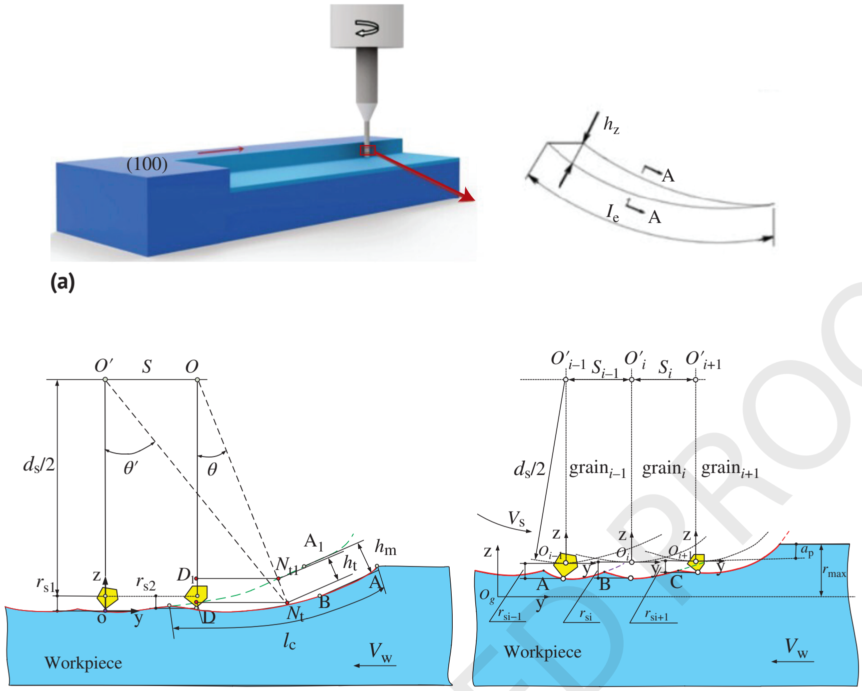

Figure 1.18 (a) Undeformed chip thickness and chip in surface grinding, and motion trajectories of (b) single abrasive particle and (c) multi-abrasive particles.

two consecutive cutting edges L, the number of cutting edges per unit wheel area C, the average effective cutting width per edge b_c, the contact arc length l_c, the average undeformed chip thickness h_a, the grinding depth a_p, the spindle speed v_s, the feed rate v_w, and the grinding rod diameter d_s. Contact arc length between grinding wheel and workpiece [112]:

$$l_c = \frac{d_s\theta}{2} = \frac{d_s \arccos\left(1 - \frac{2a_p}{d_s}\right)}{2} \tag{1.3}$$

In traditional macroscale grinding, $2a_p << d_s$. For microscale grinding, it is essential to account for the influence of size effects. The quantity of chips produced per unit of time during the grinding process of the rod is determined by the product of the volume of each chip and the MRR of the rod and the h_m can be obtained as:

$$h_m = \left[\frac{4}{Cr}\left(\frac{v_w}{v_s}\right)\left(\frac{a_p}{d_s}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}} \tag{1.4}$$

In traditional conventional-size grinding, the diameter of micro-grinding rods is typically less than 1 mm, with some micrometer-level rods developed internationally.

In microscale grinding, the grinding mechanism significantly differs from that of conventional grinding. During the process, the contact arc length between the grinding rod and the workpiece is reduced, often approaching the same order of magnitude as the maximum undeformed cutting thickness of the abrasive grains. Therefore, when modelling the maximum undeformed cutting thickness for micro-grinding, it is crucial to consider the influence of the size effect. In the micro-grinding process, where h_m is nearly equal to l_m, as illustrated in Figure 1.18, the maximum undeformed cutting thickness for microscale grinding is:

$$h_m = \frac{2a_p v_w}{KC \cdot v_s b_c d_s \arccos\left(1 - \frac{2a_p}{d_s}\right)} \tag{1.5}$$

1.4.2 Characteristics and Challenges of Micro-grinding Process

Micro-grinding achieves high machining accuracy and excellent surface quality for micro-parts or structures through micro–nano mechanical removal on the workpiece surface using micro-abrasive tools with ultrafine abrasive particles. These micro-abrasive tools are generally classified into ultrathin grinding discs with a grinding section thickness of less than 1 mm and micro-abrasive rods with diameters under 1 mm.

Due to the significant reduction in the diameter of these micro-abrasive tools, factors typically negligible in conventional grinding, such as grinding wheel deformation and ploughing forces, have a substantial impact on the micro-grinding process and cannot be ignored. Additionally, in micro-grinding, the grinding depth of the abrasive particles often falls below the grain size of the workpiece material, resulting in size effects and microstructure recrystallization that significantly alter the material removal mechanism. Consequently, the micro-grinding mechanism differs markedly from that of traditional grinding, as summarized in the comparison of conventional and micro-grinding in Table 1.5.

Therefore, the mechanisms underlying micro-grinding processes are markedly distinct from those of traditional grinding. The comparison of highlighting key differences and characteristics between conventional and micro-grinding processes is emphasized in Table 1.5.

Table 1.5 Comparisons of micro-grinding and conventional grinding processes.

Content	Conventional grinding	Micro-grinding
Ratio of grinding radius to grinding depth	50~100	0.1~1
Plough effect	Not significant	Significant (20–30%)
Front rake angle	Constant negative	Variable negative
Feed rate (v_w)	1~30 m/min	0.000045~0.18 m/min
Cutting speed (v_s)	20~60 m/s	0.018~6 m/s
Material removal rate	10^2~10^{-1} $mm^3/mm \cdot s$	10^{-1}~10^{-3} $mm^3/mm \cdot s$

Micro-grinding can produce micro-parts and components with high dimensional accuracy and surface quality. It is a common choice for final finishing and can handle a wide range of materials, including hard and brittle substances like glass and ceramics, which are difficult to machine by traditional cutting methods. Microscale grinding can yield excellent results and is an effective way to improve micromachining quality. It typically uses small-sized grinding tools and processes the workpiece at a specific linear speed via a high-speed spindle.

Compared to micro-milling, research on micro-grinding started relatively late. Despite growing interest and progress, it remains an area with limited research. Brittle materials, which are prone to fracture under mechanical stress, are often machined by grinding. Achieving a transition to a ductile mode of removal can significantly improve machining quality. The current research progress of various scholars on micro-grinding is as follows:

Cheng et al. [35] conducted micro-grinding experiments on soda-lime glass to explore the material removal mechanism in brittle materials. They proposed a predictive model for brittle material removal in micro-grinding, considering size effects and abrasive tool surface topography. Based on the undeformed chip thickness, they classified the removal mechanisms into ductile, ductile-brittle transition, and brittle removal. Chip-type experiments showed that the edge chipping length varies significantly with the undeformed chip thickness. Coolant was found to be essential for ductile removal in soda-lime glass micro-grinding. The critical chip thicknesses for ductile-brittle transitions were determined to be 2 and 5 nm, respectively, and this was validated through grinding force variations.

Park [36] studied the influence of material grain structure, integrating thermal-mechanical coupling and size effects, to develop an interaction model for single-abrasive-grain removal at the microscale. This model incorporated a heat-transfer analysis based on a moving heat source to predict micro-grinding forces. By combining plowing and friction effects, the model evaluated the thermal influences on micro-grinding forces. Experimental calibration of heat distribution in the workpiece, using thermocouples and analytical calculations, confirmed the model's accuracy. Sensitivity analysis highlighted micro-grinding wheel and grain size as key influencing factors.

Wen et al. [32] systematically investigated the thermal characteristics of micro-grinding forces, surface roughness, and tool wear using electroplated micro-grinding tools. They established a mathematical model relating grinding forces to surface roughness and validated it against experimental data. FE simulations and thermocouple methods were used to analyze the workpiece temperature distribution during micro-grinding. Incorporating factors such as the minimum chip thickness and size effect, they created a model for the microscopic wear of grinding grains and studied the relationship between tool wear and workpiece surface roughness.

To improve micro-grinding performance, researchers have incorporated ultrasonic vibration-assisted technology into micro-grinding processes. Zhang et al. [18] conducted theoretical and experimental studies on ultrasonic vibration-assisted face micro-grinding. They developed a theoretical model based on how ultrasonic vibration geometry affects the instantaneous cutting thickness of abrasive grains.

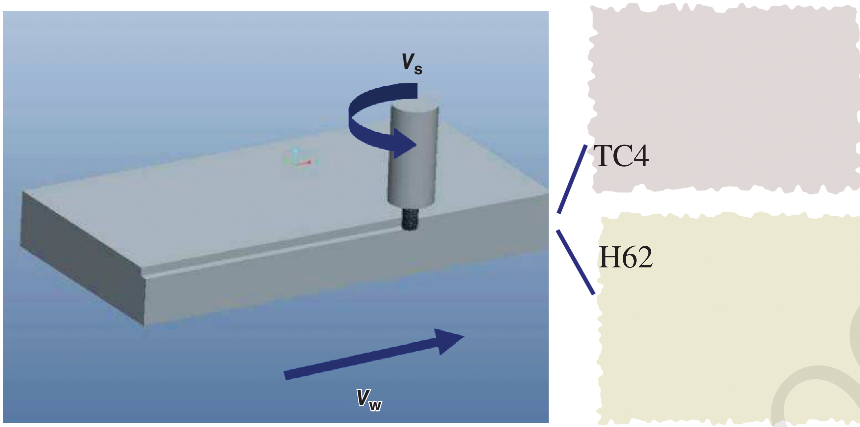

Figure 1.19 Micro numerical control machine, micro-grinding tool, and micro-manufacturing feature of Northeastern University.

Experiments on quartz glass showed that ultrasonic assistance significantly reduced grinding forces and enabled ductile-mode machining, improving surface quality. Moreover, the decrease in grinding forces expanded the range of grinding parameters, allowing the use of larger parameters to enhance processing efficiency.

Lubrication is crucial in grinding as it reduces friction, lowers processing temperatures, and improves both grinding performance and abrasive lifespan.

Dull abrasives significantly reduce grinding performance. While dressing dull grinding wheels is relatively easy in conventional grinding, the small size and fine abrasives of micro-grinding tools make dressing more challenging. Feng et al. [17] investigated the micro-grinding of ceramic end-faces and examined how tool wear and stiffness affect grinding forces, system vibration, acoustic emission signals, and spindle load. They introduced a tool-wear monitoring approach that combines grinding force and system vibration signals and validated its feasibility under various processing conditions. Although the study focused on ceramics, challenges remain due to the low stiffness of micro-tools and the high grinding forces required for hard, brittle materials.

Gong et al. [14] developed a micro-grinding machine and produced micro-feature components, as shown in Figure 1.19, while analyzing how different parameters affect the surface quality of TC4 and H62 in micro-grinding.

1.5 Contents of this book

The main contents of this book are as follows:

Part I: A brief description of grinding technology (including conventional and micro-grinding) for single-crystal nickel alloys is provided. Particularly, the development of understanding in grinding mechanisms, grinding characteristics, grinding process simulation, and control for single-crystal nickel alloys is analyzed, and some crucial issues in high-efficiency and high-quality grinding of single-crystal nickel alloys are provided and need more attention. In addition, the grinding mechanism of single-crystal nickel alloy, both in conventional and micro-grinding, is presented by means of FEM and theoretical analysis. These contents provide a foundation for an in-depth understanding of the following analysis on the grindability of single-crystal nickel alloy.

Part II: This section evaluates the grinding characteristics of single-crystal nickel alloys comparatively and comprehensively, in terms of grinding force, temperature, and grinding wheel wear behavior in both conventional and micro-grinding processes. The massive data on such aspects is valuable and could be used for optimization and further control of single-crystal nickel alloy grinding.

Part III: The surface integrity of single-crystal nickel alloy in conventional grinding (i.e., surface grinding and profile grinding) is examined both at micro- and nano-scales. Many indicators of surface integrity, such as grinding surface topography, surface roughness, microhardness, subsurface microstructure, residual stresses, and even fretting behavior, are assessed in detail.

Part IV: The micro-grinding-induced surface integrity of single-crystal nickel alloy is studied. In particular, the effects of micro-grinding parameters on surface integrity indicators (i.e., surface roughness, surface topography, subsurface damage, recrystallization, and so on) are analyzed comprehensively and deeply.

Part V: This section develops the simulation and theoretical models for predicting the grinding temperature and residual stresses in profile grinding of single-crystal nickel alloy components. The obtained results agree well with the experimental ones, indicating the feasibility of the present models to be used for optimization and controlling the grinding process of the single-crystal nickel alloy component with complex shape/structure.

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