Molecular dynamics simulations of scratching characteristics in vibration-assisted nano-scratch of single-crystal silicon

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ABSTRACT

Vibration-assisted grinding improves machining quality and efficiency over conventional grinding, whereas its atomistic mechanism remains unclear. In this study, we investigated vibration-assisted machining using molecular dynamics simulations of the nano-scratching process by considering single-crystal silicon as the paradigm material. Vibration dynamically redistributes and rebalances the existing anisotropy among the applied forces, thereby leading to unique scratch characteristics including homogeneous deformation. Vibration reduces the tangential and normal force components and effectively suppresses the anisotropic stress state, resulting in a reduction of the amorphous-layer thickness and enlargement of the scratched surface area. The magnitudes of the tangential and normal components vary cyclically with a frequency that is twice that of the applied vibration. Furthermore, when the frequency increases, the tangential and normal components and amorphous-layer thickness decrease gradually, opposite to the scratched surface area. In addition, as the vibration amplitude increases, the tangential and normal components decrease, in contrast with the behaviour of the amorphous layer, which thins gradually and then slightly increased to a constant thickness. Vibration-assisted scratch effectively turns the brittle material at the working spot into a ductile material. Thus, our atomistic insights suggest a new route for optimization of vibration-assisted grinding processes.

1. Introduction

In recent decades, vibration-assisted grinding has been applied to conventional grinding via vibrations at a particular frequency and amplitude for the processing of hard and brittle materials [1–2], such as Si, Al 2 O 3 and SiC. Given that silicon is an important semiconductor material and is widely used in the optoelectronic precision engineering and electronic devices [3–6], single-crystal silicon is used as the paradigm material in this study. Several vibration-assisted grinding studies indicated that the application of vibration to conventional grinding can reduce grinding force, surface roughness and grinding temperature, and it can improve the material removal rate [7–11]. However, the interactive mechanism between the abrasive grains and workpiece in vibration-assisted grinding is complex and remains unclear. The pursuit of further mechanistic insights is hampered by the limitations of experimental technologies and the potentially high cost involved in conducting such studies.

The essence of grinding, as a comprehensive process, involves spreading a large quantity of abrasive grains on the surface of the grinding wheel. The grains slide, plow and cut on the workpiece surface, as revealed in a scratch experiment involving a single abrasive grain. Similarly, a vibration-assisted scratch experiment involving a single abrasive grain can be used to study the mechanism of vibration-assisted grinding. Zhang compared the deformation behaviors of sapphire in conventional and vibration-assisted scratches [12]. It was determined that vibration-assisted scratch can effectively inhibit the expansion of scratch micro-cracks and increase the plastic removal ratio and can simultaneously shift the residual stress distribution from tensile stress to...
compressive stress with increasing in scratching depth. A vibration-assisted scratch experiment on SiC ceramic was conducted and found that the critical cutting depth of the brittle–plastic transition increased with the application of vibration [13]. Yang performed a vibration-assisted scratch experiment on ZrO2 ceramic and observed that the scratch force decreased with increasing vibration amplitude [14]. In a scratch experiment on reactive sintered SiC, Zheng found that the application of vibration reduced the scratch force and significantly increased the material removal rate [15]. Li revealed the formation mechanism of damage due to vibration-assisted grinding via nano-scratch experiments at various depths [16]. The aforementioned studies indicate that the vibration-assisted grinding mechanism can be revealed to some extent by conducting vibration-assisted scratch experiments. However, it is difficult to understand the relationships between scratching process parameters, vibration variants and machine quality and efficiency solely based on vibration-assisted scratch experiments.

With the rapid development in computational technology, various simulating tools for machining processes have emerged. Recently, molecular dynamics (MD) methods, used for simulating the nano-scratch process for a single abrasive grain based on atomic-level insights, have been effective in studying the mechanism of ultra-precision grinding and cutting [17–21]. Specifically, MD was used to study the distribution and evolution of the subsurface defect structure during nano-cutting of single-crystal copper [22]. In an MD study of the interaction between an abrasive grain and a workpiece in the scratching process, the temperature of the workpiece surface increased and the tangential force gradually decreased as the scratch speed was increased [23]. In MD simulation of the scratching process for single-crystal silicon, most of the surface damage, which was incurred in the process, was due to the amorphous silicon phase [24]. In MD simulation for the nano-cutting process of single-crystal silicon [25], phase transformation occurred during cutting, and amorphous structure was observed due to plastic deformation. Ren examined an ultra-high-speed scratch in single-crystal nickel via MD and determined that the appearance of dislocations and stacking faults were the main reasons for the recorded changes in scratch force [26, 27]. Li investigated a high-speed scratch of single-crystal copper in nanoscale diamond [28, 29] and observed that the cutting volume and workpiece temperature increased with increase in scratch speed, which in turn led to larger cutting-edge radius and greater cutting depth. However, it was found that these grinding parameters can be controlled and optimized by texture density, direction, and shape for improving the integrity and finish of the machined surface. Recently, in several additional studies, MD was used to study the vibration-assisted scratching process. The tangential force and normal force in vibration-assisted scratch single-crystal copper were much smaller than those in conventional scratch. So the wear of abrasive tip was less in vibration machining [30, 31]. Jun used MD to study vibration-assisted cutting of aluminium and observed that vibration can effectively reduce the cutting force and improve the machining surface [32]. The process of vibration-assisted cutting of a diamond tool was simulated, and it was determined that the cutting force of the tool periodically changed owing to the vibration, thereby reducing tool wear [33, 34]. Furthermore, MD simulation of vibration-assisted scratch was used to study the mechanism of material removal at atomic level during the chemical and mechanical polishing of SiC with the assistance of ultrasonic vibration [35]. Vibration can significantly reduce the tangential and normal forces on the abrasive grain. These studies indicate that the forces in conventional scratches are concentrated in tangential and normal directions, and vibration-assisted scratch generates significant lateral force, which aids in rebalancing the force components in all three directions. However, the anisotropic behavior of the tangential, normal and lateral components of scratch force due to the vibration is still unclear. Furthermore, the effect of this anisotropy on scratch characteristics has not been examined.

In the present work, the vibration-assisted nano-scratch process of a single abrasive grain on single-crystal silicon is studied using MD simulations. The scratch force, micro-stress distribution, amorphous-layer thickness and scratched surface area are compared between conventional scratch and vibration-assisted scratch, and the vibration reduced anisotropic behavior of the three components of scratch force are analyzed, in association with the effects of vibration frequency and amplitude.

2. Molecular dynamic model and simulation setup

To study the effect of vibration on the scratching process for single-crystal silicon, MD simulations of vibration-assisted scratch were conducted. All the MD simulations in this study were performed using a large-scale atomic/molecular parallel simulator [36].

First, the model for a single abrasive grain scratch was established, as shown in Fig. 1. The workpiece was made of single-crystal silicon whose dimensions were 30 nm × 30 nm × 15 nm and was comprised 677,738 atoms. Then, the atoms in the workpiece were divided into three regions: the boundary atoms, thermostat atoms and Newton atoms. The motion of thermostat atoms and Newton atoms followed classical Newtonian mechanics, as described by a combination of Newton’s equations of motion and the Velocity Verlet algorithm. In the MD simulation, the thermostat atoms were maintained at a constant temperature of 293 K via the method of velocity rescaling [37]. The atoms in the boundary layer remained stationary during the entire time to reduce the boundary effect by zeroing the velocity and displacement of these atoms, thereby ensuring the symmetry of the crystal lattice. The abrasive grain is modeled as a hemisphere capping a cylinder of equal radius with perfect diamond atoms. This model is based on the fact that nanoscale abrasive grains are approximately spheres and just a part lower hemisphere surface contacts with the workpiece surface in the process. This model has been extensively used in literature [38, 39]. Here the radii of the hemisphere and the cylinder were 4 nm and height of the cylinder was 4 nm, containing a total number of 34,593 atoms. In the
3. Results and discussion

3.1. Comparison of scratch characteristics in conventional and vibration-assisted scratching processes

3.1.1. Comparison of scratch force and work

Given that the scratch force is an important parameter in scratching process, the tangential (X-direction), lateral (Y-direction) and normal (Z-direction) force components in the conventional and vibration-assisted scratch were computed at every scratch distance interval of 0.5 nm. The results are shown in Fig. 4(a-c), where the vibration frequency and amplitude were set to be 16.67 GHz and 3 nm, respectively, in the vibration-assisted scratch. The total force was calculated using the force components and is shown in Fig. 4(d).

In the first stage of scratching with scratch distance in the range of 0–3 nm, the scratch force increased linearly with distance, and the workpiece deformed elastically, and no significant material removal was observed. However, in the second stage, the material removal rate gradually increased as the scratch distance increased.

With the increase in scratch distance, the tangential force initially increased rapidly and then slowed down, while the normal force increased steadily. The total force also showed a similar trend.

In the third stage, when the material was worn, the amplitude of the variation in the total force decreased, and the force became more stable. The workpiece was deformed plastically, and material removal occurred.

In summary, the results of the simulations showed that the scratching process can be divided into three stages: elastic deformation, plastic deformation, and material removal.
observed. When the scratch distance increased from 3 to 6 nm, the scratch force increased non-linearly and the workpiece was subjected to plastic deformation. After the scratch distance exceeded 6 nm, the scratching process became stable and the scratch forces slightly increased in the conventional scratch, while the forces fluctuated periodically with the vibration of the abrasive grain in the vibration-assisted scratch. To further understand the relation between the fluctuation period of the scratch force and vibration period of the abrasive grain, the five key points (A, B, C, D and E in Fig. 1 (a)) corresponding to one complete cycle in the abrasive grain trajectory were marked in Fig. 4. It was found that when the abrasive grain vibrated for one cycle, the tangential and normal force components fluctuated for two cycles, while the lateral force component fluctuated for one cycle. The results also indicated that the scratch force was concentrated in tangential and normal directions during the conventional scratch, while it was redistributed and balanced in the vibration-assisted scratch.

To further clarify the force redistribution, the scratch force and its components within the scratch distance of 6–18 nm were averaged, as shown in Fig. 5(a). The symbol of the lateral force denoted the direction. The lateral force component is an average over the absolute values for ease of comparing the magnitude. The results indicated that the averaged tangential and normal force components in the vibration-assisted scratch were lower than that in the conventional scratch, while the average lateral force was higher than that for the conventional scratch. An anisotropic factor ($\eta$) was defined to describe the inhomogeneity of forces in three directions:

$$\eta = \frac{|F_t| - \overline{F_t}| + |F_l| - \overline{F_l}| + |F_n| - \overline{F_n}|}{3\overline{F}}$$

where $\overline{F}$ is the averaged value of the force components: $(F_t + F_l + F_n)/3$. Furthermore, $F_t$, $F_l$ and $F_n$ denote the tangential, lateral and normal force components.
components, respectively, which are calculated at every 0.5 nm scratch distance. Fig. 5 (b) showed that the anisotropic response in the conventional scratch was significantly larger than that in the vibration-assisted scratch. Simultaneously, the conventional $\eta$ varied in a relatively stable manner, while it fluctuated with the movement of the abrasive grain in the vibration-assisted scratch. These results indicated that vibration-assisted scratch effectively suppressed the anisotropic stress state. Furthermore, the anisotropic features significantly affect the thickness of the amorphous layer and scratching efficiency, as discussed in later subsections.

Since the work is an important factor in determining the energy consumption in the scratching process, cumulative work $W$ was calculated using $W = \int F \cdot du$, where $F$ is the total scratch force at the scratch displacement $u$ during scratching. Then, the relations between $W$ and scratch distance (i.e., the tangential component of the displacement $u$) in the conventional and vibration-assisted scratch were provided in Fig. 6. It was found that the work done in the vibration-assisted scratch was greater than that in the conventional scratch. When the vibration was applied, the velocity of the abrasive grain was higher and the impact of the abrasive grain was strengthened because of the increase of the vibration trajectory. As a result, more atoms were displaced greatly. The workpiece atoms have obvious splash, which made the work done larger and the scratched surface larger. Simultaneously, as the scratch distance increased, $W$ increased gradually in the conventional scratch, while it increased in a fluctuating manner in the vibration-assisted scratch. The results indicate that the introduction of vibration significantly increases energy consumption in the scratching process.

3.1.2. Comparison of effective equivalent stress distribution and atomic displacement

As local stress in workpiece can reveal the scratch characteristics, which in turn leads to a further understanding of deformation mechanism during machining, the local effective equivalent stress and its distribution on the scratched surface of the workpiece in the conventional and vibration-assisted scratching processes were calculated and compared in Fig. 7.

To further examine the displacement of atoms on the scratched surface, the top-view and perspective-view displacement of atoms at the key points (A, B, C, D and E) in the conventional and vibration-assisted scratch were compared in Fig. 7.

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**Fig. 6.** The workdone to the system during the vibration-assisted scratch (red line) as a function of scratch distance, compared to that of conventional scratch (blue dashed line).

**Fig. 7.** Comparison of the local effective equivalent stress distribution, atomic displacement on the scratched surface (top-view) and in the amorphous region of the workpiece (perspective-view) at the key points (A, B, C, D and E) in the conventional and vibration-assisted scratch, where the red box was marked as the scratched surface area and different colors along the Y-direction, the thickness of each colored layer was 2 nm. (1: light blue layer, 2: pink layer, 3: orange layer, 4: purple layer).
surface during the nano-scratch, four different areas were marked with different colors along the Y-direction, and the thickness of each colored layer was 2 nm, as shown in Fig. 7. Because of the symmetry of abrasive trajectory, the color setting also presented symmetry. Then the Y-direction displacement of atoms in different colored layers was calculated to analyze the relationship between atomic displacement and lattice constant (0.543 nm). The atoms number in different multiples of the lattice constant was calculated for each marked layer and compared between conventional scratch and vibration-assisted scratch, as shown in Fig. 8.

In the conventional scratching process, as shown in Fig. 7(a) and Fig. 8(a), the region of local stress concentration on the workpiece surface was located in front of the abrasive grain with a crescent shape and moved forward in a straight manner along the tangential direction during scratching. The stress magnitude and shape approximately remained constant. Although, the atoms were gradually squeezed forward, the atoms layered boundary was clear and the displacements of the atoms in the Y-direction were 2.72 nm smaller. However, in the vibration-assisted scratch, as shown in Fig. 7(b) and Fig. 8(b), owing to the continuous change of the abrasive grain trajectory direction, the stress concentration region on the surface changed continuously during scratching and this concentration region was smaller than the conventional one. The Y-direction displacement of the atoms near the abrasive grain (layer 1 and 2) increased significantly, the maximum displacement was more than 8 times of the lattice constant, which was much larger than the atomic lattice constant, and the scratched area on the workpiece surface was larger. Given that the abrasive grain moved in the form of a sinusoidal curve in the vibration-assisted scratch, the length of the abrasive grain trajectory was longer than that of the conventional scratch. Therefore, the anisotropy of the atomic movement was enhanced, and the accumulation of atoms on both sides of the groove increased more rapidly, which in turn enabled removal of surface materials with greater ease. The removal of surface materials was associated with the reduction in the tangential force and normal force and the region of stress concentration on the scratched surface. Therefore, the implement of vibration can change the stress state, which may affect the

Fig. 8. The frequency of atoms number in the interval of different multiples of the lattice constant: (a) conventional scratch and (b) vibration-assisted scratch (1: light blue layer, 2: pink layer, 3: orange layer, 4: purple layer).
formation of amorphous layer and damage. This conjecture will be further analyzed in the following subsections.

3.1.3. Comparison of amorphous-layer thickness and scratched surface area

During the scratching process, the amorphous layer is produced in the workpiece under the abrasive grain wherein the atom is inconsistent with the perfect lattice structure of the crystal in the workpiece. The features of the amorphous layer, such as thickness and surface area, significantly affect the quality and efficiency of scratching. In this study, the amorphous-layer thickness was defined as the normal distance between the surface and the deepest non-diamond-structured Si atom, which is determined via identifying diamond structure algorithm under the abrasive grain in the workpiece. Furthermore, the scratched surface area was estimated by the amorphous layer volume with respect to its thickness, wherein the volume of the amorphous layer was determined via the summation of volume of all amorphous atoms in the workpiece. To clearly analyze the formation of debris and scratched surfaces, different regions were marked with different colors along the Z-direction to track the movement trajectories of atoms.

The amorphous-layer thickness, scratched surface area and atomic displacement along Z-direction were shown in Fig. 9, where the amorphous-layer thickness values were marked in the Fig. 9(c). The scratched surface was composed of atoms in different regions. The atoms moved under the action of shear and extrusion of the abrasive grain. The atomic layer in the shear slip zone formed a shear slip, which was stacked in front of the abrasive grain and finally removed as debris. The atoms below the abrasive grain did not move considerably. In the conventional scratch, the atoms in the contact area between the workpiece and the abrasive grain were extruded firstly. The extrusion deformation area was formed in the front and bottom of the abrasive grain. With the movement of the abrasive grain, the contact area increased gradually. The extrusion deformation area below became larger. The thickness of the amorphous layer increased gradually. This indicated that the number of removed atoms, and the thickness of the amorphous layer. As a result, the vibration-assisted scratch removed more material with less damage at the same scratch distance when compared with those of the conventional scratch. Thus, both scratch efficiency and quality of vibration-assisted scratch were improved over conventional ones.

3.2. Effects of vibration parameters on scratch characteristics

3.2.1. Effect of vibration amplitude

Vibration amplitude is an important vibration parameter that affects the scratching process. To study the effect of the vibration amplitude, various vibration amplitudes (0 [i.e., conventional scratch], 1, 2, 3, 4 and 5 nm) were selected at scratch speed (100 m/s), scratch depth (4 nm) and vibration frequency (16.67 GHz).

The scratch force components were computed at every 0.5 nm scratch distance and averaged in the range of 6.0–15.0 nm, as shown in
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Fig. 10. Effect of vibration amplitude from 0 to 5 nm. (a) Tangential force, (b) Lateral force (c) Normal force trend as a function of scratch distance. (d) The three scratch forces average as well as anisotropic factor profile as a function of the vibration amplitude. (e) The work profile as function of scratch distance at various vibration amplitudes. (f) The cumulative work at 15.0 nm as a function of vibration amplitude.

Fig. 11. Effect of vibration amplitude on the amorphous-layer thickness and scratched surface area at 15 nm.

Fig. 10 (a-d). As the vibration amplitude increased, the scratched area increased, with displacement and speed in the lateral direction and the fluctuation range the scratch force increased, thereby leading to a significant impact. Therefore, the atoms were easier to remove with the given amplitude. The tangential and normal force components gradually decreased, and the lateral force components initially increased to a stable level, while the anisotropy factor \( \eta \) decreased and then increased. At an amplitude of zero, \( \eta \) was at its maximum value, which implied that the force components were unbalanced to the maximum level in the conventional scratch. When the amplitude was 3 nm, \( \eta \) reached its minimum value, thereby indicating maximum homogeneity among the force components in the three directions.

The relation between the work and scratch distance was shown in Fig. 10(e). The work increased gradually with respect to scratching, and the fluctuation of work increased slightly with increase in amplitude. When scratching at 15 nm, the cumulative work was calculated as shown in Fig. 10(f). As the amplitude increased, the cumulative work increased and tended to be stable after about approximately 3 nm.

The amorphous-layer thickness and scratched surface area at various amplitudes were compared and shown in Fig. 11. As the vibration amplitude increased, the width of the groove increased, and the side flow formed by the removed atoms became more evident, thus gradually increasing the scratched surface area. The thickness of the amorphous layer decreased initially and then slightly increased to a stable value. However, when the amplitude was greater than 3 nm, the abrasive grain moved faster per unit time. This temporal shortening indicated that the abrasive grain can reach the next position before the material is formed a stable amorphous structure. Therefore, at these high amplitudes, the number of removed atoms reached a peak, the amorphous-layer
thickness tended to be stable and the amplitude had slight effect on material removal or surface quality. By considering all the evaluation indexes, when the amplitude is 3 nm, the anisotropy factor was the smallest, the scratch force distribution in three directions is the most uniform. The thickness of amorphous layer was relatively small. The scratched area was relatively large. Therefore, the vibration amplitude of 3 nm has the optimal performance in this study.

3.2.2. Effect of vibration frequency

Frequency is another important vibration parameter. In the previous section, higher machining quality and efficiency were realized at an amplitude of 3 nm. Therefore, different vibration frequencies (0, 4.17, 8.33, 16.67, 33.33 and 66.67 GHz) were selected to study the influence of frequency under the conditions of constant scratch speed (100 m/s), scratch depth (4 nm) and amplitude (3 nm).

The scratch force components were computed at every 0.5 nm scratch distance and averaged within 6.0–15.0 nm, as shown in Fig. 12(a-d). When the frequency increased, the trajectory became denser, overlapping area was larger, and the scratch force fluctuated more violently. Given that some of the workpiece atoms in front of the abrasive grain were already in a broken state, the accumulation and obstruction of the workpiece atoms were reduced in the direction of abrasive grain movement. Thus, the scratch force required to remove workpiece atoms was reduced. Therefore, the tangential and normal force components significantly decreased, while the lateral force component increased and then gradually decreased. The anisotropic factor $\eta$ decreased and then increased with increasing frequency. At a frequency of zero (i.e., conventional scratch), $\eta$ corresponded to its maximum value, thereby indicating maximum inhomogeneity of force

Fig. 12. Effect of vibration frequency from 0 to 66.67 GHz. (a) Tangential force, (b) Lateral force (c) Normal force trend as a function of scratch distance. (d) The three scratch forces average as well as anisotropic factor profile as a function of the vibration frequency. (e) The work profile as function of scratch distance at various frequencies. (f) The cumulative work at 15.0 nm as a function of vibration frequency.

Fig. 13. The variation of amorphous-layer thickness and scratched surface area at 15 nm with respect to vibration frequency.
distribution in all three directions. At a frequency of 8.33 GHz, \( \eta \) corresponded to its minimum value, thereby indicating maximum homogeneity of force components in all three directions.

By comparing the work during the scratching process and calculating the cumulative work of the abrasive grain at 15 nm at different frequencies, the results were as shown in Fig. 12 (e-f). When the frequency increased from 0 to 16.67 GHz, the number of fluctuations in the work gradually increased, and the work performed by the abrasive grain gradually increased. At a frequency of 16.67 GHz, the work corresponded to its maximum value, and then gradually decreased. The results indicated that repeated scratch reduced the obstruction of abrasive grain in the direction of movement to a certain extent.

The amorphous-layer thickness and scratched surface area at various frequencies were compared and shown in Fig. 13. As the frequency increased, the amorphous-layer thickness decreased to a stable value, while the scratched surface area increased. Considering all the scratch characteristics, when the abrasive grain frequency corresponded to 33.33 GHz, the anisotropic factor and work were relatively small and the amorphous thickness corresponded to its minimum value. This indicated a favorable impact of machining with low energy consumption. Hence, a frequency of 33.33 GHz can be considered as the optimize choice.

4. Conclusions

We have simulated vibration-assisted scratch of a single abrasive grain on a single crystal silicon by means of molecular dynamics simulations. The scratch force, micro-stress distributions, and amorphous-layer thicknesses have been compared with that of conventional (non-vibration) scratch. The effects of vibration frequency and amplitude are further analyzed. The conclusions are summarized as follows:

(a) For the conventional scratching process, the scratch force components were concentrated in the tangential and normal directions. Conversely, for the vibration-assisted scratching process, the force components were balanced in all three directions. Furthermore, the scratch force fluctuated periodically, and the vibration period of lateral force matched the period of the applied vibration. Conversely, the periods of the tangential and normal forces were half that of the applied vibration. Moreover, the tangential and normal forces were significantly lower for the vibration-assisted scratch than for the conventional scratch.

(b) For a vibration-assisted scratch, the micro-stress distribution and the amorphous-layer thickness fluctuated periodically with the vibration of the abrasive grain. The amorphous layer was thinner for vibration-assisted scratch when compared to that for conventional scratch. However, the scratched surface area increased. The vibration-assisted scratch effectively suppressed the anisotropic stress state, facilitated homogeneous deformation, and improved machining efficiency.

(c) With increasing vibration frequency, the tangential and normal forces and thickness of the amorphous layer decreased gradually. The scratched surface area gradually increased. The lateral force initially increased and then decreased. The anisotropy factor \( \eta \) initially decreased and then increased. With increasing amplitude, the tangential and normal forces decreased. Conversely, the lateral force initially increased and then remained stable. The amorphous-layer thickness initially decreased, then slightly increased, and finally became stable, while the anisotropy factor \( \eta \) initially decreased and then slightly increased.

(d) The vibration-assisted scratching process effectively suppresses the anisotropic deformation during the facile machining of brittle materials. Overall, the machining effect was observed at its maximum level at a vibration frequency of 33.33 GHz and an amplitude of 3 nm.

Our atomistic simulations revealed that vibration-assisted scratching effectively turns the brittle material at the working spot into a ductile material. The efficiency is tunable via vibration parameters. These findings represent an optimal combination of vibration frequency and amplitude, and thereby suggest superior machining quality and efficiency in vibration-assisted grinding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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