cylindrical rod (Fig. 28) of diameter d , constrained at a certain point X definitive to the protruding length of the tool l_t and force F representing the deflection force resulting from the grinding torque, applied at point Y, definitive to the tool engagement depth a_e .

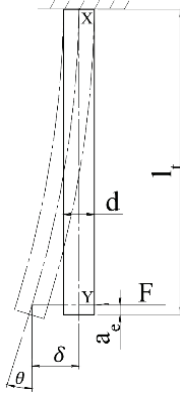


Fig. 28. Determination of the maximum deflection and the deflection angle of the grinding pin

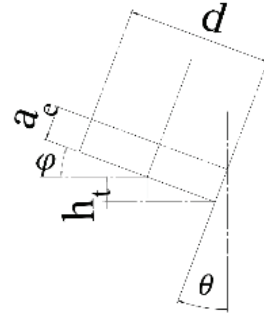


Fig. 29. Analysis of the tilt at the tip of the grinding pin

The maximum deflection and the deflection angle of such a case can be calculated by using the following beam deflection equations:

$$\delta = \frac{64 F(l_t - a_e)^2(3l_t - (l_t - a_e))}{6 E\pi d^4} \quad (2.2)$$

and

$$\theta = \frac{32 F(l_t - a_e)^2}{E\pi d^4} \quad (2.3)$$

As a result, the maximum virtual tilt and the tilt angle of the bottom surface of the tool (Fig. 29), while assuming the symmetric pivot condition, whereby the length of the deflected tool equalizes with the initial length at the center of the bottom surface of the tool, with the central axis at Y point height serving as the pivot point and the edge of the bottom tool surface serving as the fulcrum, can be approximated following the geometric relations of the tool and the grinding depth. From this, it follows that the tilt angle is $\varphi = \theta$, therefore, the maximum tilt at the edge is expressed as:

$$h_t = \frac{d \sin(90 - \theta)}{2} \quad (2.4)$$

Taking into account the above stated relationships and considering the typical grinding depth to the tool dimension ratio – the deflection should not vary significantly with the change of the depth.

From here, it follows that in order to fully determine F_n , it is necessary to define F which depends on the grinding force generated by the cylindrical tool surface interaction with the side surface of the grinding path. Several models have been developed by different authors for determining the grinding forces in this setup, and they are reviewed in further paragraphs

(Agrawal, *et al.*, 2017) developed a grinding force model based on UCT. The study by (Park & Liang, 2008) modeled micro-grinding forces in good agreement to the experimental results by including crystallographic effects in the process and expressing the forces as functions of workpiece properties, the experimentally obtained grinding wheel topography, the heat transfer and process parameters. Excessive tool wear is prominent in the conventional DRM processes. The tool wear during the machining of the single point diamond turning (SPDT) of Si has been studied experimentally and numerically, by conducting smoothed particle hydrodynamics (SPH) simulations by (Mir, *et al.*, 2016), and it was found to play a significant role in the formation of lateral cracks and brittle deformation as the tool wear progresses.

During the machining of brittle materials, when the critical resolved shear stress exceeds the elastic yield stress at any point in the material, the removal mechanism will change from the elastic mode (the ploughing mode in grinding) to the irreversible mode. Irreversible modes can either be brittle or ductile. Brittle deformation mechanisms are accomplished through the propagation of cracks, while ductile mechanisms are a result of the plastic flow. The theory derived the relation between the material removal mode and the machining scale from the ratio of the plastic flow and the fracture energies in a manner outlined below.

First, the plastic flow energy E_p was expressed as a product of yield stress σ_y which characterizes the resistance of the material to the plastic deformation of a specific volume of material V_p . Then, the fracture energy E_f was defined as a product of Griffith's crack propagation parameter G , and the surface of the newly created crack surface A_f . Assuming that the order of magnitude of parameters V_p and A_f can be approximated by cutting depth d , the orders of magnitude were defined as d^3 and d^2 for V_p and A_f , respectively. Thus, the following expression of the material removal energy ratio shows that, with the decrease of the machining scale, the plastic flow condition becomes more favorable:

$$\frac{\text{Plastic Flow Energy}}{\text{Fracture Energy}} \sim \frac{E_p}{E_f} \propto d \quad (2.5)$$

Based on this theory and the carried out experiments (Bifano, *et al.*, 1991), we were able to derive the critical depth of the cut model relating the material hardness H , the fracture toughness K_c , and the modulus of elasticity E :

$$d_c \propto \left(\frac{E}{H}\right) \left(\frac{K_c}{H}\right)^2 \quad (2.6)$$

Any changes to the BDT behavior in the vibration assisted grinding of HBM to the behavior in the conventional grinding can only be a result of the grain behavior changes due to the vibrations applied during the process. Hence, the changes in the grain behavior during VAG should be analyzed in order to understand the changes to the BDT behavior. In order to properly analyze the grinding grain behavior in VAG, it is first necessary to properly account for the influence of using the different pathways of excitation allowed by VAM.

2.2. Definition of experimental studies

Experimental studies carried out in order to test out the semi-analytical DRM-VAG model were outlined in the previous chapter. We decided to study the shortcomings and benefits of various VAG methods so that to further develop an improved approach to DRM in VAG. The design of experimental studies begins with the outline of the study of VAG in DRM by using the tool excitation approach.

2.2.1. Study of back grinding using ultrasonic excitation of a rotating tool

The tool excitation approach is the most commonly encountered technique in the VAM methods employing rotary tools. The aim of this experimental study was to evaluate the performance of the method in DRM of WC.

The main performance criteria under evaluation were the following:

- Changes to the surface roughness upon introduction of vibration assistance;
- Changes in the frequency of occurrence of ductile mode deformations upon introduction of vibration assistance;
- Versatility and design limitations of the method.

The study was designed to employ an ultrasonically excited abrasive grinding stem, to machine a cylindrical sample of WC (Fig. 30).

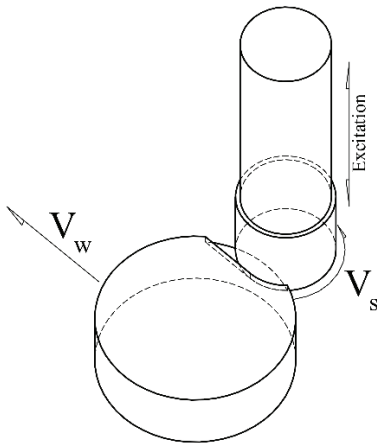


Fig. 30. A schematic diagram of the tool excitation approach

We discuss here in brief only the results and observations relevant to the development of further experimental studies. The results of the study provided several insights into the performance of the method. The surfaces exhibited brittle deformation and yielded high average roughness values. It was assumed that the poor performance was a result of the tool actuation approach suffering from three main limitations:

1. Low spindle speed;
2. Poor adaptability of the method to different machines;
3. Low assistive vibration frequency.

The first two limitations arise as a result of the general challenges to operating an ultrasonic actuator in a rotating interface. The piezoceramic rings require supply of an electric signal to operate. In this case, since the tool is rotating, the contact of the carbon brush and the commutator ring was used. Therefore, additional construction was required to hold the brushes in perfect alignment with the commutator rings. The design of such a construction would change on a machine-to-machine basis as the construction would be allowed to feature different workspace footprints. In the current case, the existing holes on the machine head could be utilized, however, not without impeding the rotational degree of freedom of the head. This, along with the availability of differently sized spindle chucks and chuck interface standards, severely impacts the applicability of the approach for different machines.

Additionally, the carbon brush holder construction must feature resonant frequencies outside of the operational frequencies of the spindle, which is not always allowed by the design of the machine in use. Also, the effect of the high rotation speeds can be worsened by misalignment of the actuator which is inherent to multicomponent assemblies, such as this one. In the current case, the carbon brush holder could only handle spindle rotation speeds of up to 5,000 rpm. Upon exceeding this limit, sparking between the brushes occurred, which resulted in a lower efficiency of ultrasonic actuation.

In order to increase the operating frequency of the tool actuator, the length of the ultrasonic waveguide would need to be greatly reduced. This would leave very little design allowance for such crucial features as the fixture flange, the sufficiently big back mass, the gradually tapered horn, and, most importantly, the tool holder section. If the actuator employed in this study was to be designed to be operated at higher frequencies of 40 or 80 kHz, the length of the front mass could be estimated to be about 0.043 m and 0.012 m in length for each frequency, respectively. Therefore, the operating frequency of the tool actuator was limited to a low ultrasonic range of 16–30 kHz.

These challenges can be addressed and perhaps even eliminated, however, not without introducing high costs and involving complicated solutions. Therefore, it is more promising to focus on the excitation of the workpiece itself. All the three of the drawbacks, in this case, can be eliminated. The workpiece experiences no

movement, therefore, a simply crimped connection can be used; thus, the approach can be applied easily to different machines, and there is no spindle speed limitation (the rotation speed was still kept at 5000 rpm in order to comply with the tool actuator results).

2.2.2. Study of cylindrical grinding using the ultrasonic excitation of a rotating workpiece

Considering the challenge of the rotating interface excitation exposed in the previous study, an attempt was made to reduce the issues related to driving signal transmission through rotating interfaces. The core idea of the solution to this issue is to remove the need for commutation through rotating interfaces by attaching the actuators to the static structures of the machine that house the rotating interfaces instead of trying to control the actuator already in the rotating interface in an attempt to induce vibrations onto the rotating interface itself.

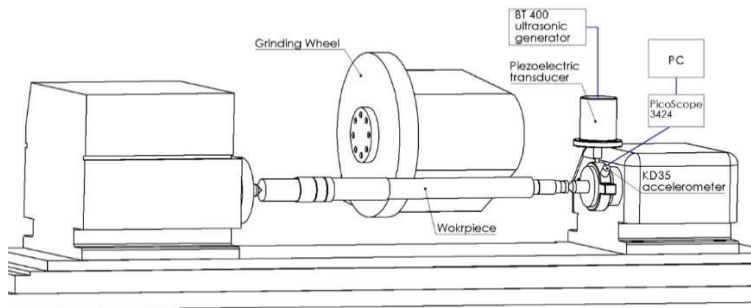


Fig. 31. A scheme of the experimental setup

The challenge of the rotating interface excitation is the most prominent in cylindrical grinding, when both the tool and the workpiece are in the rotating interfaces. The schematic of ultrasonic excitation application is presented in Fig. 31. The proposed solution was to apply excitation onto the stationary bushing of the dead-center of the machine.

2.2.3. Study of back grinding using ultrasonic excitation of a stationary workpiece

Based on the observations from previous studies, it was decided that the best approach for vibration assisted machining of hard, brittle materials was to achieve excitation of a stationary workpiece. For that purpose, an ultrasonic workpiece holder was developed, tested and patented by the author.

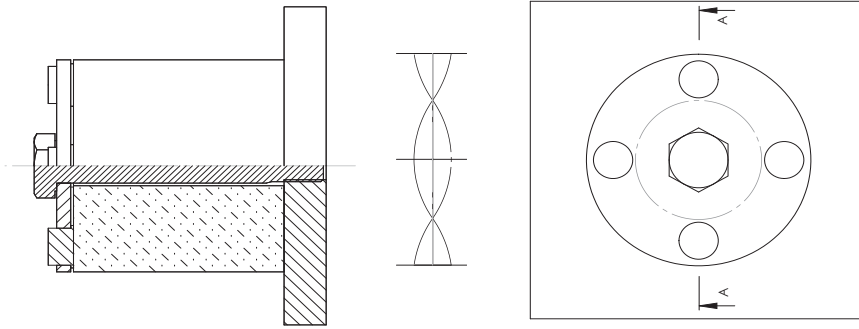


Fig. 32. Actuator design for ultrasonic workpiece excitation

The proposed design is intended to utilize the concentric displacement zones occurring at the higher vibration modes on the actuator's surface in order to achieve higher excitation frequencies while also allowing for the mounting of multiple samples for a single machining run.

2.3. Design of ultrasonic actuators

The development of ultrasonic excitation equipment is crucial in order to successfully carry out the experimental studies. The development of each actuator follows a similar sequence. Previously outlined experimental studies were used for the specification of design parameters of each actuator. According to the specification parameters, the initial dimensions of the actuators were approximated by using analytical relations outlined previously. The designs were validated and adjusted by employing numerical techniques.

All the actuators developed in this thesis are of the Langevin, sandwiched piezo transducer type. These actuators consist of a piezoceramic element stack along with electrodes (8 in Fig. 33) placed in between two masses (7 and 9 in Fig. 33) that are connected with a bolt (6 in Fig. 33) in such a way that as the bolt gets tightened, the piezoceramic stack is compressed. The mass commonly used for transmitting the vibrations to the working end of the device is commonly termed the front mass, whereas the piezoceramic stack is commonly termed as the center mass, and the counterbalance mass is termed as the back mass.

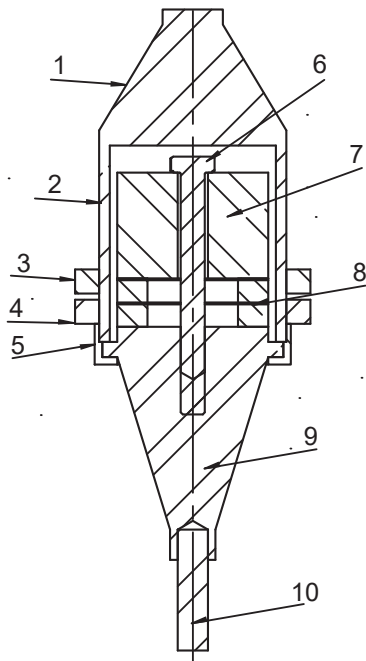


Fig. 33. Schematic of a Langevin type actuator in a tool holder configuration: 1 – tool holder interface, 2 – housing cylinder, 3/4 – commutation rings, 5 – retention nut, 6 – retention bolt, 7 – back mass, 8 – piezoceramic stack, 9 – front mass, 10 – tool

Actuator cross-sections may vary along with the range of different shapes, as does the symmetry axis and the conditions. In the case of rotary tool applications, in order to reduce the effects of the eccentric load, all the parts are best kept in concentric assembly with each part maintaining the circular cross-section. This design condition was maintained for all the three cases.

The front mass geometry can either stay uniform or have a widening or a narrowing profile in order to disperse or concentrate the vibrations respectively. The generally accepted front mass profile shapes are cylindrical (stepped), conical, or catenoidal (Fig. 34).

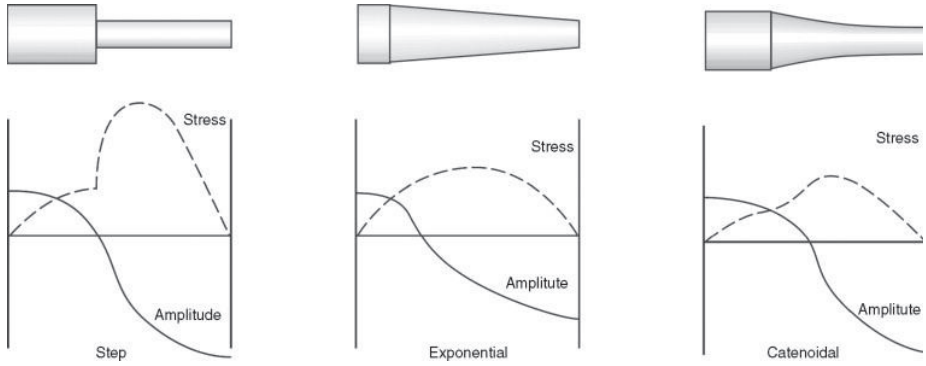


Fig. 34. Different front mass profile shapes

The general practice for constraining the actuators is via a flange along the nodal plane (Fig. 35). This method is employed in the tool excitation approach, however, in the static workpiece study and in the rotating workpiece study, the constraint is placed at the exposed back-mass face and at the exposed front mass face, respectively.

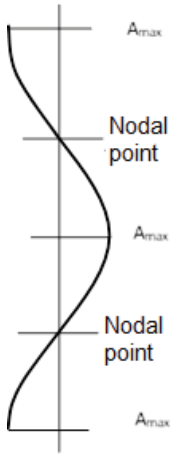


Fig. 35. A nodal point and displacement diagram in a Langevin transducer

The initial approximation of dimensions can be conducted following the assumption of the initial design constraints, such as the piezoceramic stack height and the diameter, the mass materials, etc. The length of a wave at a resonant frequency f for each cylindrical section is calculated from the following relation:

$$\lambda = \frac{c}{f} \quad (2.20)$$

where c is the wave velocity of the longitudinal vibration in the given medium, and it depends on its material properties.

$$c = \sqrt{\frac{E}{\rho}} \quad (2.21)$$

where E and ρ are Young's modulus and the density of the medium, respectively. Assuming that the piezoceramic stack dimensions are known, the part of the half wavelength already fulfilled in the design can be determined as:

$$r = \frac{2l}{\lambda} \quad (2.22)$$

Since the actuator is a collection of parts with differing geometries that are made from different materials, it is important to match the impedances of these different parts in order to ensure the propagation of vibrations to the output end and to avoid wave reflections at part junctions. Following from this condition, a relation for impedance matching from (Abdullah *et al.*, 2009) can be employed in order to determine the length of the back mass:

$$\frac{Z_b}{Z_c} \tan\left(\frac{2\pi f l_b}{c_b}\right) \tan\left(\frac{2\pi f l_c}{c_c}\right) = 1 \quad (2.23)$$

here, Z_b , Z_c , c_b , c_c , l_b , l_c are the impedances, speeds of sound, and lengths of the back mass and the center mass, respectively. To obtain the impedances, first, characteristics impedances (Z_0) must be determined by multiplying the density (ρ) of the material by its sound velocity (c) which are then multiplied by the cross-sectional area of the part (A):

$$Z = Z_0 A = \rho c A \quad (2.24)$$

Once the lengths of the back and center masses are known, their length part in half wavelength can be calculated. This enables the determination of the front mass length in the following manner:

$$l_f = \frac{\lambda_f}{2} (1 - r_c - r_b) \quad (2.25)$$

The front mass is the most complex part of the entire assembly. In order to avoid internal reflections, the front mass still has to be impedance-matched to the rest of the system, therefore, the following condition from (Abdullah *et al.*, 2009) should be ensured:

$$Z_c = \sqrt{Z_f Z_b} \quad (2.26)$$

Additionally, it must be ensured that, in order for the vibrations to be transferred to the front of the actuator, the back-mass impedance is greater than the front mass:

$$Z_b > Z_f \quad (2.27)$$

Unlike the back and center masses, the front mass cross-sections tend to vary along the length of the mass. Hence, the determination of impedance is made more complex. The front mass in each case consists of two cylindrical sections, one at the contact face with the piezoceramic stack, which is termed the base, and one at the output end, which is termed the tip. These sections are usually of different diameters, and they terminate the middle section, which is referred to as the variable section, at both ends. Whereas, the two other sections could be characterized by uniform impedance, the variable sections vary in the cross-section which is dependent on a specific function; therefore, the determination of the correct impedance is made difficult. Since impedance is a function of the cross-sectional area and material properties, it is assumed that each section's average impedance contributes to the overall impedance of the front mass as a weighted relative value of the overall front mass length (Abdullah, *et al.*, 2009):

$$Z_f = \frac{l_{base}}{l_f} Z_{base,avg} + \frac{l_{var}}{l_f} Z_{var,avg} + \frac{l_{tip}}{l_f} Z_{tip,avg} \quad (2.28)$$

where l_{base} , l_{var} , l_{tip} and $Z_{base,avg}$, $Z_{var,avg}$, $Z_{tip,avg}$ are the lengths and average impedances of the base, the variable, and the tip sections, respectively.

The initial values of l_{base} and l_{tip} , are commonly determined from the design requirements, for instance, the lowest value of l_{base} could be established in order to accommodate a flange, or a clearance for limited play between the piezoceramic stack and the variable section of the front mass. Similarly, the lowest value of l_{tip} could be established to accommodate a fixing stem, a tool holder, or a clearance between the variable section of the front mass and the workpiece. From here, l_{var} can be determined as:

$$l_{var} = l_f - l_{base} - l_{tip} \quad (2.29)$$

Similarly, the diameter of the base section would be known because it would have to match the radius of the piezoceramic stack (excluding the flange dimensions), while the tip diameter would be decided upon by the engineer to

accommodate the necessary features. As two of the sections are cylindrical, $Z_{tip,avg}$ and $Z_{base,avg}$ can be determined from the basic formula for impedance (2.34). To obtain the average impedance of the variable section, the same formula can be used, but it is necessary to determine the average radius along the cross-section in order to calculate the average cross-section area. Typically, the exponential section radius is defined by function ABD:

$$r_{exp}(x) = r_0 e^{-\gamma x} \quad (2.30)$$

where r_0 is the radius at the base section, and γ is a coefficient for defining the exponential section profile decay which is obtained as ABD:

$$\gamma = \frac{\ln\left(\frac{r_0}{r_l}\right)}{l_{exp}} \quad (2.31)$$

where l_{exp} is the length of the exponential section, r_l is the radius at the tip. A conical profile can be defined in a similar way (Dakhil, 2012):

$$r_{con}(x) = r_0 - ax \quad (2.32)$$

where a is a decay constant for a conical profile over the section length l_{exp} and is defined as (Dakhil, 2012):

$$a = \frac{r_0 - r_l}{l_{con}} \quad (2.33)$$

From here, the average impedance for a variable front mass section with characteristic impedance Z_0 and geometry defined by function $r_{var}(x)$ can be defined as (Dakhil, 2012):

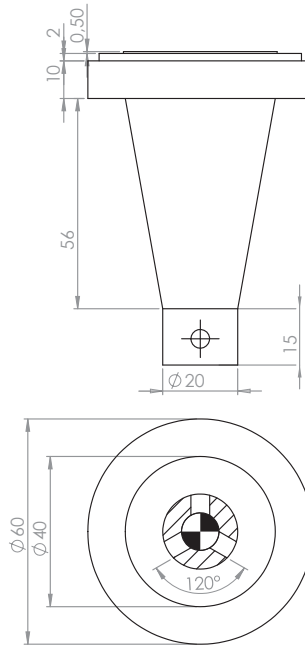
$$Z_{var,avg} = Z_0 \pi \left(\frac{\int_0^{l_{var}} r_{var}(x) dx}{l_{var}} \right)^2 \quad (2.34).$$

2.3.1. Design of a rotary tool actuator

The tool actuator front and back masses were designed to be manufactured from 40X steel. Two PZT4, 5 x 40 mm piezoceramic rings served as the piezoceramic stack. The relevant material properties are presented below (Table 8). The actuator was designed to exhibit the first longitudinal mode at 15 kHz. This, along with the dimensions of the piezoceramic rings, served as the starting design conditions. Therefore, the front mass length was determined to be 0.0835 m (Fig. 36), while the back mass was determined to be 0.043 m.

Table 8. Properties of the materials used to produce the rotary tool actuator

Material	Young's modulus E (GPa)	Density ρ (kg/m ³)
40x steel	211	7800
PZT4 piezoceramic	78	7600

**Fig. 36.** Front mass geometry of the rotary tool actuator

2.3.2. Design of a rotating workpiece actuator

The initial design of the actuator is based on the pre-existing dimensional and material requirements, as well as on the wavelength considerations. The actuator is to be mounted on an M30 thread at the output end of the horn, hence the variation of the output end diameter is limited (for the sake of safety, the wall thickness is chosen as 4 mm, which results in the minimum output end diameter of 38 mm). The piezoelectric stack consists of two piezoceramic rings of the dimensions 80 mm $\times$ 30 mm $\times$ 12 mm. This, in turn, defines the diameter of the input end of the horn and the backing mass to be equal to 80 mm. For safe operation, the actuator is to be encased in a protective housing which is mounted on an additionally formed flange. It is, however, relatively light, and, therefore, it will be neglected in further studies. In order to determine the lengths of the horn and the back mass, it is necessary to first define their materials; the relevant data can be found in Table 9.

Table 9. Actuator material properties and physical dimensions

	Tool steel	PZT	Aluminum
Young's modulus [GPa]	170	73	78
Density [g cm^{-3}]	7.700	7.600	2.850
Sound velocity [ms^{-1}]	4698.715	3099.236	5231.484
Wavelength [m]	0.297	0.196	0.330
Length [m]	0.074	0.025	0.041

With all of the data obtained, the derivation of the front mass length is straightforward – a quarter of the wavelength for the tool steel. Since the value of the center stack length was already known, it was determined to take up an eighth of its wavelength thus making it possible to derive the back mass value – an eighth of the wavelength for the aluminum alloy.

2.3.3. Design of a stationary workpiece actuator

The tool actuator front and back masses were designed to be manufactured from an aluminum alloy. Two PZT4, 5 x 35 mm piezoceramic rings served as the piezoceramic stack. The relevant material properties are presented below (Table 8). The actuator was designed to exhibit the first longitudinal mode at 40 kHz. This, along with the dimensions of the piezoceramic rings, served as the starting design conditions. Therefore, the front mass length was determined to be 0.027 m, while the back mass was determined to be 0.015 m.

Table 10. Properties of materials used to produce the stationary workpiece actuator

Material	Young's modulus E (GPa)	Density ρ (kg/m^3)
Aluminum alloy	72	2850
PZT4 piezoceramic	78	7600

2.4. Finite element analysis of ultrasonic actuators

Numerical analysis is used in this thesis in order to determine the performance criteria of the actuators and for the validation of designs obtained in the previous section. FEM is used to carry out two types of analyses – modal analysis and frequency response analysis. The first analysis allows determining the modal shapes at different frequencies, while the frequency response analysis helps to identify the dominant modes. This knowledge is crucial to ensuring that the design is correct and that the actuator is capable of operating in modes specified in the design of the experimental study.

If the law of the motion of the excited end of the workpiece is to be considered known and defined by the nodal displacement vector $\mathbf{U}_K$, the block form of the equation of motion (EOM) of the workpiece is written as (Eq. 4.1):

$$\begin{bmatrix} M_{NN} & M_{NK} \\ M_{KN} & M_{KK} \end{bmatrix} \begin{Bmatrix} \ddot{U}_N \\ \ddot{U}_K \end{Bmatrix} + \begin{bmatrix} K_{NN} & K_{NK} \\ K_{KN} & K_{KK} \end{bmatrix} \begin{Bmatrix} U_N \\ U_K \end{Bmatrix} = \begin{Bmatrix} 0 \\ R \end{Bmatrix}. \quad (4.1)$$

Here, N and K are indices representing the nodes whose displacements are unknown (free nodes) and known (excited or constrained nodes), respectively. Hence, $\mathbf{U}_N$ and $\mathbf{U}_K$ are nodal displacement vectors for free and constrained vectors, respectively, while pair combinations of these indices relay the position of these nodes in the respective property matrices $\mathbf{M}$ (the mass matrix) and $\mathbf{K}$ (the stiffness matrix). Additionally, $\mathbf{R}$ is the vector of the unknown reaction forces of nodes under excitation.

The modal analysis of an undamped oscillatory motion determines resonant frequencies by solving the following (Eq. 4.2) where ω is the angular frequency, while $\hat{\mathbf{U}}$ is the mode shapes vector.

$$(\mathbf{K} - \omega^2 \mathbf{M})\hat{\mathbf{U}} = \{0\}. \quad (4.2)$$

The modal analysis of the workpieces is performed by employing *ANSYS Workbench* and *Salome Meca/Code Aster* software packages, the modal analysis module. *ANSYS Workbench* and *Salome Meca/Code Aster* are suitable for the use of the Block Lanczos extraction method when seeking to obtain the vibration modes in the prescribed frequency ranges.

2.4.1. Finite element analysis of the rotary tool actuator

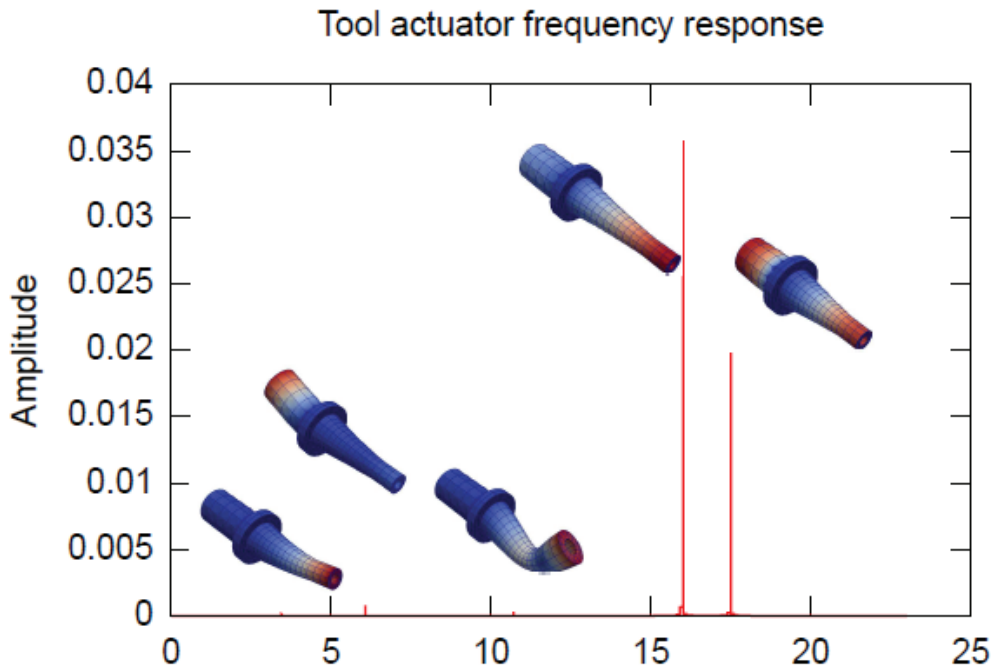


Fig. 37. Frequency response and modal analysis of the tool actuator

Based on the results of our numerical analysis (Fig. 37), it can be observed that the longitudinal modes occur at around 16 kHz frequency. Therefore, the actuator performance is considered to be in sufficient agreement with the design specification.

2.4.2. Finite element analysis of the rotating workpiece actuator

Before studying the behavior of the rotating workpiece, a set of target conditions is set forth: 1. Since the tool approaches perpendicularly to the workpiece axis, the latter should vibrate in the transverse mode; 2. The frequency of excitation must not be lower than 15 kHz as any lower values would be too far away from the ultrasonic threshold; 3. The target amplitude of excitation needs to be above $1\text{ }\mu\text{m}$ as most encountered applications tend to employ amplitudes of such an order of magnitude. The two initial conditions can be tackled by employing modal analysis.

The knowledge of the appropriate frequencies of the workpieces allows applying the periodic forcing condition at the tailstock mount (Fig. 38). Transverse deformation amplitudes can be observed as a result, and the most suitable force value and frequency can be determined. In *ANSYS Workbench*, the harmonic response module can be used for this purpose.

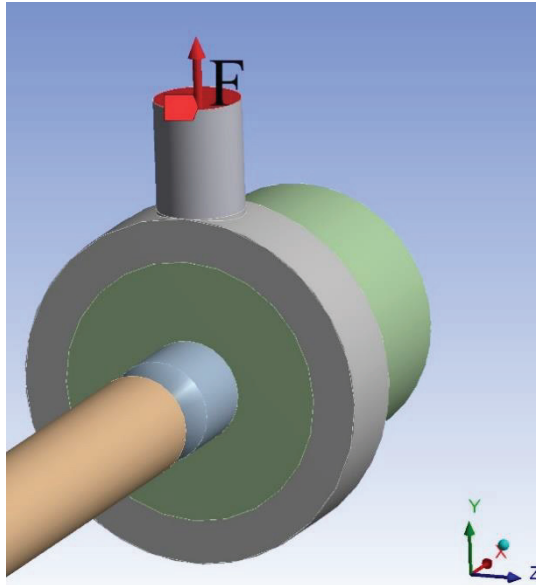


Fig. 38. Excitation force F application at the tailstock attachment

In the case of the two workpieces, both are constrained at the tailstock end, and are pre-stressed by the headstock. The mode search is performed between 15 kHz and 25 kHz; the resulting mode frequencies are then used to define the excitation of the workpiece at an arbitrary magnitude of 1 N.

The choice of the most suitable frequency was simplified to fitting the three criteria in a descending order of importance: 1. The neighborhood of the frequency needs to be clear of any other modes; 2. the average peak-to-peak, workpiece displacement value is an average of the absolute values of oscillation amplitudes across the length of the workpiece; it needs to be relatively high; 3. the mode frequency is in close proximity to a similar mode frequency in the other workpiece. As a result, excitation frequencies at around 15.8 kHz were chosen for both workpieces.

When carrying out a parametric sweep of the excitation force, the yields average the deformation amplitude of $1.5\ \mu\text{m}$ at 2.1 N. Hence, the actuator will have to be able to be driven at 15.85 kHz and 15.794 kHz and will need to produce a reaction force of 2.1 N at the fixture.

These values were used in the initial design for modal analysis (Fig. 39). Here, a longitudinal mode was expected to occur at 15.794 kHz. However, the mode search at 15 kHz to 25 kHz yielded frequency values 2 kHz above this value. A parametric sweep of the horn's length was conducted, and a longitudinal mode was observed at 15.939 kHz when the horn's length was 111 mm.

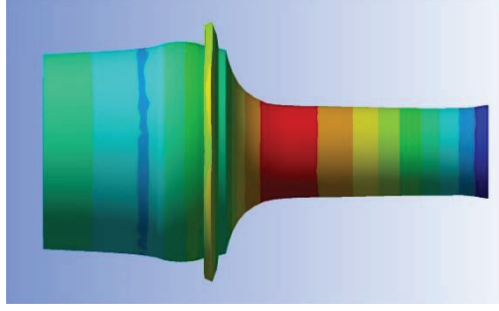


Fig. 39. The longitudinal mode of the initial actuator design

The newly designed actuator was tested in a harmonic response study; here, both planar faces of the piezo stack were assigned arbitrary forces of the opposite sign in order to simulate excitation from the piezo-stack. The force at the output end of the horn was measured, thus allowing to perform parametric sweep in order to determine the required input force so that to produce 2.1 N at 15.8 kHz and 15.9 kHz on the output end, as required for the excitation of the uniform cylinder and stepped shaft to 1.5 μm , respectively. The required input force was determined to be 19 N and 20 N for 15.8 kHz and 15.9 kHz cases, respectively.

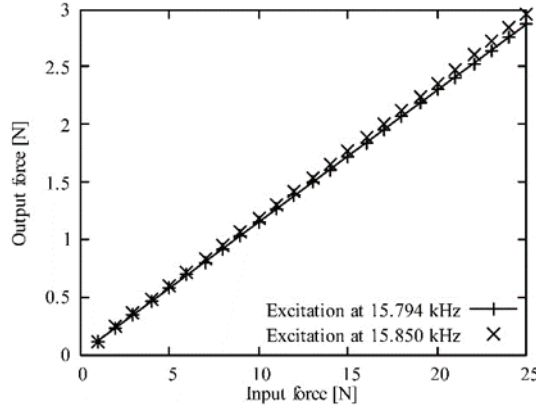


Fig. 40. Input-output force dependency for the actuator at 15.8 kHz and 15.9 kHz

Knowledge of the required force and velocity of vibration allows determining the power requirements:

$$P = Fv \cos \phi. \quad (4.6)$$

Here, ϕ is considered to be the phase difference between the velocity and the force. The obtained result shows the required power input of the transducer which is required to achieve force F during excitation. Since accelerations at the piezo-

material to front-mass interface were determined to be 2070 mm/s² and 2000 mm/s² for 15.794 kHz and 15.850 kHz cases, respectively, the peak velocities in both cases were found to be 20 mm/s. Assuming the force and velocity to be in phase, (Eq. 4.6) yields the following values:

$$P_{15.794} = Fv \cos \phi = 19 \times 20 = 380W, \quad (4.7)$$

$$P_{15.855} = Fv \cos \phi = 20 \times 20 = 400W. \quad (4.8)$$

This demonstrates that the approach requires realistic power values and is theoretically feasible. Further investigations of the fully assembled system are necessary.

With the working modes being determined and the design of the actuator being verified, a fully assembled system needs to be tested. Initial tests are performed by using harmonic analysis in the *ANSYS* workbench; here, the displacement of the workpiece in the fully assembled system, when the piezo stack is excited at the predetermined force and frequency, is observed. Afterwards, the excitation output is tested on a physical system. Lastly, the effectiveness of the approach is tested by observing surface grinding results with and without the operation of the actuator.

The harmonic analysis data for both workpiece configurations is presented in Table 11.

Table 11. Workpiece excitation parameters

Workpiece	Excitation force, [N]	Frequency, [kHz]
Uniform cylinder	20	15.850
Stepped shaft	19	15.794

The workpiece displacement graphs (Fig. 41, Fig. 42) show a noticeable reduction in the amplitude.

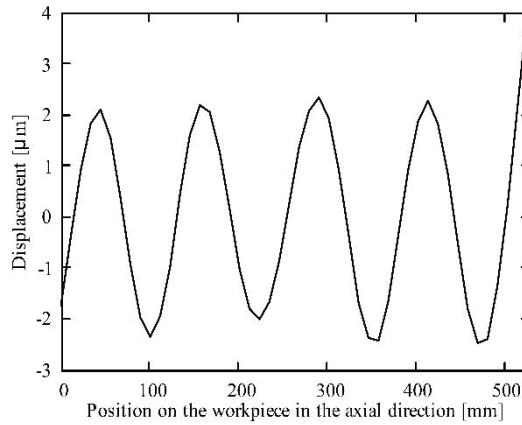


Fig. 41. Response of the uniform cylinder workpiece driven by 20 N at 15.85 kHz frequency, with the actuator attached

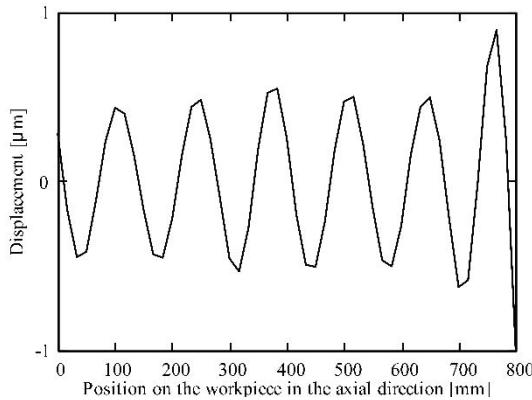


Fig. 42. Response of the stepped shaft workpiece driven by 20 N at 15.794 kHz frequency with the actuator attached

Additional modal analysis of the entire assembly was performed, which demonstrated that the addition of the actuator to the system shifted the transverse mode frequency to 17.349 kHz and 17.722 kHz for the uniform cylinder and stepped shaft workpieces, respectively (Fig. 43, Fig. 44), which was the cause for the decrease in displacement.

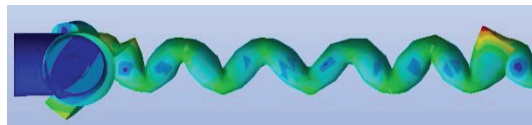


Fig. 43. Shifted transverse mode for the uniform cylinder at 17.349 kHz

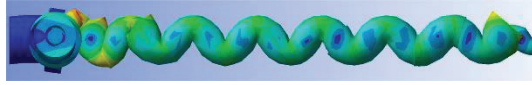


Fig. 44. Shifted transverse mode for the stepped shaft at 17.722 kHz

Driving the systems at 17.349 kHz and 17.722 kHz yielded more appropriate responses in the order of micrometres (Fig. 45). Similar changes are expected to occur in the physical system as well; therefore, experimental vibration analysis is essential in this case.

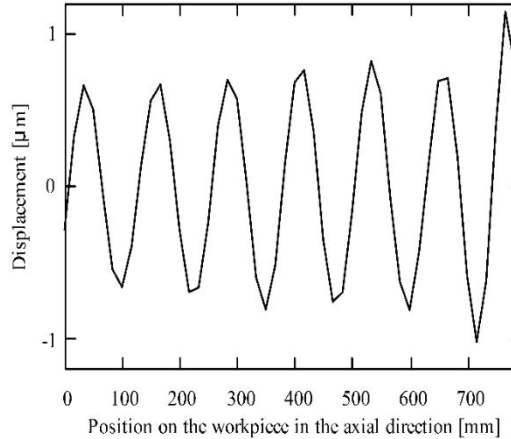


Fig. 45. Response of the stepped shaft workpiece driven by 19 N at 17.722 kHz frequency with the actuator attached

2.4.3. Finite element analysis of the stationary workpiece actuator

It can be seen that purely longitudinal modes in the case of the tool actuator are only expected in the range between 15–20 kHz (Fig. 37). The pure longitudinal mode of the workpiece actuator can be seen to occur above 20 kHz (Fig. 46). However, higher order modes actually produce similar or even higher amplitudes at higher frequencies. These modes can be leveraged for workpiece excitation as they produce displacement zones in concentric ring patterns, which might be suitable for workpiece excitation during grinding.

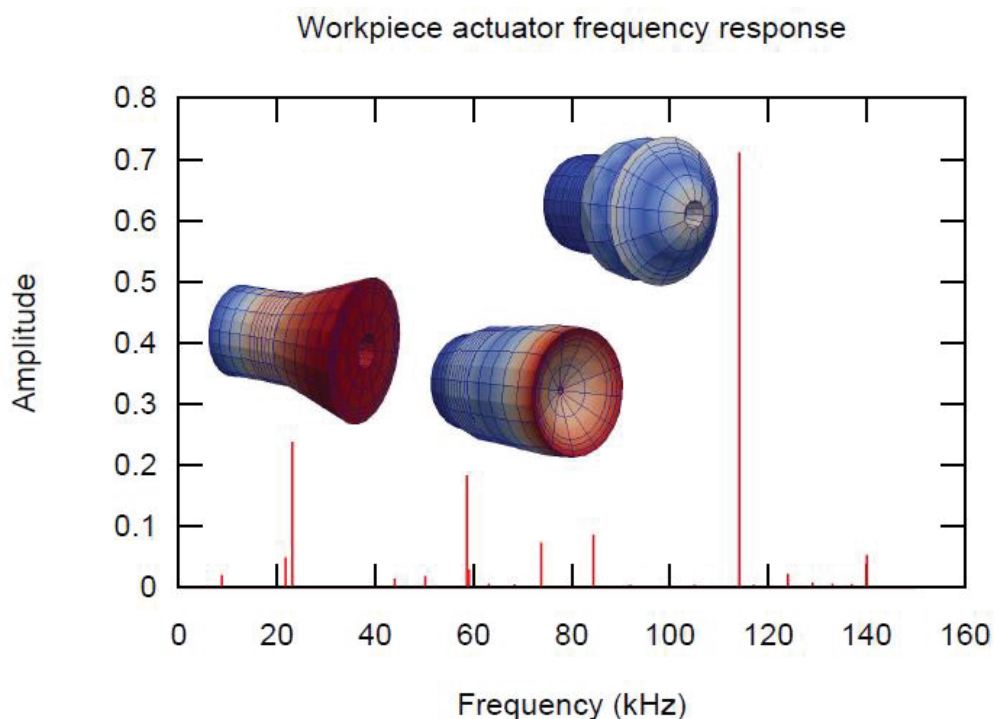


Fig. 46. Frequency response and modal analysis of the workpiece actuator

2.5. Chapter conclusions

This chapter determined the equipment and its parameters to be used in further experimental studies. The equipment development process followed a problem oriented sequence from the design of one piece of equipment to the other in the following order:

1. The sequence was first initiated with the tool excitation approach for the back grinding of WC. It was observed that limitations of the approach arose from the challenges of having the actuator within the rotating interface.
2. The second step in the sequence was to address the core problem of having the actuator in the rotating interface by removing it from the interface and applying it to the static point immediately outside of the rotating interface in order to allow for the transfer of vibrations into the rotating object. To achieve this, an actuator in a system with a cylindrical grinding machine was designed.
3. The third step within the sequence was to simply apply the vibration to an immovable workpiece in the back grinding of WC while eliminating the need to work in a rotating interface altogether. The size of the actuator was still limited. However, numerical simulations revealed that it is possible to utilize the peripheral displacement zone occurring at the higher vibration

modes of the actuator in order to achieve higher frequencies of workpiece excitation.

3. EXPERIMENTAL STUDIES

Experimental grinding studies are crucial for investigating the DRM performance of various VAG methods described in the previous chapter. Performance is evaluated based on both qualitative insights and measurements. Quantitative analysis involves the following aspects:

- Surface roughness.
- Grinding force measurements.
- Ductile and brittle deformation site distribution.
- Grinding chip morphology analysis.

Meanwhile, the qualitative analysis which was used to evaluate the performance involved:

- Design restrictions on the machining parameters.
- Applicability on the machine-to-machine basis.

Each characterization allows defining certain aspects of the VAG method performance to a certain degree of success. Descriptions of the meaning of each parameter and the relevant limitations are given below.

Surface roughness. The measurement of average arithmetic roughness R_a is the main quantitative measurement of the machining performance as it is the main parameter defining the final applicability of the machined part. It can be evaluated by using either optical or contact measurement techniques. Although it is the most application-relevant measurement of the grinding process performance, it is not a definitive qualifier regarding the question whether the DRM process took place.

It is reasonable to suggest that brittle deformation, while not producing a mirror-like finish, may produce acceptable low roughness, while assuming that the crack propagation is maintained and that sufficiently fine and frequent fracture takes place pulverizing the material as a result. It is also likely that, while ductile deformation produces a mirror-like finish as a result of plastic deformation, brittle deformation may be exhibited around the plastic deformation zone, which can result in the removal of a large piece of material, which, although initially deformed in the ductile mode, would leave a large void upon its removal, which, in addition to increasing the surface roughness value, could also, due to its irregular characteristics, mistakenly characterize the void as a brittle deformation site upon visual inspection.

Therefore, it is necessary to conduct additional measurements in order to characterize the machining modes themselves. However, it must be noted that it is the balance of the two modes that determines the quality of the resultant surface finish. The ductile mode is analyzed namely because the brittle machining mode is already readily achievable in the machining of HBM.

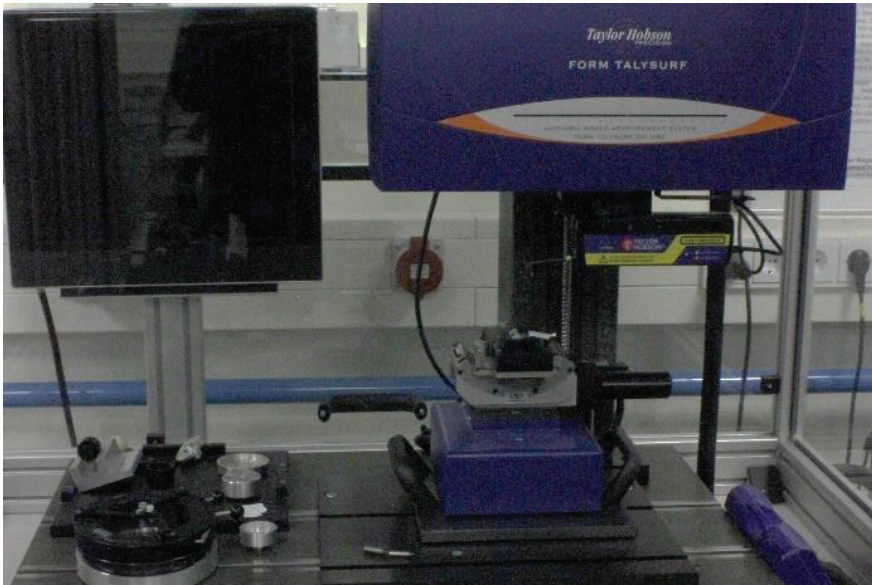


Fig. 47. *Talysurf* contact profilometer

Grinding force measurement. Force measurements obtained in real time can give an aggregate expression of tool grain interaction with the workpiece's surface. These force measurements can then be deconstructed into different force components (whose relations are outlined), which may help to evaluate the critical load, as well as the maximum undeformed chip thickness, which both serve as a threshold between ductile and brittle deformation.

Observation of these parameters gives a great insight into the deformation mechanisms taking place. However, this approach, while highly methodical and replicable, is not without caveats. Although the deformation mode identification based on these parameters can be highly definitive, the accuracy of parameter values is highly dependent on the adherence of the model outputs to the experimental results. Additionally, new mechanisms (pressure fluctuations, micro-impact) and trajectory changes (grain depth fluctuation, changes in the grinding direction) introduced in VAG may render the deformation mechanism criteria invalid, as the material behavior may be influenced by a different mechanism at this point.

Therefore, in addition to our real time measurements using a *Kistler 9257B* force plate (Fig. 48), it is necessary to identify the grinding modes after the physical test. The 'ex-situ' grinding mode identification can be performed through analysis of the geometric features of the products and byproducts of grinding.



Fig. 48. Kistler 3 channel 9257B force sensor

Ductile and brittle deformation site distribution. In its wake, the grinding tool leaves a machined surface along with a myriad of artefacts. It is impossible to deduce the manner of a single grain's interaction with the workpiece from a practical machining study, however, it is still possible to observe the result of the aggregate interactions of all the involved tool grains and the workpiece. The obtained artefacts on the surface are best observed visually, and they give an insight into which machining mode was the most dominant during the grinding run.

The ductile mode is generally characterized by flat surfaces patterned by straight, uninterrupted streaks as shown below (Fig. 49), which is indicative of the material being pushed off and, sometimes, of shiny edges along the grinding grooves, which is indicative of a metallic phase or the mirror finish. Meanwhile, the brittle mode is indicated by fractured debris along the grinding surface, deep voids, irregular and/or interrupted grinding groove patterns, visible cracks, and propagated fractures.

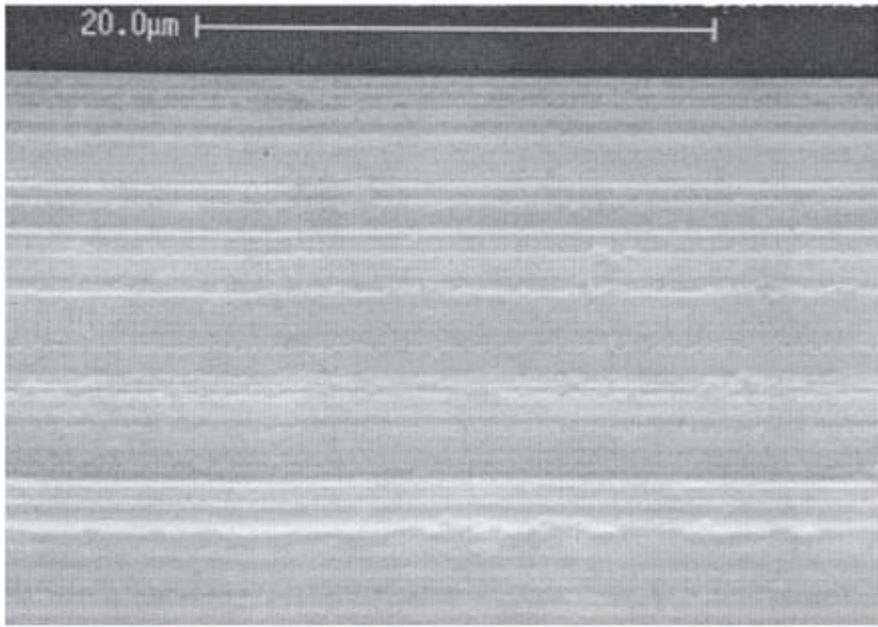


Fig. 49. SEM micrograph of a Si sample surface ground in the ductile mode (Zhong, 2003)

While the visual analysis of the surfaces was still performed by using a *Bruker* white light interferometer (Fig. 51), however, it was still considered to be too subjective of a method to reliably apply for side-by-side comparisons. The first caveat of the visual inspection method was the consistency of the sampled surfaces across different runs. As the size of grinding artefacts is very small ($\sim 10\ \mu\text{m}$), and also because there are very few visual landmarks to determine the location of the intended observation window and the positioning of the tool before each run varies, it is nearly impossible to obtain a consistent sample from workpiece to workpiece. The second caveat is the reliability of the observing party – it is nearly impossible to differentiate between different fracture modes as a sharper fracture (fracture depth $\gg$ width) is more indicative of a severe brittle failure, while a shallow fracture is indicative of a semi-brittle failure or a pullout. Additionally, it is extremely difficult to quantify these occurrences based on visual observations alone.

The first caveat cannot be reliably addressed without fabrication of additional precise positioning stands and jigs. However, a sufficient degree of consistency can be ensured through deliberate machining and measurement practices – thus ensuring that the most similar topography areas in similar proximities are produced and identified for use in analysis.

The second caveat is best addressed through computational means. Surface topography can be characterized in a 3D space through such methods as white light interferometry. The obtained 3D characterization can then be analyzed by counting the peaks (voids in 3D space) along multiple cross-sections of the grinding path, and

we can evaluate them based on the peak depth-to-width ratio. Such a procedure is easily automatable by employing a basic peak identification algorithm which is presented in the diagram below (Fig. 50).

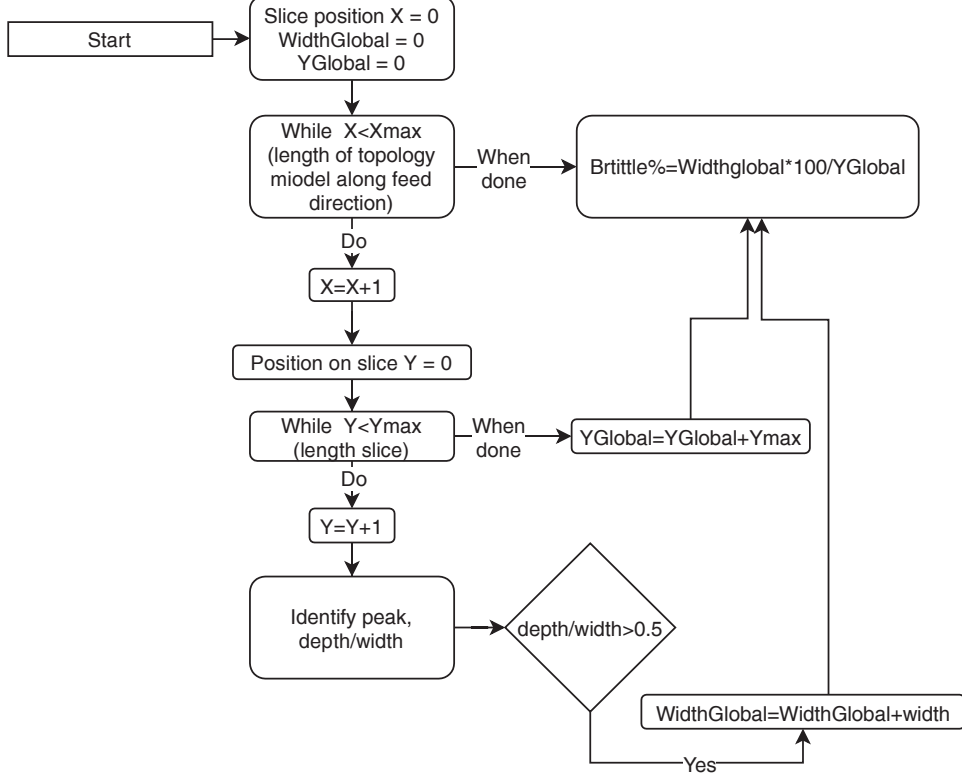


Fig. 50. Brittle peak identification algorithm

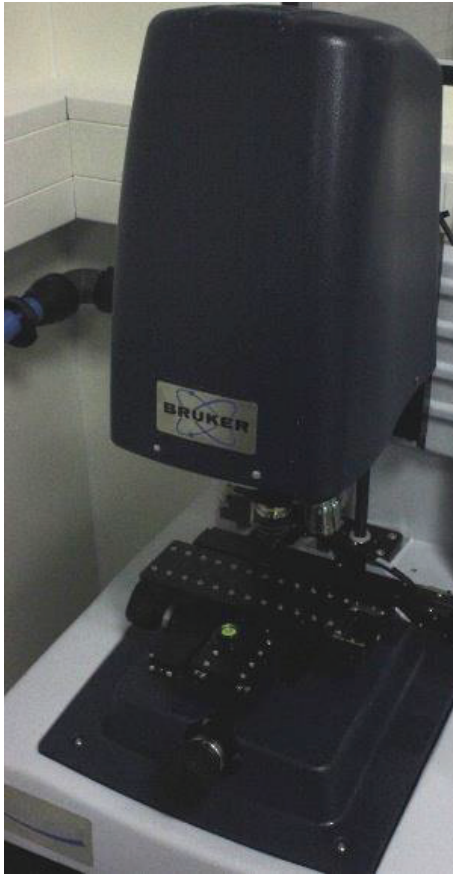


Fig. 51. *Bruker white light interferometer*

However, as mentioned at the beginning of this parameter description, there is very little with regard to the means of identification of the alternating machining modes during the grinding run from a machined surface. As the machining paths of separate grains overlap, they produce different results influenced by a wide complex of factors on different scales, which makes it hard to define the dominant process taking place during the run.

Grinding chip morphology analysis. Where a machined surface is a product of the grinding process, the chips are its byproduct. The chips are produced in discrete quantities, which makes it easier to characterize the different deformation mechanisms taking place while allowing the determination of the dominant machining mode. The chip characteristics defining the ductile machining mode are the continuity of the chip (similar to turning, but smaller in size), whereas the temperature induced ductile mode is often characterized by a spherical chip. Brittle deformation is commonly characterized by fine, powdery residue, and, in the presence of a severe brittle fracture, by a larger – jagged-edged – chip.

While visual analysis is commonly used to characterize the machining mode by chip, it is prone to the same caveats as the visual surface topography analysis. They can be addressed through the use of bulk powder characterization techniques, such as X-ray diffraction (XRD), which allows for the determination of the chemical and structural characteristics of the powder, as well as the approximation of the average crystallite size. Based on the previous description on the mode characterizing chip traits, it is assumed that a larger average crystallite size will be indicative of a larger chip, thus suggesting the dominance of the ductile machining mode. In this work, bulk powder XRD was performed by using *Discovery D8* X-ray diffractometer (Fig. 52) with a powder analysis diffractometer head (Fig. 53).



Fig. 52. X-ray diffractometer stand
Discovery D8

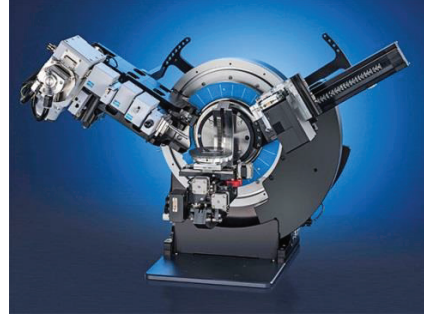


Fig. 53. X-ray diffractometer head
for XRD analysis of powders

Design restrictions on the machining parameters and their applicability on machine-to-machine basis. The identification of design restrictions on the machining parameters, as well as the degree of adaptability to different grinding equipment, is crucial to the development flow of the improved VAG methods. The restrictions of the design on the machining parameters are certain conditions which are crucial to the implementation of the proposed VAG method that limit the choice of the machining parameters, such as the cutting speed or the excitation frequency. The identification of such conditions provides a clear improvement target for the subsequent design.

Applicability is closely related to the design restrictions. However, it relates more to the overall footprint of the equipment in the machining environment, as well as to the imposed restrictions on the intended movement axes of the machine.

3.1. Investigation of vibration assisted grinding employing ultrasonic excitation of a rotating tool

The tool excitation study is the initial starting point of the experimental study sequence of this thesis. Tool excitation is the most commonly encountered approach to VAM in the literature. This study was used to determine possible improvement venues or to determine alternative approaches to VAM.

3.1.1.Experimental equipment

In order to facilitate the process of VAG while using ultrasonic tool excitation, a high speed precision milling machine capable of reliably supporting the mass of the VAG tool holder manufactured according to the specifications obtained previously in its spindle was required. Access to such a 5-axis *Starrag Heckert LX 151* milling machine (Fig. 55) was provided by *Fraunhofer IPT* (Aachen, Germany) during the author's traineeship in the second year of doctoral studies (2015). The tool and workpiece setup is outlined in the figure below (Fig. 54).

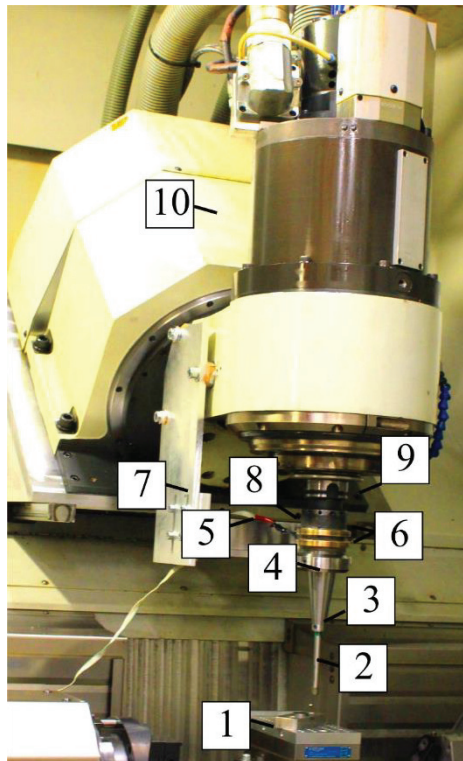


Fig. 54. Tool excitation grinding setup: 1. Workpiece, 2. Tool, 3. Tool holder horn, 4. Retention nut, 5. Carbon brush connection, 6. Commutation rings, 7. Carbon brush holder structure, 8. Actuator housing cup, 9. *HSK 65A* spindle interface, 10. Milling machine head

Here, the workpiece (1 in Fig. 56) was attached to the *Kistler 9257B* force plate (Fig. 48) which was used to collect the grinding force data along *X*, *Y* and *Z* axes in real time, during grinding runs, via an aluminum pocket stand. The workpiece was machined by using a galvanically bonded CBN grinding pin (2 in

Fig. 54). The ultrasonic vibrations were transferred into the tool via an ultrasonic horn/tool holder (3 in Fig. 54) with a piezoceramic stack attached to it which was secured onto the actuator housing (8 in Fig. 54) while using a retaining nut (4 in Fig. 56). The actuator housing cup (8 in Fig. 54) along with the attached ultrasonic horn, and the tool assembly was attached onto the *HSK 65A* spindle interface (9 in Fig. 54) which is inserted into the milling machine's head (10 in Fig. 54) spindle. The piezoceramic stack is connected via wires to commutation rings (6 in Fig. 56) which are attached to the actuator housing cup (8 in Fig. 54) and transfer an electric signal through carbon brushes (5 in Fig. 54) which are held by the brush holder assembly (7 in Fig. 56) and receive the signal generated by the *Agilent 33522A* signal generator with a custom-made amplifier. To achieve and identify the appropriate vibration modes and frequencies of the tool holder, the tool length tuning procedure was performed while using a *Polytec* laser vibrometer (Fig. 57). The dust from each run was collected and observed by using a *Leica DM RXE* microscope (Fig. 58). Then, the machined surface quality was evaluated by using white light interferometry employing a *Bruker* white light interferometer (Fig. 51) and additionally using a *Talysurf* contact profilometer (Fig. 47).



Fig. 55. *Starrag Heckert LX 151* milling

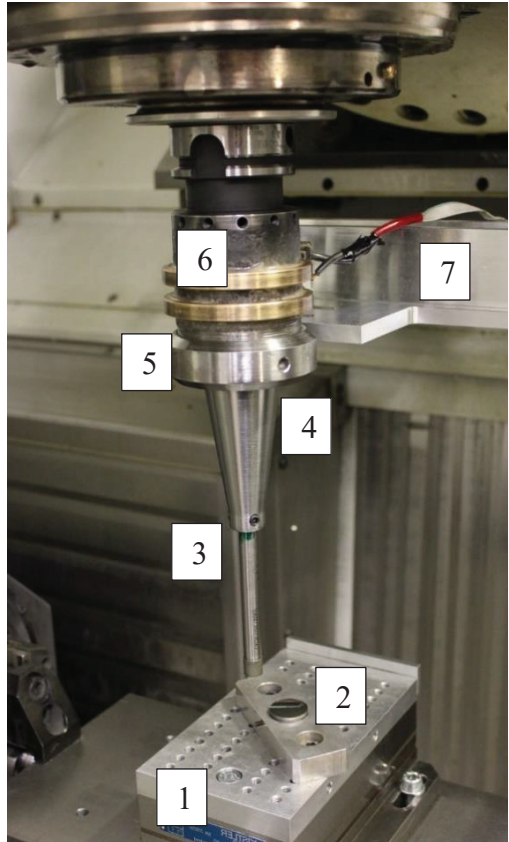


Fig. 56. VAG tool holder and brush

machine used for the experiments

holder assembly in the *Starrag Heckert LX 151* milling machine: 1 – dynamometer; 2 – workpiece; 3 – tool; 4 – horn; 5 – retaining nut; 6 – commutator rings 7 – brush holder assembly

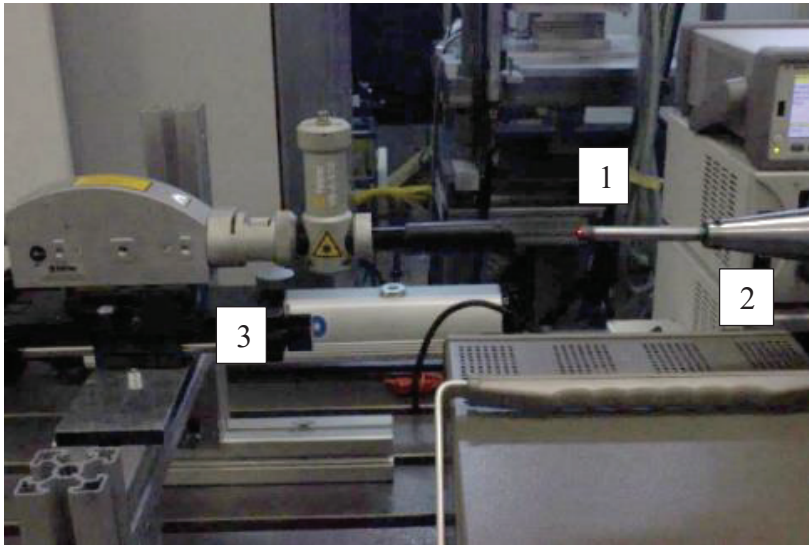


Fig. 57. Tool length tuning procedure using a *Polytech* vibrometer: 1 – tool; 2 – actuator; 3 – vibrometer

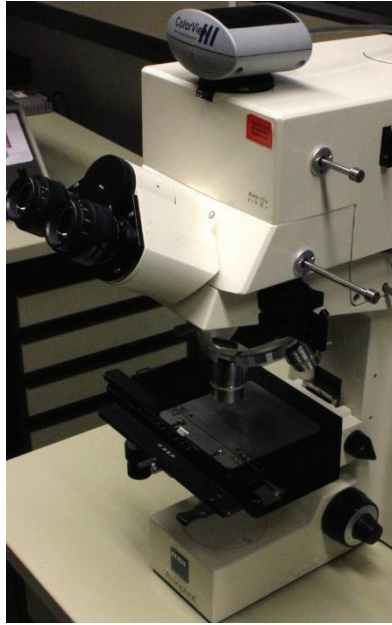


Fig. 58. *Leica DM RXE* microscope

3.1.2.Experimental setup

By employing a custom-made signal amplifier, it was possible to achieve the effective voltage of 200 V at frequencies of 11–13 kHz. Two vibration modes of the tool actuator were identified – a transversal vibration mode that occurred at 11.75 kHz and a longitudinal mode that occurred at 13.21 kHz. Both modes were observed to induce amplitudes on the order of 1 μm due to a comparable displacement and frequency, yet a different vibration mode. It has been decided to use both modes in the experiments.

The experiments were conducted at 5000 rpm spindle speed and 20 mm/min feed rate. The effect of both modes was investigated at two different depths of 25 and 50 μm . This setup resulted in six grinding runs outlined below (Table 12):

Table 12. Grinding run parameters

Depth	Excitation frequency [kHz]	Spindle speed rpm	Feed rate mm/min
25	0	5000	5
	11.75		
	13.21		
50	0		
	11.75		
	13.21		

Following the completed run, the post-process collection of grinding chips was conducted. The WC dust samples were collected on pieces of a clear tape after each test run while making sure to eliminate any residue before proceeding with the subsequent test run.

3.2. Investigation of vibration assisted grinding employing ultrasonic excitation of a rotating workpiece

During the tool excitation study, it was observed that immense design restrictions on the machining parameters as well as applicability difficulties arise when dealing with the challenge of high frequency excitation of a high speed rotating tool (discussed in greater detail in Chapter 4). As follows from these insights, a study on the excitation of a rotating interface is carried out.

3.2.1. Experimental equipment

Based on previously established estimations, an ultrasound generator *VT-400* was applied for inducing high frequency vibrations on the piezoceramic transducer (Fig. 59). This generator is specified for the lab and industrial use. The generator's max power capacity corresponds to 400 W. The generator was powered by an AC single phase network with a power supply of 220 V and a frequency of 50 kHz; the relevant specifications are listed below (Table 13).

Table 13. Power supply specifications

Specifications	
Power supply voltage (AC), V	200 ... 240
Power output, W	up to 400
Number of channels	1
Output frequency, kHz	15–60
Dimensions, mm, LxWxH	300x425x135
Power consumption, W	max 500



Fig. 59. Ultrasound Generator *VT-400*

Common applications of WC rarely require cylindrical grinding; in addition, the commonly encountered sizes of blank workpieces in cylindrical grinding are impractical for most WC applications requiring grinding; they are also costly to procure. Therefore, since this study focused namely on the challenge of rotating interface excitation, commonly used materials were employed instead of WC. Two different steel workpieces – 1.1186 and 1.7225 42CrMo4 – were machined by using a vitrified bond ZrA grinding wheel. The consumable materials used in this experiment are presented below (Table 14).

Table 14. Experimental study consumable list

Grinding wheel	Vitrified bond ZrA grinding wheel, grain size 80, 405/210/50
Workpiece 1	1.1186 medium carbon steel, hardness 55 HRC (L=814 mm, Ø=50 mm)
Workpiece 2	1.7225 42CrMo4, hardness 255 (HBW) (L=500 mm, Ø=35 mm)

The grinding itself was carried out on a *Supertec G32D 100NC* cylindrical grinding machine (Fig. 60). The ultrasonic excitation of the workpiece was induced through the application of a *VT-400* (3 in Fig. 60) actuator onto the dead-center (5 in Fig. 60). The actual excitation of the workpiece was measured by using a *KD-35* accelerometer (2 in Fig. 60) connected to an oscilloscope – *Picoscope 3424* (4 in Fig. 60). Upon the completion of this process, the surface roughness of the samples was measured by using a surface roughness tester – *Mitutoyo Surftest SJ-210*.



Fig. 60. Experimental setup of ultrasonic-assisted grinding. 1 – Workpiece 1 (steel bar); 2 – accelerometer (*KD35*); 3 – piezoelectric transducer; 4 – *PicoScope* (3424); 5 – tailstock of a cylindrical grinding machine (*Supertec G32P-100NC*)

3.2.2. Experimental setup

In this case, a uniform 1.1186 steel shaft and a stepped 1.7225 steel shaft were rotated during cylindrical workpiece grinding in a similar setup to a lathe. Here, a powerful actuator was placed outside of the rotating interface, onto the dead-center supporting the workpiece. It was expected, based on previous numerical simulations, that the workpiece would be excited in the transverse direction at frequencies ~ 16.81 kHz, thus yielding deformations perpendicular to the rotating grinding disc axis. Therefore, the workpiece displacements were first tested by using an accelerometer in order to confirm the suitable frequency.

In order to test the effectiveness of the system, a grinding trial was conducted. The runs were conducted under dry and wet grinding conditions. After each grinding run, the surface quality was measured by using a surface roughness tester *Mitutoyo Surftest SJ-210*. Each measurement was performed 5 times at sampling and cutoff lengths of 0.8 mm. The parameters employed in the experimental runs are presented below (Table 15).

Table 15. Major machining parameters

Grinding process	Dry/wet cylindrical grinding	
Conventional grinding conditions		Feed speed $v_f=5\text{m/min}$; depth of cut $a=0.01\text{ mm}$; cutting speed $v_c=34\text{ m/s}$

Ultrasonic vibration assistance conditions	Frequency $f=16.81$ kHz; power $P=40$ %; amplitude $A=0.386$ μm .
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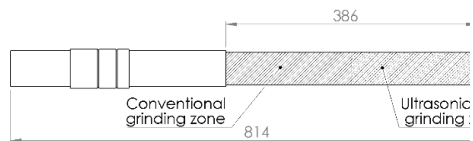


Fig. 61. Grinding zones during the cylindrical grinding of a shaft

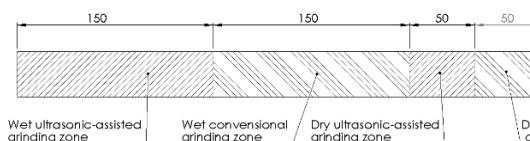


Fig. 62. Grinding zones during the cylindrical grinding of a bar

The first experiment was carried out on a 1.1186 steel shaft. Conventional (without ultrasonic vibrations) and ultrasonic-assisted grinding zones are shown in Fig. 61. During the cylindrical grinding process, the surface being ground was divided into two equal zones for surface roughness measurement, and the obtained data was subsequently processed.

The second experiment was carried out on a 1.7225 steel bar. The grinding zones of the experiment are shown in Fig. 62. The bar was divided into four zones for wet/dry grinding with and without ultrasonic vibrations.

After the experiments, the roughness of the shaft and the bar was measured with a surface roughness tester (*Mitutoyo Surftest SJ-210*) at defined zones for the conventional and ultrasonic-assisted grinding with and without a cooling fluid.

3.3. Investigation of vibration assisted grinding employing ultrasonic excitation of a stationary workpiece

Based on the rotating workpiece excitation study (outlined in Chapter 4), direct excitation of a stationary workpiece was the next logical step in the investigation of VAM performance in DRM of HBM. Elimination of the need for the vibrations to pass through the periphery of the machining equipment into the workpiece would allow to achieve higher amplitudes and frequencies of excitation while preventing potential negative effects of vibration on the machine itself. Here, higher excitation frequencies are available as a result of elimination of the design constraints related to electrically driving a system rotating at high speeds as well as the employment of higher order modes that yield peripheral deformation sites at the output surface of the actuator. This approach is shown below in Fig. 63 and is patented by the author under *LT2019 505 Patent*.

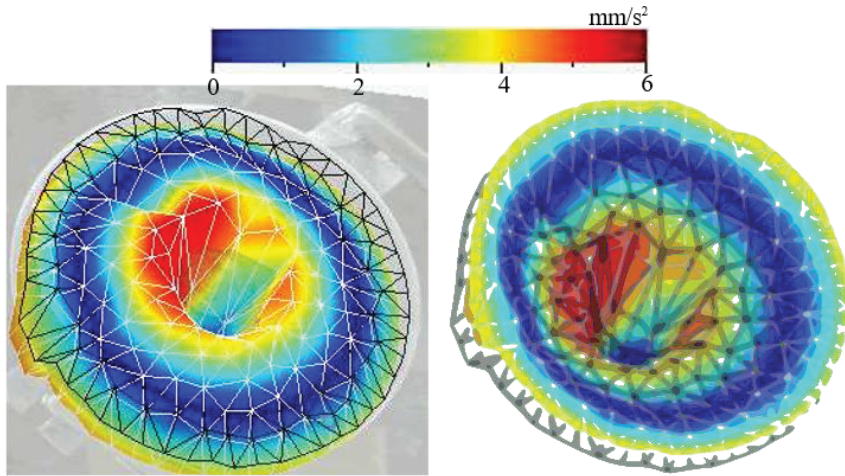


Fig. 63. Workpiece actuator surface at 84.5 kHz as measured with *Polytec PSV 500* 3D scanning laser vibrometer

3.3.1. Experimental equipment

As the actuator system is not contained inside the tool holder, the spindle power is not as important. These latter experiments were conducted on a *Leadwell V-20 CNC* milling machine. The sample (1 in Fig. 64) is attached to the surface of the actuator (2 in Fig. 64), and the actuator is held on a vise (3 in Fig. 64) attached to a single channel, a *Kistler* dynamometer (4 in Fig. 64) that can record either the normal force or the torque and whose signal is transferred through the charge amplifier (1 in Fig. 65) into a digital oscilloscope (2 in Fig. 65) and recorded on a PC (3 in Fig. 65). The actuator's signal is supplied through alligator clips that carry over the signal generated by a signal generator and amplified by a signal amplifier.

As well as in the previous study, the grinding dust was collected after the run. However, this time, it was analyzed by using XRD analysis employing a *Discovery D8 X-Ray* diffractometer (Fig. 52). The ground surfaces were also analyzed via SEM and white light interferometry using a *Polytec MSA 500* microsystem analyzer (Fig. 66).

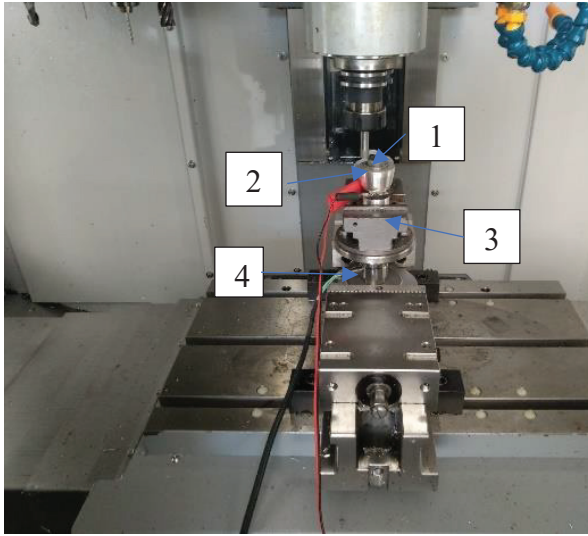


Fig. 64. Workpiece excitation study assembly

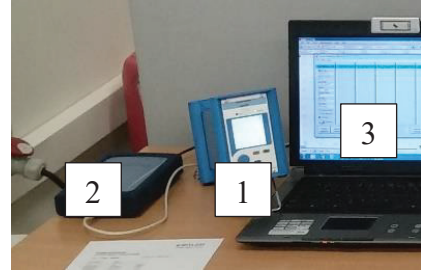


Fig. 65. Data acquisition hardware

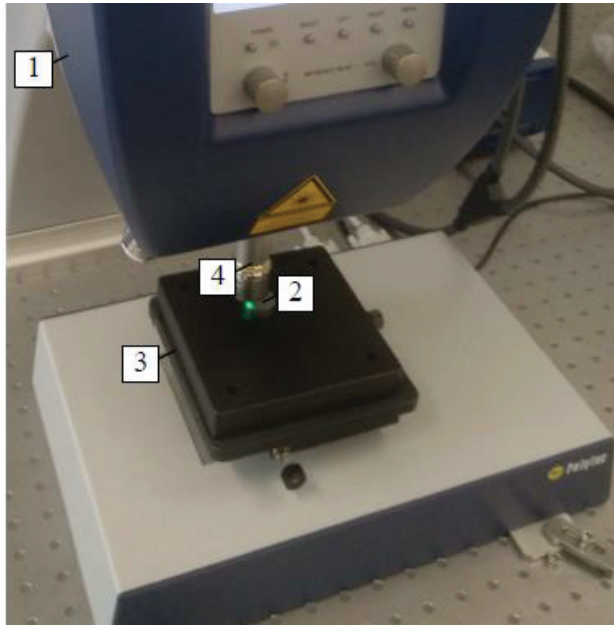


Fig. 66. Polytec MSA 500 microsystem analyzer setup used for white light interferometry

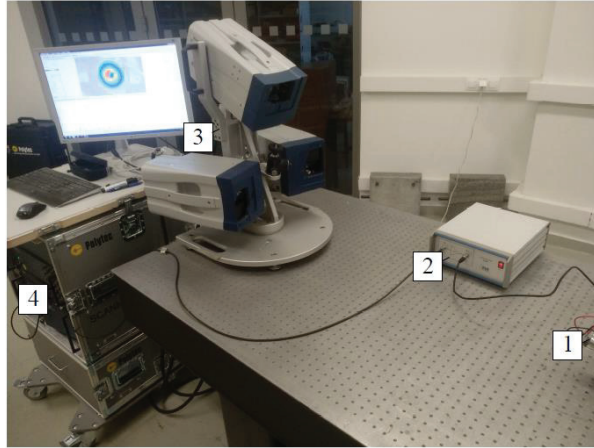


Fig. 67. *Polytec PSV 500* 3D scanning laser vibrometer

3.3.2. Experimental setup

The setup of the experimental study is similar to the tool excitation study. However, in this case, there is no need for carbon brush or commutation ring assemblies to be present. Alligator clips are attached to the actuator electrodes in order to drive it. In this case, the workpiece is stationary, and, in many other applications, the movement, if present, would not be as rapid and would only occur in the translational mode and not in the rotational mode. This allows for a simpler configuration of the entire setup and easier transferability of application from one machine to another.

The range of the grinding depths was expanded to evaluate the machining performance at lower grinding depths. It is expected that the reduction of the grinding depth may result in insufficient hydrostatic pressure, which may cause ductile mode deformation at the grinding site or an improper tool-workpiece contact causing the chipping of the workpiece (i.e., destructive brittle failure) as a result. The achieved frequency of excitation was 85 kHz – which is several times higher than the frequencies employed in the previous studies within this research. In addition to the variation of the depth, the amplitude was varied over 4 values (0, 0.25, 0.5, 1 μm) as well.

Table 16. Experimental workpiece excitation study grinding run parameters

Depth	Excitation frequency kHz	Spindle speed rpm	Feed rate mm/min	Excitation amplitude
25	0	5000	5	0
	84.5			1
				0.5
				0.25
50	0			0
	84.5			1
				0.5
				0.25
1	0			0
	84.5			1
				0.5
				0.25
5	0			0
	84.5			1
				0.5
				0.25

The dust was collected from several 50 μm grinding depth runs by using a glass test tube and funnel assembly. The obtained dust samples from ultrasonically assisted and conventional grinding runs were analyzed by using XRD. The ground surfaces were visually evaluated by using SEM and then characterized while using white light interferometry

3.4. Chapter conclusions

This chapter established the general experimental methodology as well as outlined the basic equipment and techniques used to carry the experiments out. It was established that:

1. A study of the ultrasonic back grinding using tool excitation technique was to be carried out at two depths of 25 and 50 μm under three different excitation configurations: no excitation, longitudinal excitation, and transversal excitation of the tool.
2. The experimental working frequency values for the tool excitation case were to be established through a tool length tuning procedure using a laser profilometer with the performance of the experiment being evaluated through force measurement and analysis, machined chip microscopy, and surface interferometry.

3. A study of the ultrasonic cylindrical grinding technique was to be carried out on two different steel samples while alternating between ultrasonic excitation at 16.81 kHz frequency and no excitation modes and between the dry and wet grinding setups.
4. The experimental working frequency values for the rotating workpiece excitation case were to be determined by using an accelerometer and were found to be 16.81 kHz, while the machining performance itself was to be evaluated through surface profilometry.
5. A study of the ultrasonic back grinding using stationary workpiece excitation technique was to be carried out at 4 different excitation configurations: no excitation, 25%, 50% and 100% excitation amplitude while researching 4 different depths of 1, 5, 25 and 50 μm .
6. The experimental working frequency values for the stationary workpiece actuator were to be determined by using a scanning laser interferometer, while the performance of the technique itself was to be evaluated through the use of: surface topography via white light interferometry, scanning electron microscopy of the surface, and X-ray diffraction of the grinding chips.

4. RESULTS AND DISCUSSION

The experimental study results give an insight into the performance of each method. The experiments were carried out in accordance to the previously outlined experimental setups. While each experimental run produced unique results that can be analyzed to evaluate performance parameters outlined in Chapter 3, it still needs to be noted that a direct comparison of the results between all the three methods is not possible.

Each time an approach was tested, it was done with a motivation to eliminate certain design restrictions and performance limitations observed in the previous approach. Therefore, the design may change radically, thus making it impossible to compare or even obtain the same measurement values.

For instance, in the tool excitation approach, the very premise of the actuator being located inside the tool holder was found to limit the applicability of the approach in terms of supplying power to the actuator in different settings. Therefore, a new approach was proposed, whereby an actuator could be placed outside of the rotating interface. This resulted in the rotating workpiece excitation approach. However, this method is applied to cylindrical grinding, therefore, the workpiece geometry, its material, tool, and obtainable measurements are completely different. In this case, the only measurable quantity was the surface roughness; hence, little insight can be offered into the difference in the force production or mode ductility among the three different methods.

4.1. Tool excitation study results

In order to observe the morphology of the chips obtained during the tool excitation study, WC dust samples were collected on pieces of clear tape after each test run while making sure to eliminate any residue before proceeding with the subsequent test run. The samples were then observed and photographed on a Microscope at 100x magnification (frame size 100x100 μm). To better observe the morphology of the dust, a conscious effort was made to focus on the parts of the sample where a significant amount of background is not covered by the dust.

Provided in figures below (Fig. 68, Fig. 69, Fig. 70) are samples from machining tests at 25 μm cutting depth without ultrasonic excitation, with longitudinal excitation, and transversal excitation in the respective order. It can be seen in all of the pictures that the dust is of irregular size in all the three instances; however, the most consistent size of dust particles can be observed in the sample obtained from longitudinal excitation, followed by the no excitation sample thus making the transversal excitation sample the least consistent as some particles measure up to 10 μm . Such irregularity may have an effect on the obtained surface's roughness of the sample and may indicate the occurrence of destructive processes – which is most likely the case in the transversal excitation sample. The grinding dust sample in the no excitation case features larger particles measuring up to 3.5 μm (circled in red in Fig. 68). These particles are of the spherical nature and are

indicative of thermally induced plastic deformation. Meanwhile, the longitudinal excitation case produced small 1.5–2 μm chips (circled in red in Fig. 69) which were more common in the ductile turning induced by large hydrostatic pressures. The transverse excitation case provided large flat-faced chips (circled in red in Fig. 70) which are indicative of a brittle fracture.

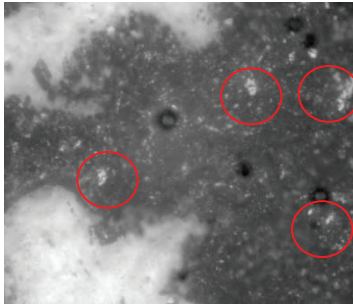


Fig. 68. WC dust obtained without excitation at 25 μm cutting depth

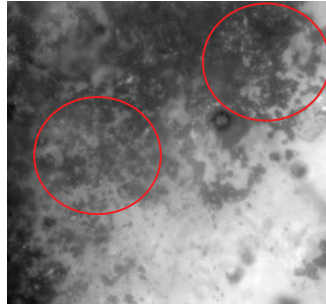


Fig. 69. WC dust obtained with longitudinal excitation at 25 μm cutting depth

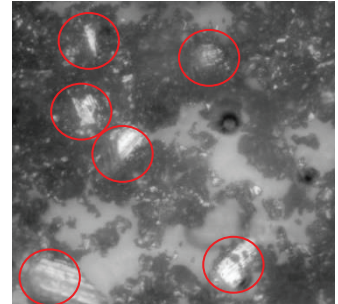


Fig. 70. WC dust obtained with transversal excitation at 25 μm cutting depth

Data resulting from a repeated test run at the cutting depth of 50 μm shows sample photos for all the three conditions in the previously mentioned order (Fig. 71, Fig. 72, Fig. 73). In this case, the transversal excitation sample demonstrates the same behavior (particles circled in red in Fig. 71), yet the control condition sample seems to exhibit similar signs of irregular fracture (circled in red in Fig. 72) as it also features irregular size particles in the image. The consistency of the grain size changes and includes particles indicative of thermally induced ductile mode deformation (circled in red in Fig. 73).

Surface profilometry provides an adequate quantitative picture of the surface quality, and hence it was used to further evaluate the different machining techniques tested in the experiments. The table below (Table 17) provides the surface roughness parameters (R_a and R_z) of both machining setups (at 25 and 50 μm cutting depth).

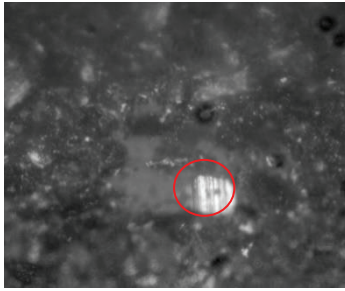


Fig. 71. WC dust obtained without excitation at 50 μm

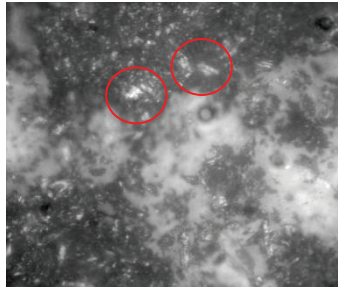


Fig. 72. WC dust obtained with longitudinal excitation at 50 μm

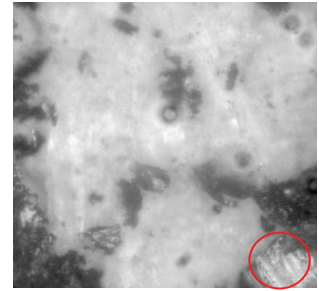


Fig. 73. WC dust obtained with transversal excitation at 50 μm

Provided below (Table 17) are comparisons of the obtained results.

Table 17. Surface roughness parameters of WC samples

Setup	Excitation condition	Ra	Rz
25 μm cutting depth	No excitation	0.198 μm	1.8448 μm
	Longitudinal excitation	0.1536 μm	1.0699 μm
	Transversal excitation	0.2696 μm	1.8059 μm
50 μm cutting depth	No excitation	0.408 μm	2.4072 μm
	Longitudinal excitation	0.2471 μm	1.5807 μm
	Transversal excitation	0.5651 μm	3.9809 μm

From the obtained surface profilometry results, the transversal excitation resulted in the worst surface finish at both depths. By a small margin, the longitudinal excitation resulted in a better surface finish than the conventional method in both cases. However, the margin is not high enough to claim the superiority of the method. Future research should focus on the effect that the cutting depth exerts on the surface roughness during the longitudinal excitation condition, and on the extent to which surface roughness is affected by the frequency and amplitude in both cases of excitation.

Even though white-light interferometry may serve as a quantitative guide to the surface quality (as it provides calculated surface roughness values), it will be used as a qualitative measure to investigate surface morphology changes at different machining conditions. When removing material, the tool leaves behind grooves characteristic to the geometry of the cutting edge. As the cutting edge in the grinding process is not clearly defined, it is expected to be characteristic to the galvanically bonded grain size of the tool. The expected output from excitation is the blending of these grooves. Provided below are white light interferometry pictures of the samples

at a 25 μm depth of cut (Fig. 74, Fig. 75, Fig. 76). The overlap of the grooves is more apparent in the case of longitudinal excitation.

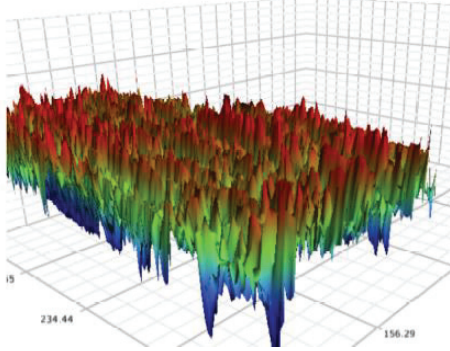


Fig. 74. White light interferometry of the surface obtained without excitation at 25 μm

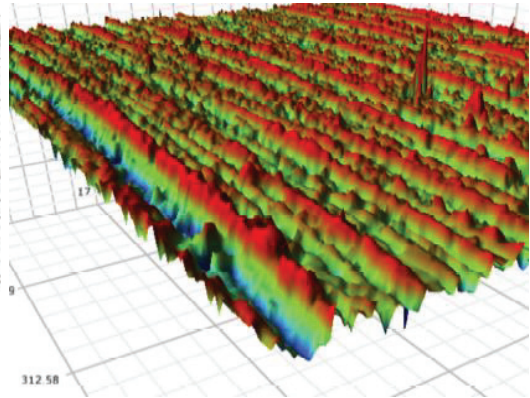


Fig. 75. White light interferometry of the surface obtained with longitudinal excitation at 25 μm

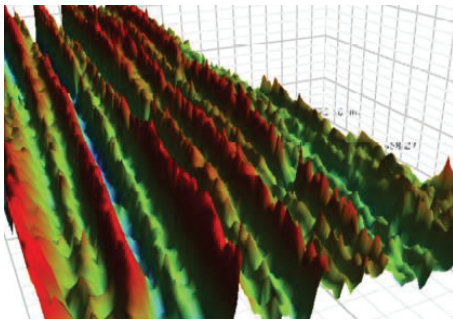


Fig. 76. White light interferometry of the surface obtained with transversal excitation at 25 μm

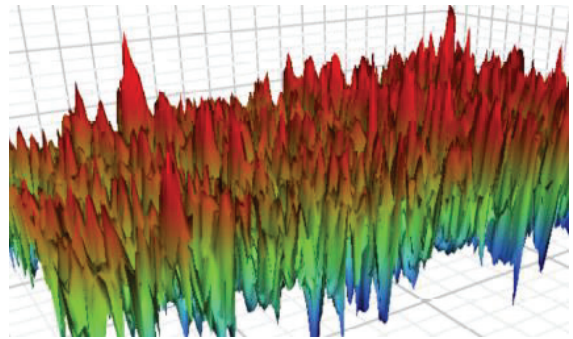


Fig. 77. White light interferometry of the surface obtained without excitation at 50 μm

In the case of the 50 μm cutting depth, as provided below (Fig. 77, Fig. 78, Fig. 79), the blending effect is more apparent in the case of transversal excitation. A better distinction should be available at a higher excitation amplitude and an increased feed rate.

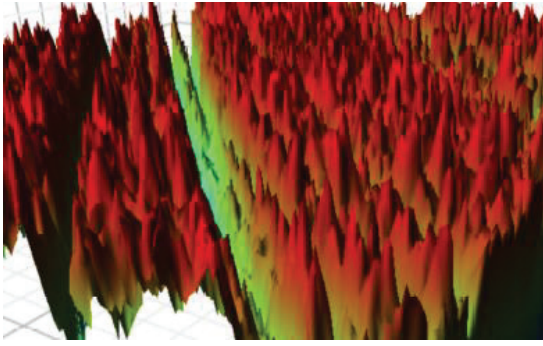


Fig. 78. White light interferometry of the surface obtained with longitudinal excitation at 50 μm

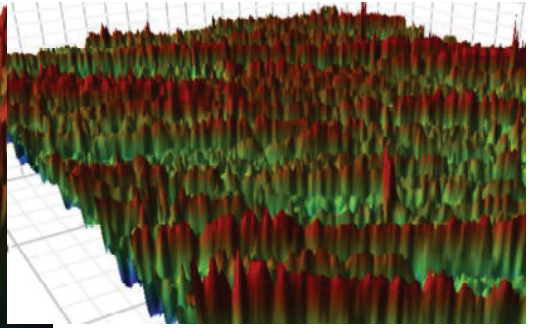


Fig. 79. White light interferometry of the surface obtained with transversal excitation at 50 μm

The cutting force generally serves as a predictor of the ductile mode deformation. It is assumed that the condition for ductile deformation is the reduction of the grinding force. However, depending on the ductile deformation mechanism (thermally induced or high pressure induced plasticity), the reduction may not be as apparent.

The force component along the Z axis allows determining the load applied to the bottom of the grinding path by the bottom face of the tool as a result of tool deflection and other effects. It can be seen from the graphs below that the depth change does not noticeably influence the force along the Z axis when grinding without ultrasonic excitation. While the average value remains unchanged, the force more noticeably fluctuates when the depth is increased.

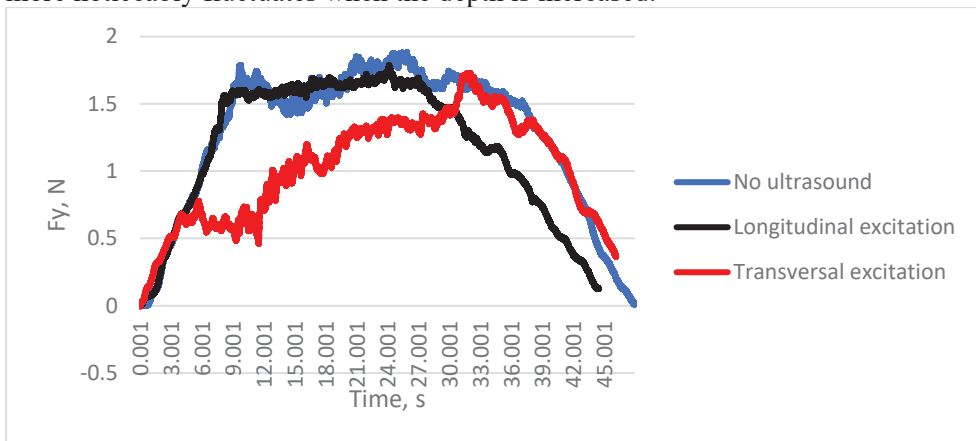


Fig. 80. Normal grinding force at 25 μm depth with and without ultrasonic excitation

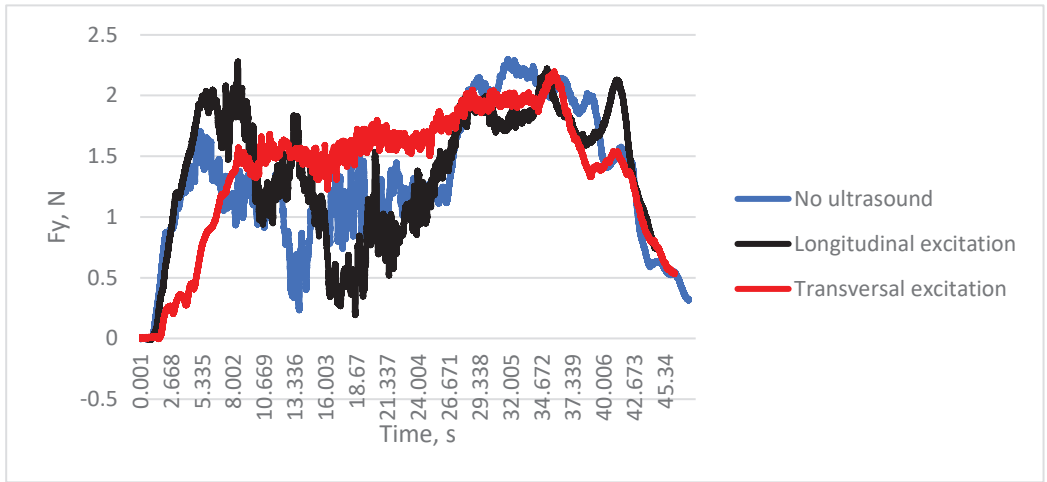


Fig. 81. Normal grinding force at 50 μm depth with and without ultrasonic excitation

Upon application of ultrasonic excitation along the longitudinal direction, a noticeable decrease (about 50%) of the grinding force and fluctuations was observed at 25 μm grinding depth (Fig. 80). At 50 μm grinding depth (Fig. 81), the fluctuations became more apparent than in the case without ultrasonic excitation, while the average force value increased. Compared to the case of longitudinal vibration, when grinding at 25 μm , the analogous case with lateral vibration produces a larger force (~20%). At 50 μm , the fluctuations are not as apparent; however, the average force value is about the same as in the longitudinal case, which is higher than in the conventional case.

4.2. A novel excitation approach to ultrasonically assisted cylindrical grinding

Experiments were carried out with and without vibrations for wet (Fig. 82) and dry grinding. The first experiment was carried out on a 1.1186 steel shaft while using the conventional grinding method (without ultrasonic vibrations).



Fig. 82. Wet cylindrical grinding process

For our measurement, a *PicoScope 3424* oscilloscope with a *KD-91* accelerometer is used. With the ultrasonic generator at 40% power, amplitudes of $0.368\text{ }\mu\text{m}$ were observed to occur at 16.818 kHz for both workpieces. The acceleration (Fig. 83) is in close proximity to the values obtained during the simulation. This change corresponds with the observations made in the previous subchapter regarding the shift of the mode frequency due to the addition of the actuator. These conditions were further used in our vibration assisted grinding (VAG) experiments.

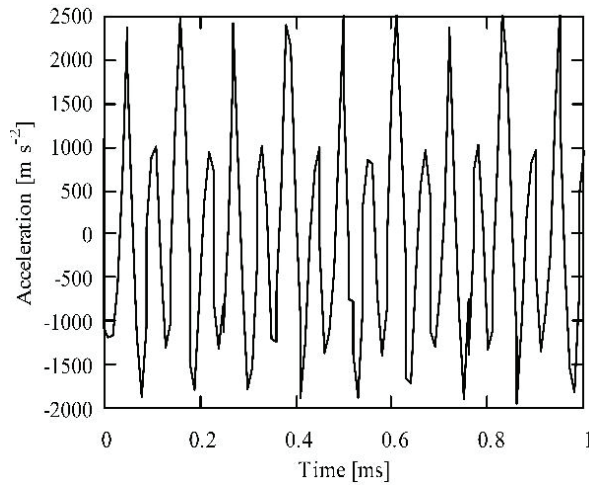


Fig. 83. Acceleration at 16.818 kHz

After the experiments, the roughness of the shaft and the bar was measured with a surface roughness tester at the defined zones for conventional and ultrasonically-assisted grinding with and without a cooling fluid. The results of surface roughness are summarized in Table 18 and shown in **Error! Reference source not found.** and Fig. 85. Here, UG and CG refer to wet grinding with and without ultrasound, when applied to the stepped shaft, while UDG and CDG stand for ultrasonic and conventional dry grinding with UWG and CWG applying for wet grinding, respectively, when dealing with the uniform steel bar.

Table 18. Surface roughness values

Roughness parameter, [μm]	1.7225 steel bar			
	Dry grinding		Wet grinding	
	UG	CG	UG	CG
R_a	0.442	0.491	0.418	0.432
R_q	0.556	0.611	0.516	0.545
R_z	3.323	3.315	2.818	2.843
Roughness parameter, [μm]	1.1186 shaft			
	Wet grinding			
	UG		CG	
R_a	0.251		0.298	
R_q	0.334		0.408	
R_z	2.291		2.939	

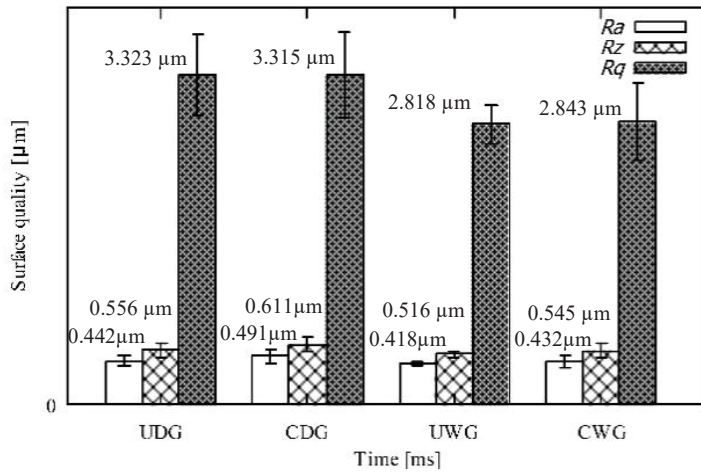


Fig. 84. Surface roughness values for grinding trials on a uniform cylinder workpiece

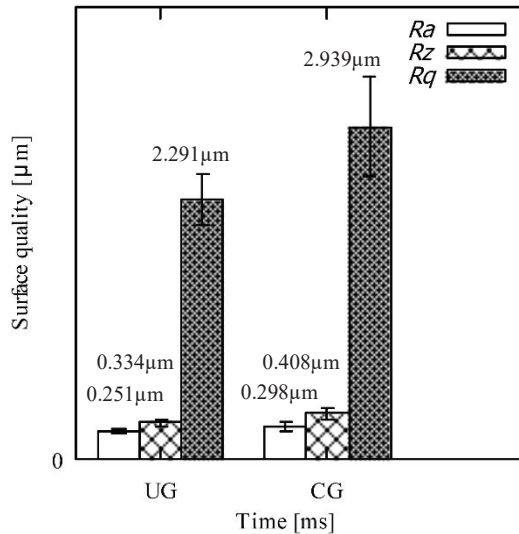


Fig. 85. Surface roughness values for grinding trials on a stepped shaft workpiece

The results in the case of dry grinding are not substantially different between the ultrasonic and conventional counterparts. However, more noticeable improvements were observed in the ultrasound application to wet grinding of a stepped shaft (UG and CG in Fig. 85). This may suggest that high amplitudes may exert a destructive effect on the surface. However, the lack of noticeable improvement in dry grinding also suggests that vibrational assistance should best be applied to stationary interfaces.

4.3. Stationary workpiece excitation study

The grounded surfaces using workpiece excitation were evaluated by using white light interferometry and SEM characterization. Comparisons of the SEM and interferometric images, along with the surface roughness values, are presented below. When machining at a depth of 5 μm , the best results were achieved at 50% amplitude (*c* in Fig. 86), with the roughness value for no ultrasonic assistance case exceeding it by almost 10 times. However, the increase of the amplitude did not translate into any further improvement of the surface; in fact, the surface quality deteriorated. When observing the surfaces of all the other machining depths (Fig. 87, Fig. 88, Fig. 89), a similar trend can be spotted as a certain value of the excitation amplitude underperforms when compared either to a lower amplitude case or to the no excitation case. This suggests that there may be a specific contact condition where insufficient contact of the grain occurs under specific combinations of the excitation amplitude and the grinding depth, which results in microimpacts that deteriorate the surface in a brittle manner.

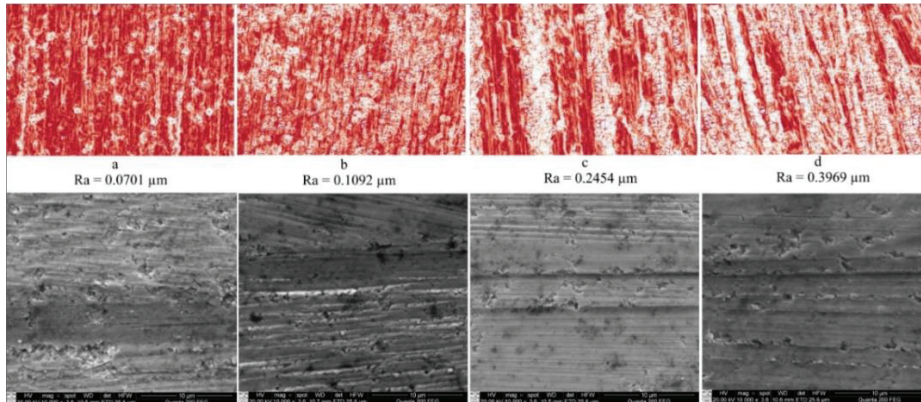


Fig. 86. White light interferometry image comparisons to SEM at a grinding depth of 1 μm : a – 100% ultrasonic excitation amplitude, b – 50% ultrasonic excitation amplitude, c – no ultrasonic excitation, d – 25% ultrasonic excitation amplitude

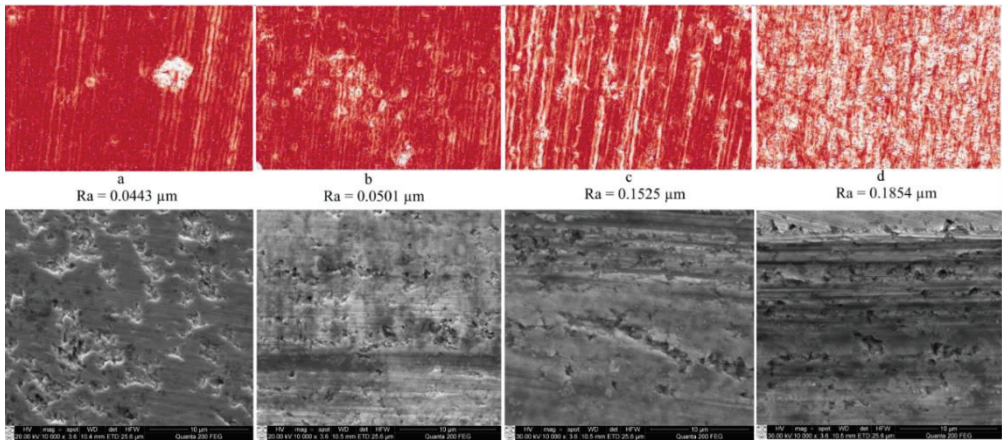


Fig. 87. White light interferometry image comparisons to SEM at a grinding depth of 5 μm : a – no ultrasonic excitation, b – 50% ultrasonic excitation amplitude, c – 100% ultrasonic excitation amplitude, d – 25% ultrasonic excitation amplitude

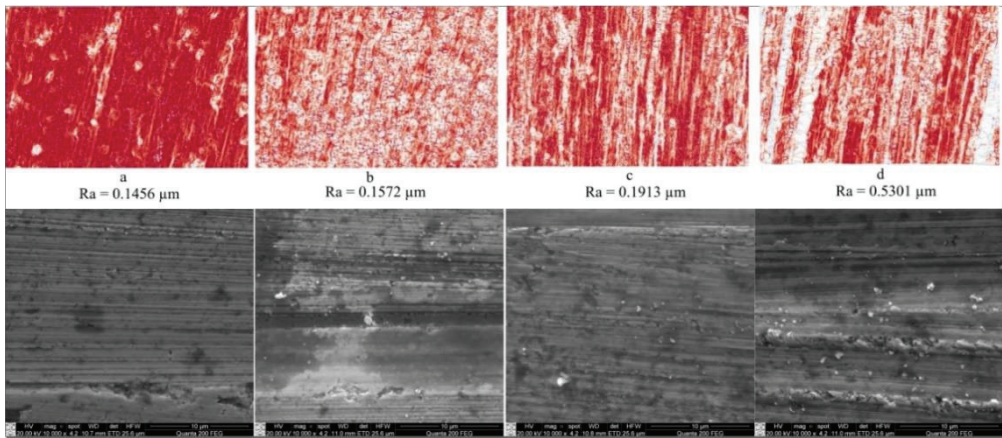


Fig. 88. White light interferometry image comparisons to SEM at a grinding depth of 25 μm : a – 100% ultrasonic excitation amplitude, b – 50% ultrasonic excitation amplitude, c – 25% ultrasonic excitation amplitude, d – no ultrasonic excitation

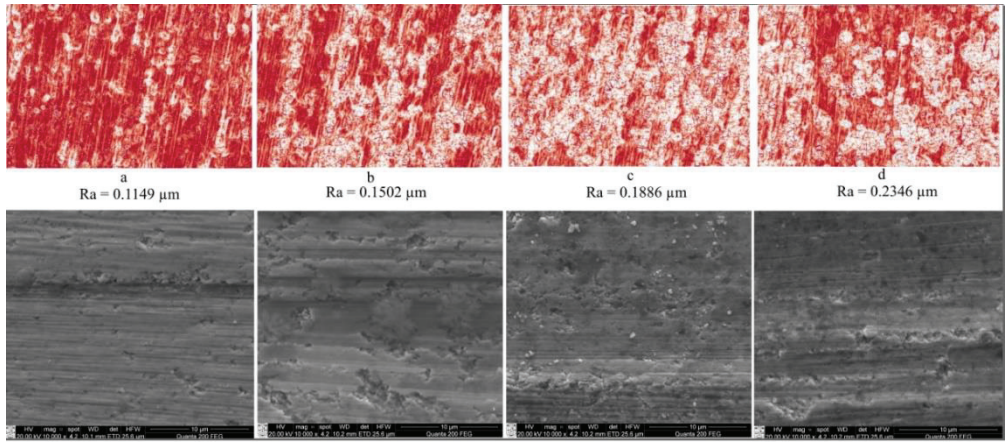


Fig. 89. White light interferometry image comparisons to SEM at a grinding depth of 50 μm : a – 50% ultrasonic excitation amplitude, b – 100% ultrasonic excitation amplitude, c – no ultrasonic excitation, d – 25% ultrasonic excitation amplitude

The surface roughness results obtained at a 1 μm depth suggest that the grains may have been rubbing against the surface during excitation instead as the obtained roughness difference between the conventional case and excitation case is unrealistically high. Similarly, the datapoint for the no excitation case during 25 μm depth grinding should also be disregarded. Based on the percentile distribution of the ductile and brittle sites in the scanning area, the obtained sample surfaces were termed as either brittle, mostly brittle, mostly ductile, and ductile (Fig. 90). It can be seen here that the surface roughness does not fully depend on the deformation mode. However, in all cases, it is observed that ductile deformation occurred in the presence of ultrasound but at different amplitudes.

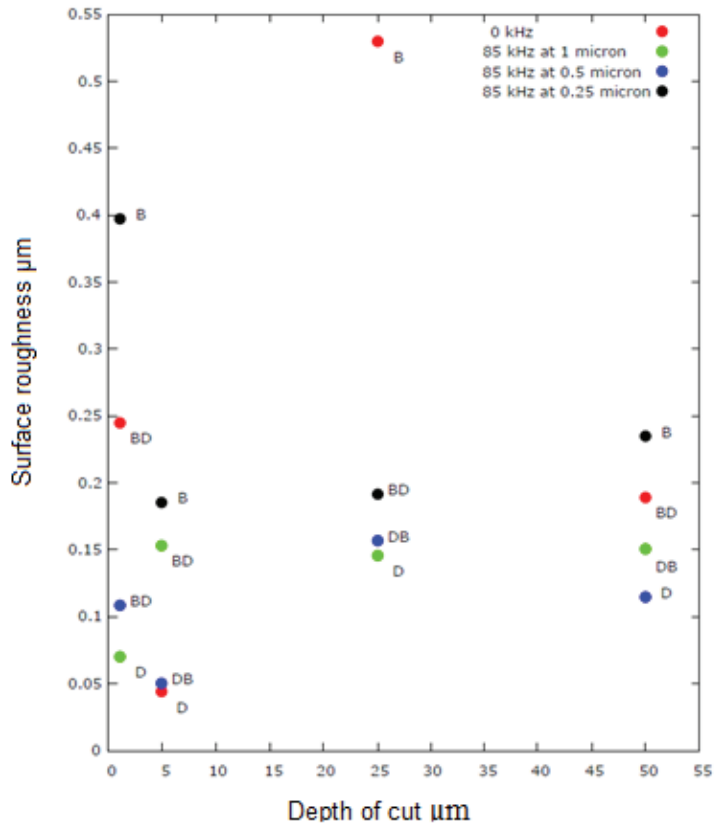


Fig. 90. Brittle site distribution and deformation evaluation for workpiece excitation when grinding at 1, 5, 25, and 50 mm depths. D – ductile deformation, DB – mostly ductile deformation, BD – mostly brittle deformation, B – brittle deformation

The tool workpiece excitation studies yielded grinding chips that were analyzed by using XRD. The XRD analysis yielded the following average crystallite sizes:

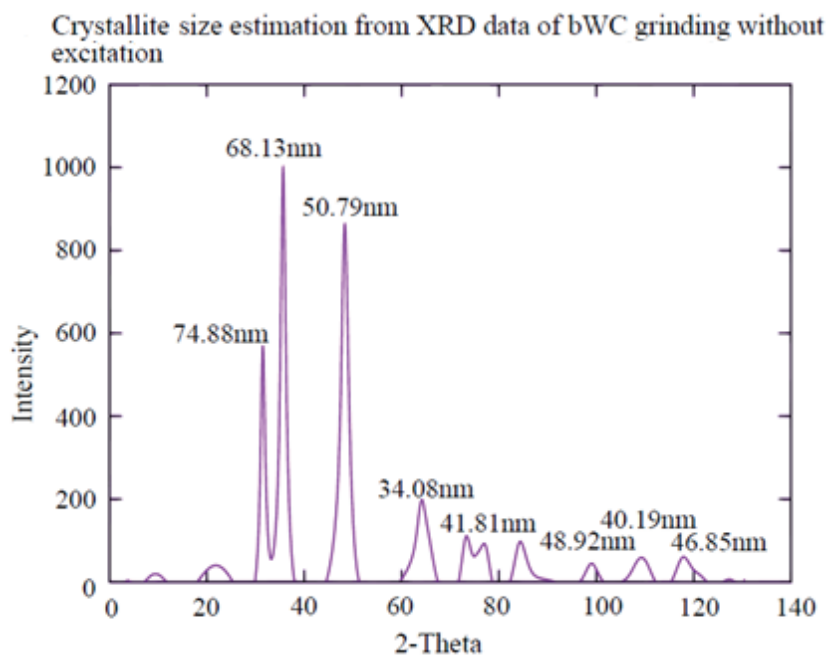


Fig. 91. Crystallite size estimation for case of no excitation grinding

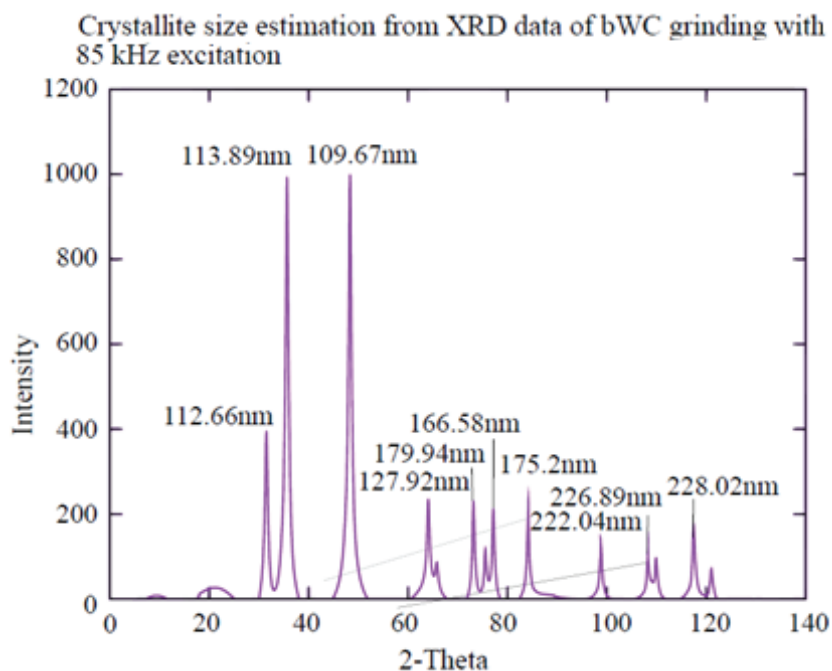


Fig. 92. Crystallite size estimation for case of ultrasonic excitation

The crystallite size of the ground chip is noticeably larger in the workpiece excitation case, which suggests that the chip underwent the ductile mode deformation during removal.

From the obtained results, it is apparent that irregular grain sizes are more prevalent in the cases of no excitation or transversal excitation than in the case of longitudinal excitation. The exact mechanism is still unclear, however, future research should consider the influence of the amplitude, and both configurations should be compared at higher amplitudes in order to observe whether the irregularities in the transversal case are more pronounced and whether they manifest in the longitudinal case at higher amplitudes.

4.4. Chapter conclusions

The results obtained throughout the experiments lead to a conclusion that, with varying degrees of success, in all the experimental studies, the ultrasonic excitation cases dominate over the conventional counterparts with regard to performance. The experimentally obtained working frequencies for the equipment seemed to differ slightly from the theoretical and numerical estimations but were well within acceptable margins. The performance result breakdown according to the studies can be presented as follows:

1. In the tool excitation case, at both 25 and 50 μm depths, the best surface roughness was observed under the condition of longitudinal excitation when the average roughness of the surface, if compared to the conventional grinding case, was lower by 23% and 40% for 25 and 50 μm depths, respectively
2. In the cylindrical grinding case, improvements to the average surface roughness ranged over 4%–16% for the ultrasonic assistance case, however, other surface measurement parameters did not seem to differ substantially.
3. In the stationary workpiece excitation case, the average surface roughness value was several times lower for ultrasonic excitation configurations than for the conventional configuration at 1 and 25 μm depths. This can be attributed to poor tool-workpiece contact and some yet unknown relationship between the engagement depth and the excitation amplitude.
4. The average surface roughness in the stationary workpiece excitation case was observed to improve by 41% for the excitation case.

For back grinding, a dependence on the tool depth and amplitude was observed, which suggests that there may be contact, micro-impacting, and grain over-penetration mechanisms at play. Also, despite the ductile mode being observed in ultrasonically assisted machining cases, the chip crystallite size seems to be almost 40% higher in the vibration assisted grinding case, which suggests that pull-outs could be occurring under such conditions. These possibilities should be investigated in future research.

CONCLUSIONS

Throughout this research work, substantial new insight into the topic of hard, brittle material machining was gained. Two new vibration assisted grinding approaches were created and tested. The main conclusions could be summarized as follows:

1. Upon literature analysis of HBM, it was established that a material could be considered to be HBM if its fracture toughness is below 6.5 and its hardness on the Moh's scale exceeds 6.9. Among these materials, SiC and WC are the most prominent ones, with WC being chosen as the material of interest for the back grinding investigations in this research.
2. Two novel vibration assisted grinding approaches were proposed to combat the intrinsic limitations of the conventionally encountered rotary grinding tool excitation approach. The first attempt was to apply excitation externally to the rotating interface, without introducing the actuator into the rotating interface itself. The second approach removed the rotating interface altogether by applying excitation to the stationary workpiece instead.
3. In all the experimental runs, the ultrasonically assisted process configuration performances exceeded those of their conventional counterparts. The best performance of all the approaches was determined to be the stationary workpiece approach (41% improvement to R_a at 50 μm depth). This approach was therefore patented.
4. Despite the promising results, the performance of the presently available technology lacks consistency in terms of the attained surface quality under varying cutting depths, primarily, due to a yet unknown relation between the tool engagement depth and the excitation amplitude. It is possible that the grains could overpenetrate the surface at too high an amplitude, or, in the absence of a sufficient contact, impact the surface.

REFERENCES

1. Agrawal, S., Khare, S. K., Pandey, V. P. & Patel, M., 2017. An Analytical Chip Thickness Model for Performance Assessment in Silicon Carbide Grinding. *45th SME North American Manufacturing Research Conference*, 10(doi: 10.1016/j.promfg.2017.07.060), pp. 298-306.
2. Alisir, S. & Cevik, S., 2019. The effects of foundry sand components on the cast iron. *Research on Engineering Structures & Materials*, Issue DOI:<http://dx.doi.org/10.17515/resm2019.148ma0911>.
3. Alkhalefah, H., 2020. Precise Drilling of Holes in Alumina Ceramic (Al₂O₃) by Rotary Ultrasonic Drilling and its Parameter Optimization using MOGA-II. *Materials*, 13(1059, doi:10.3390/ma13051059), pp. 1-19.
4. Anderson, D., Warkentin, A. & Bauer, R., 2011. Experimental and numerical investigations of singleabrasive-grain cutting. *International Journal of Machine Tools and Manufacture*, 51(12, <https://doi.org/10.1016/j.ijmachtools.2011.08.006>), pp. 898-910.
5. Arif, M., Zhang, X., Rahman, M. & Kumar, S., 2012. A predictive model of the critical undeformed chip thickness for ductile-brittle transition in nano-machining of brittle materials. *International Journal of Machine Tools and Manufacture*, 64 tomas, pp. 114-122.
6. Bifano, T. G., Dow, T. A., Scattergood, R. & O., 1991. Ductile-regime grinding: a new technology for machining brittle materials. *Journal of Engineering for Industry*, 113(2).
7. Bifano, T. G., Dow, T. A. & Scattergood, R. O., 1991. Ductile-Regime Grinding: A New Technology for Machining Brittle Materials. *J. Eng. Ind.*, 113(2, <https://doi.org/10.1115/1.2899676>), pp. 184-189.
8. Bridgman, P. W. & Šimon, I., 1953. Effects of Very High Pressures on Glass. *Journal of Applied Physics*, 24(4), p. 405.
9. Cao, J. *et al.*, 2014. Material removal behavior in ultrasonic-assisted scratching of SiC ceramics with a single diamond tool. *International Journal of Machine Tools and Manufacture*, 79(<https://doi.org/10.1016/j.ijmachtools.2014.02.002>), pp. 49-61.
10. Cerniway, M. A., 2001. Elliptical diamond milling: kinematics, force and tool wear. *MS thesis. North Carolina State University*.
11. Cheng, J., Wang, C., Wen, X. & Gong, Y., 2014. Modelling and experimental study on micro-fracture behavior and restraining technology in microgrinding of glass. *International Journal of Machine Tools and Manufacture*, vol. 85, pp. 36-48.
12. Cheng, J. *et al.*, 2017. Grinding forces in micro slot-grinding (MSG) of single crystal sapphire. *International Journal of Machine Tools and Manufacture*, 112(<https://doi.org/10.1016/j.ijmachtools.2016.10.004>), p. 7-20.

13. Chen, J., Fang, Q. & Li, P., 2015. Effect of grinding wheel spindle vibration on surface roughness and subsurface damage in brittle material grinding. *International Journal of Machine Tools and Manufacture*, Issue <https://doi.org/10.1016/j.ijmachtools.2015.01.003>, pp. 12-23.
14. Chen, S. & Jiang, Z., 2015. A force controlled grinding-milling technique for quartz-glass micro-machining. *Journal of Materials Processing Technology*, 216(<https://doi.org/10.1016/j.jmatprotec.2014.09.017>), pp. 206-215.
15. Cheong, W. C. D. & Zhang, L. C., 2000. Molecular dynamics simulations of phase transformations in silicon monocrystals due to nano-indentation. *Nanotechnology*, 11(3, <https://doi.org/10.1088/0957-4484/11/3/307>), pp. 173-180.
16. Duan, N., Yui, Y., Wang, W. & Xu, X., 2017. Analysis of grit interference mechanisms for double scratching of monocrystalline silicon carbide by coupling the FEM and SPH. *International Journal of Machine Tools and Manufacture*, 120(<https://doi.org/10.1016/j.ijmachtools.2017.04.012>), pp. 49-60.
17. Duan, N., Yu, Y., Wang, W. & Xu, X., 2017. SPH and FE coupled 3D simulation of monocrystal SiC scratching by single diamond grit. *International Journal of Refractory Metals and Hard Materials*, 64(<https://doi.org/10.1016/j.ijrmhm.2016.09.016>), p. 279–293.
18. Elhami, S. & Razfar, M. R., 2020. Application of nano electrolyte in the electrochemical discharge. *Precision Engineering*, 64(<https://doi.org/10.1016/j.precisioneng.2020.03.010>), pp. 33-44.
19. Gaidys, R. *et al.*, 2017. Ultrasonic tooling system design and development for single point diamond turning (SPDT) of ferrous metals. *International Journal of Advanced Manufacturing Technologies*, 93(DOI 10.1007/s00170-017-0657-7), pp. 2841-2854.
20. Guo, B. & Zhao, Q., 2017. Ultrasonic vibration assisted grinding of hard and brittle linear micro-structured surfaces. *Precision Engineering*, 48(<https://doi.org/10.1016/j.precisioneng.2016.11.009>), pp. 98-106.
21. Guojun, D., Lang, C., Li, C. & Zhang, L., 2020. Formation mechanism and modelling of exit edge-chipping during ultrasonic vibration grinding of deep-small holes of microcrystalline-mica ceramics. *Ceramics International*, Issue <https://doi.org/10.1016/j.ceramint.2020.02.008>.
22. He, P. *et al.*, 2011. Development of a low cost high precision fabrication process for glass hybrid aspherical diffractive lenses. *Journal of Optics*, 13(8, doi:10.1088/2040-8978/13/8/085703).
23. Jiang, J. *et al.*, 2016. From the microscopic interaction mechanism to the grinding temperature field: An integrated modelling on the grinding

- process. *International Journal of Machine Tools & Manufacture*, 110(<http://dx.doi.org/10.1016/j.ijmachtools.2016.08.004>), pp. 27-42.
24. Jiang, J. L. *et al.*, 2013. 2D/3D ground surface topography modeling considering dressing and wear effects in grinding process. *International Journal of Machine Tools and Manufacture*, 74(<https://doi.org/10.1016/j.ijmachtools.2013.07.002>), pp. 29-40.
 25. Kailer, A., Gogotsi, Y. G. & Nickel, K. G., 1997. Phase transformations of silicon caused by contact loading. *Journal of Applied Physics*, 81(7), pp. 3057-3063.
 26. King, R. & Tabor, D., 1954. The strength properties and frictional behaviour of brittle solids. *Proceedings Of The Royal Society*, 223(1153), pp. 225-238.
 27. Lai, M., Zhang, X. D. & Fang, F. Z., 2012. Study on critical rake angle in nanometric cutting. *Applied Physics A*, 108(4, <https://doi.org/10.1007/s00339-012-6973-8>), pp. 809-818.
 28. Lawn, B. R. & Marshall, D. B., 1979. Hardness, toughness, and brittleness: an indentation analysis. *Journal of the American Ceramic Society*, 62(7-8, <https://doi.org/10.1111/j.1151-2916.1979.tb19075.x>), pp. 347-350.
 29. Lawn, B. & Wilshaw, R., 1975. Indentation fracture: principles and applications. *Journal of Materials Science*, 10(6), pp. 1049-1081.
 30. Liang, Z., Wu, Y., Wang, X. & Zhao, W., 2010. A new two-dimensional ultrasonic assisted grinding (2D-UAG) method and its fundamental performance in monocrystal silicon machining. *International Journal of Machine Tools and Manufacture*, 50(8, <https://doi.org/10.1016/j.ijmachtools.2010.04.005>), pp. 728-36.
 31. Li, C. *et al.*, 2017. Material removal mechanism and grinding force modelling of ultrasonic vibration assisted grinding for SiC ceramics. *Ceramics International*, 43(3), p. 2981–2993.
 32. Li, H. N., Yu, T. B., Li, D. Z. & Wan, S. W., 2017. Analytical modeling of ground surface topography in monocrystalline silicon grinding considering the ductile-regime effect. *Archives of Civil and Mechanical Engineering*, 17(4, <https://doi.org/10.1016/j.acme.2017.03.010>), pp. 880-893.
 33. Li, H. N. *et al.*, 2017. Detailed modeling of cutting forces in grinding process considering variable stages of grain-workpiece micro interactions. *International Journal of Mechanical Sciences*, 126(<https://doi.org/10.1016/j.ijmecsci.2016.11.016>), pp. 319-339.
 34. Liu, K., Li, X. P. & Liang, S. Y., 2007. The mechanism of ductile chip formation in cutting of brittle materials. *International Journal of Advanced Manufacturing Technologies*, 33(9-10), pp. 875-884.
 35. Liu, Y. *et al.*, 2018. Smoothed particle hydrodynamics simulation and experimental analysis of SiC ceramic grinding mechanism. *Ceramics*

- International*, 44(11, <https://doi.org/10.1016/j.ceramint.2018.03.278>), pp. 12194-12203.
36. Li, X. P., He, T. & Rahman, M., 2005. Tool wear characteristics and their effects on nanoscale ductile mode cutting of silicon wafer. *Wear*, 259(7-12, <https://doi.org/10.1016/j.wear.2004.12.020>), pp. 1207-1214.
 37. Marshall, D. B. & Lawn, B. R., 1986. Indentation of brittle materials. *Microindentation Microindentation in Materials Science and Engineering*, 889 tomas.
 38. McDonald, A., Mohamed, A. O., Warkentin, A. & Bauer, R. J., 2017. Kinematic simulation of the uncut chip thickness and surface finish using a reduced set of 3D grinding wheel measurements. *Precision Engineering*, 49(<http://dx.doi.org/10.1016/j.precisioneng.2017.02.005>), pp. 169-178.
 39. Mir, A., Luo, X. & Sun, J., 2016. The investigation of influence of tool wear on ductile to brittle transition in single point diamond turning of silicon. *Wear*, Issue <http://dx.doi.org/10.1016/j.wear.2016.08.003>, pp. 233-243.
 40. Nuruzzaman, M. et al., 2015. Structural, elastic and electronic properties of 2H- and 4H-SiC. *International Journal of Engineering Research and Applications*, 5(5), pp. 48-52.
 41. Park, H. W. & Liang, S. Y., 2008. Force modeling of micro-grinding incorporating crystallographic effects. *International Journal of Machine Tools & Manufacture*, 48([10.1016/j.ijmachtools.2008.07.004](https://doi.org/10.1016/j.ijmachtools.2008.07.004)), pp. 1658-1667.
 42. Patnaik Durgumahanti, U. S., Singh, V. & Venkateswara, R., 2010. A New Model for Grinding Force Prediction and Analysis. *International Journal of Machine Tools and Manufacture*, 50(3, <https://doi.org/10.1016/j.ijmachtools.2009.12.004>), pp. 231-240.
 43. Redwing, R., 2017. *John A. Dutton e-Education Institute - What is a Brittle Material?*. Available at: <https://www.e-education.psu.edu/matse81/node/2106> [Kreiptasi 20 7 2019].
 44. Rizzo, A. et al., 2020. The Critical Raw Materials in Cutting Tools for Machining Applications: A Review. *Materials*, 13(6, <https://doi.org/10.3390/ma13061377>).
 45. Scattergood, R. O. & Blake, N., 1990. R.O. Scattergood, N. Blake, Ductile-regime machining of germanium and silicon. *Journal of the American Ceramic Society*, 73(4), pp. 949-957.
 46. Setti, D., Ghosh, S. & Venkateswara Rao, P., 2017. A method for prediction of active grits count in surface grinding. *Wear*, Issue <http://dx.doi.org/10.1016/j.wear.2017.04.012>, pp. 71-77.
 47. Sun, J., Qin, F., Chen, P. & An, T., 2016. A predictive model of grinding force in silicon wafer self-rotating grinding. *International*

- Journal of Machine Tools & Manufacture*, 109(<http://dx.doi.org/10.1016/j.ijmachtools.2016.07.009>), pp. 74-86.
48. Tian, L. *et al.*, 2015. The influence of speed on material removal mechanism in high speed grinding with single grit. *International Journal of Machine Tools and Manufacture*, 89(<https://doi.org/10.1016/j.ijmachtools.2014.11.010>), p. 192–201.
 49. Tsuno, K. *et al.*, 2005. *NT-SiC (new-technology silicon carbide): application for space optics*. San Diego, California, United States, <https://doi.org/10.1117/12.615841>.
 50. Varga, M., Leroch, S., Eder, S. J. & Rodriguez Ripoll, M., 2017. Meshless microscale simulation of wear mechanisms in scratch testing. *Wear*, Issue <http://dx.doi.org/10.1016/j.wear.2016.11.023>, pp. 1122-1129.
 51. Venkatachalam, S., Li, X. & Liang, S. Y., 2009. Predictive modeling of transition undeformed chip thickness in ductile-regime machining of single crystal brittle materials. *Journal of Materials Processing Technology*, 209(7), pp. 3306-3319.
 52. Wang, W. *et al.*, 2017. Elastic stressfield model and micro-crack evolution for isotropic brittle materials during single grit scratching. *Ceramics International*, 43(<http://dx.doi.org/10.1016/j.ceramint.2017.05.054>), pp. 10726-10736.
 53. Wang, Y., Zhang, X. & Lin, B., 2014. Research on the system matching model in ultrasonic vibration-assisted grinding. *International Journal of Advanced Manufacturing Technology*, 70(DOI 10.1007/s00170-013-5269-2), pp. 449-458.
 54. Yan, J., Asami, T., Harada, H. & Kuriyagawa, T., 2009. Fundamental investigation of subsurface damage in single crystalline silicon cause by diamond machining. *Precision Engineering*, 33(4, <https://doi.org/10.1016/j.precisioneng.2008.10.008>), pp. 378-386.
 55. Yin, L. *et al.*, 2005. Planar nanogrinding of a fine grained WC-Co composite for an optical surface finish. *International Journal of Advanced Manufacturing Technologies*, 26(7-8, DOI 10.1007/s00170-004-2056-0), pp. 766-773.
 56. Yu, G. *et al.*, 2019. Machining performance of hard, brittle materials by multi-layer micro-nano crystalline diamond coated tools. *Results in Physics*, 13(<https://doi.org/10.1016/j.rinp.2019.102303>).
 57. Zhang, J., Suzuki, N., Wang, Y. & Shamoto, E., 2014. Fundamental investigation of ultra-precision ductile machining of tungsten carbide by applying elliptical vibration cutting with single crystal diamond. *Journal of Materials Processing Technology*, 214(11), pp. 2644-2659.
 58. Zhang, L.-C. & Tanaka, H., 1999. On the Mechanics and Physics in the Nano-indentation process. *JSME international journal*, 42(4), pp. 546-559.

59. Zhang, L. & Zarudi, I., 2001. Towards deeper understanding of plastic deformation in mono-crystalline silicon. *International Journal of Mechanical Sciences*, 43(9), [https://doi.org/10.1016/S0020-7403\(01\)00024-8](https://doi.org/10.1016/S0020-7403(01)00024-8), pp. 1985-1996.
60. Zhang, P. et al., 2013. Influence of double-tip scratch and single-tip scratch on nano-scratching process via molecular dynamics simulation. *In Applied Surface Science*, 280(<https://doi.org/10.1016/j.apsusc.2013.05.056>), p. 751–756.
61. Zhang, Y. et al., 2017. Analysis of grinding mechanics and improved predictive force model based on material-removal and plastic-stacking mechanisms. *International Journal of Machine Tools and Manufacture*, 122(<https://doi.org/10.1016/j.ijmachtools.2017.06.002>), pp. 81-97.
62. Zhang, Y. N. et al., 2015. An Experimental Study on Mechanical Modeling of Ceramics Based on Microstructure. *Applied Sciences*, 5(4, [doi:10.3390/app5041337](https://doi.org/10.3390/app5041337)), p. 1337–1349.
63. Zhong, Z. W. & Peng, Z. F., 2007. Fractal roughness structures of precision-machined WC-Co and Inconel 625-coated steel rods. *International Journal of Advanced Manufacturing Technologies*, 33(9-10, DOI: 10.1007/s00170-006-0532-4), pp. 885-890.
64. Zhong, Z. W. & Rui, Z. Y., 2005. Grinding of Single-Crystal Silicon Using Microvibration Device. *Materials and Manufacturing Processes*, 20(4, DOI: 10.1081/AMP-200055068), pp. 687-696.
65. Zhu, D., Yan, S. & Li, B., 2014. Single-grit modeling and simulation of crack initiation and propagation in SiC grinding using maximum undeformed chip thickness. *Computational Materials Science*, 92(<http://dx.doi.org/10.1016/j.commatsci.2014.05.019>), pp. 13-21.

LIST OF AUTHOR'S PUBLICATIONS

Results published in journals with the impact factor indexed in the Web of Science database:

1. Ostaševičius, V.; Jūrėnas, V.; Balevičius, G.; Česnavičius, R. Development of actuators for ultrasonically assisted grinding of hard-brittle materials. *The International Journal of Advanced Manufacturing Technology*, vol. 106, Pages: 289-301. 2020.
2. Ostasevicius, V.; Jurenas, V.; Balevicius G.; Zukauskas, M.; Ubartas, M. Vibrational excitation of a work piece for drilling force reduction in brittle materials. *Mechanika*. Issue: 6, Pages: 596-601. 2014.
3. Ostasevicius, V.; Karpavicius, P.; Janusas, G.; Balevicius G. Design and implementation of uniform light guide based, force and deflection measurement device. *Mechanika*. Issue: 4, Pages: 279-284. 2016.
4. Ostasevicius, V.; Balevicius G.; Zakrasas, R.; Baskutiene, J.; Jurenas, V. Investigation of vibration assisted drilling prospects for improving machining characteristics of hard to machine materials at high and low frequency ranges. *Mechanika*. Issue: 2, Pages: 125-131. 2016.
5. Ostasevicius, V.; Jurenas, V.; Vilkauskas, A.; Balevicius, G.; Senkus, A.; Jotautiene, E. A Novel Excitation Approach to Ultrasonically-Assisted Cylindrical Grinding. *Strojniski Vestnik-Journal of Mechanical Engineering*, Vol.63(12) Pages: 696-704. 2017.

Results published in conference proceedings:

1. Ostasevicius, V.; Balevicius G.; Zakrasas, R. Development guidelines for models of grinding forces in ultrasonically assisted grinding of binderless tungsten carbide. *Mechanika 2016: Proceedings of the 21st International Scientific Conference*. Book Series: Mechanika. Kaunas University of Technology. Pages: 193-198. 2016.

Results presented in international scientific conferences:

1. V. Ostaševičius, G. Balevičius, “Overview of modeling methods for brittle ductile transition during drilling under inverse excitation”, 11th conference *Mechatronic systems and materials*, Kaunas, Lithuania, 2015.
2. G. Balevičius V. Ostaševičius, V. Jūrėnas, M. Žukauskas, M. Ubartas, “Investigation prospects of brittle – ductile transition in drilling under inverse vibrational excitation”, *Mechanika 20*, Kaunas, Lithuania, 2015.
3. V. Ostaševičius, G. Balevičius, R. Zakrasas, “Development guidelines for models of grinding forces in ultrasonically assisted grinding of binderless tungsten carbide”, *Mechanika 21*, Kaunas, Lithuania, 2016.
4. G. Balevičius, V. Ostaševičius, V. Jurėnas, R. Česnavičius, “Machining of Hard-brittle Materials: Ultrasonic Assistance and Its Role in Brittle-Ductile Transition”, *Mechanika 24*, Kaunas, Lithuania, 2019.
5. V. Ostaševičius, G. Balevičius, “Peculiarities of vibration assisted surface finishing methods for brittle material surfaces”, 2nd International Conference and Expo on Ceramics and Composite Materials, Berlin, Germany, 2016.

Results presented in national conferences:

1. G. Balevičius, „Molekulinės dinamikos panaudojimas kietų-trapių medžiagų apdirbimo modeliavimui“, Lithuanian Science Academy’s 7th Young Scientists conference, Vilnius, Lithuania, 2017.

