Vibration Assisted Machining

Theory, Modelling and Applications

Lu Zheng, Wanqun Chen, and Dehong Huo

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Vibration Assisted Machining

Theory, Modelling and Applications

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Preface

Precision components are increasingly in demand for various engineering industries, such as biomedical engineering, MEMS, electro-optics, aerospace, and communications. However, processing these difficult-to-machine materials efficiently and economically is always a challenging task, which stimulates the development and subsequent application of vibration-assisted machining (VAM) over the past few decades. Vibration-assisted machining employs additional external energy sources to generate high-frequency vibration in the conventional machining process, changing the machining (cutting) mechanism, thus reducing the cutting force and cutting heat and improving the machining quality. The effective implementation of the VAM process depends on a wide range of technical issues, including vibration device design and setup, process parameter optimization, and performance evaluation. The current awareness on VAM technology is incomplete; although ample review/research papers have been published, no single source provides a comprehensive comprehending yet. Therefore, a book is needed to systematically introduce this emerging manufacturing technology as a subject.

The main objective of this book is to address the basics and the latest advances in the VAM technology. The first chapter provides a brief introduction to VAM technology, including VAM process, benefits, and applications, as well as its history and development, so that the reader would have a general understanding of the subject. The second and third chapters aim to present a detailed description of the characteristics and design process for vibration devices. Chapter 2 overviews the current proposed vibration devices in the literature, and the features of each type vibration devices are critically reviewed. Chapter 3 focuses on the implementation and design of vibration devices and the corresponding design procedures are also discussed. Chapters 4 and 5 are dedicated to the effect of vibration and machining parameters on tool path/tool–workpiece separation and the surface topography generation. Chapters 4 and 5 are dedicated to the effect of vibration and machining parameters on tool path/tool–workpiece separation and its influence on the cutting performance. Chapter 4 covers the kinematic analysis of VAM, including the tool–workpiece separation type and the corresponding equations during the processing. Chapter 5 investigates the mechanisms of tool wear and burr generation under different tool–workpiece separation situations. Chapter 6 and 7 investigate VAM process through simulation modelling method. Chapter 6 models the cutting force using both numerical and finite element methods. Finite element modeling and analysis of VAM are detailed in Chapter 7 to deeply understand the cutting mechanism of VAM. The last chapter contains the modeling of surface topography using homogeneous matrix transformation and cutter edge sweeping technology, and the results are verified by the machining experiments.

This book provides state of the art in research and engineering practice in VAM for researchers and engineers in the field of mechanical and manufacturing engineering. This book can be used as a textbook for a final year elective subject on manufacturing engineering, or as an introductory subject on advanced manufacturing methods at the postgraduate level. It can also be used as a textbook for teaching advanced manufacturing technology in general. The book can also serve as a useful reference for manufacturing engineers, production supervisors, tooling engineers, planning and application engineers, as well as machine tool designers.

Some of the research findings in this book have arisen from an EPSRC-funded project “Development of a 3D Vibration Assisted Machining System.” The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council (EP/M020657/1).

The authors wish the readers an enjoyable and fruitful reading through the book.

Lu Zheng, Wanqun Chen and Dehong Huo

February 2020

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Introduction to Vibration-Assisted Machining Technology

1.1 Overview of Vibration-Assisted Machining Technology

1.1.1 Background

Precision components are increasingly in demand in various engineering fields such as microelectromechanical systems (MEMS), electro-optics, aerospace, automotive, biomedical engineering, and internet and communication technology (ICT) hardware. In addition to the aims of achieving tight tolerances and high-quality surface finishes, many applications also require the use of hard and brittle materials such as optical glass and technical ceramics owing to their superior physical, mechanical, optical, and electronic properties. However, because of their high hardness and usually low fracture toughness, the processing and fabrication of these hard-to-machine materials have always been challenging. Furthermore, the delicate heat treatment required and composite materials in aeronautic or aerospace alloys have caused similar difficulties for precision machining.

It has been reported that excessive tool wear and fracture damage are the main failure modes during the processing of such materials, leading to low surface quality and machining accuracy. Efforts to optimize a conventional machining process to achieve better cutting performance with these materials have never been stopped, and these optimizations include the cutting parameters, tool materials and geometry, and cutting cooling systems in the past decades [1–6]. Generally, harder materials or wear-resistant coatings are applied, and tool geometry is optimized to prevent tool cracking and to reduce wear on wearable positions such as the flank face [5, 7–10]. Cryogenic coolants are used in the machining process, and their input pressure has been optimized to achieve better cooling performance [2, 4, 11]. However, although cutting performance can be improved, the results are often still unsatisfactory.

Efforts to enhance machining performance have revealed that machining quality can be improved using the high-frequency vibration of the tool or workpiece. Vibration-assisted machining (VAM) was first introduced in the late 1950s and has been applied in various machining processes, including both traditional machining (turning, drilling, grinding, and more recently milling) and nontraditional machining (laser machining, electro-discharge machining, and electrochemical machining), and it is now widely used in the precision manufacturing of components made of various materials. VAM adds external energy to the conventional machining process and generate high-frequency, low-amplitude vibration in the tool or workpiece, through which a periodic separation between the uncut workpiece and the tool can be achieved. This can decrease the average machining forces and generate thinner chips, which in turn leads to high processing efficiency, longer tool life, better surface quality and form accuracy, and reduced burr generation [12–17]. Moreover, when hard and brittle materials such as titanium alloy, ceramic, and optical glass are involved, the cutting depth in the ductile regime cutting mode can be increased [18]. As a result, the cutting performance can be improved and unnecessary post-processing can be avoided, which allows the production of components with more complex shape features [14]. Nevertheless, there are still many opportunities for technological improvement, and ample scope exists for better scientific understanding and exploration.

VAM may be classified in two ways. The first classification is according to the dimensions in which vibration occurs: 1D, 2D, or 3D VAM. The other classification is based on the vibration frequency range, for example, in ultrasonic VAM and non-ultrasonic VAM. Ultrasonic VAM is the most common type of VAM. It works at a high vibration frequency (usually above 20 kHz), and a resonance vibration device maintains the desired vibration amplitude. Most of its applications are concentrated in the machining of hard and brittle materials because of the fact that high vibration frequency dramatically improves the cutting performance of difficult-to-machine materials. Meanwhile non-ultrasonic VAM uses a mechanical linkage to transmit power to make the device expand and contract, and this can obtain lower but variable vibration frequencies (usually less than 10 kHz). It is easier to achieve closed-loop control because of the low range of operating frequency, which makes it uniquely advantageous in applications such as the generation of textured surface.

1.1.2 History and Development of Vibration-Assisted Machining

The history of vibration technology in VAM can be traced back to the 1940s. During the period of World War II, the high demand for the electrically controlled four-way spool valves mainly used in the control of aircraft and gunnery circuits stimulated the development of servo valve technology [19]. Because of their wide frequency response and high flow capacity, electrohydraulic vibrators were successfully developed and applied in VAM in the 1960s with positive effects in enhanced processing quality and efficiency [20]. With the further development of technology, electromagnetic vibrators featuring higher accuracy and a wide range of frequency and amplitude generation were developed based on electromagnetic technology, and these were successfully applied to various VAM processes [21]. The need for complex hydraulic lines was eliminated, and greater tolerance for the application environment was allowed, which also leads to smaller devices. As a result, a transmission line or connecting body can be attached to the vibrator to achieve a wide range of vibration frequencies and amplitude adjustments [22]. In the 1980s, the maturity of piezoelectric transducer (PZT) piezoelectric ceramic technology had brought a new choice for the vibrator. A piezoelectric ceramic stack could be sandwiched under compressive strain between metal plates, and this has advantages including compactness, high precision and resolution, high frequency response, and large output force [23]. Various shapes of piezoelectric ceramic elements can be used to make different types of vibration actuators, which indicate that the limitations of traditional vibrators were overcome and the application of VAM technology for precision machining was broadened. In addition, it helped in the development of multidimensional VAM equipment. Elliptical VAM has received extensive attention since it was first proposed in the 1990s. Although this process has many advantages compared to its 1D counterpart in terms of reductions in cutting force and prolongation of tool life, it requires higher performance in the vibrator, producing a more accurate tool tip trajectory [24–28]. Piezoelectric actuators with high sensitivity can fulfill the requirements of vibration devices and promote the development of elliptical VAM technology.

1.2 Vibration-Assisted Machining Process

This section briefly introduces commonly used VAM processes, including milling, drilling, turning, grinding, and polishing. Different vibration device layouts are required to implement these vibration-assisted processes and to achieve advantages over the corresponding conventional machining processes.

1.2.1 Vibration-Assisted Milling

Milling is one of the most common machining processes and is capable of fabricating parts with complex 3D geometry. However, uncontrollable vibration problems during the cutting process are quite serious and can affect processing stability, especially in the micro-milling process, leading to excessive tolerance, increased surface roughness, and higher cost. Vibration-assisted milling is a processing method that combines the external excitation of periodic vibrations with the relative motion of the milling tool or workpiece to obtain better cutting performance. In addition to the same advantages as other VAM processes, complex surface microstructures can also be obtained because of the combination of a unique tool path and external vibration. Currently, the application of vibration-assisted milling mainly focuses on the one-dimensional direction. The vibration may be applied in the feed direction, cross-feed direction, or axial direction, and tool rotational vibrations may also be applied [14]. Little research has been carried out on 2D vibration-assisted milling because of the difficulty of developing two-dimensional vibration platforms (motion coupling and control difficulty), and the vibration mode of these 2D vibration devices mainly involves elliptical vibration and longitudinal torsional vibration.

1.2.2 Vibration-Assisted Drilling