Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-12-0108

Improving the machinability of brittle materials by ion implantation

Jinshi Wang[1], Fengzhou Fang[1,2,#] and Xiaodong Zhang[1]
1 State Key Laboratory of Precision Measuring Technology and Instruments, Laboratory of Micro/Nano Manufacturing Technology (MNMT), Tianjin University, Tianjin, 300072, China
2 Centre of Micro/Nano Manufacturing Technology (MNMT-Dublin), University College Dublin, Dublin 4, Ireland
Corresponding Author / Email: fzfang@tju.edu.cn, TEL: +86-022-27407503

KEYWORDS: Diamond cutting, Brittle materials, Ion implantation, Surface modification

Brittle materials find extensive applications in modern optical systems and precision engineering. Compared with traditional machining methods such as grinding and polishing, ultra-precision diamond cutting has the advantages of large efficiency and generating complex surfaces. However, the fracture damage and tool wear are critical issues that seriously influence the surface integrity. This paper presents a method improving the machinability of brittle materials via ion implantation, which can enhance the ductility and reduce the mechanical strength of the workpiece. The principle is introduced at first, then, the effect of surface modification on the material removal process during nanometric cutting is investigated by molecular dynamics simulation. Finally, several experimental examples on both single crystals and ceramics are provided to demonstrate the capability of the proposed method.

NOMENCLATURE

BDT = brittle-to-ductile transition
UCT = undeformed chip thickness
NiIM = nanometric machining of ion-implanted materials
MD = molecular dynamics

1. Introduction

Brittle materials find extensive applications in modern optical systems and precision engineering. Compared with traditional machining methods such as grinding and polishing, ultra-precision diamond cutting has the advantages of large efficiency and generating complex surfaces. However, fracture damage and tool wear are critical issues that seriously influence the surface integrity. It has been discovered in 1950s that plastic deformation could happen on brittle materials at small scale [1], and indentation test was conducted to investigate the critical depth of brittle-to-ductile transition (BDT) to optimize grinding process [2]. For diamond cutting, hydrostatic pressure near the tool edge is critical to realize a ductile-regime material removal, accompanied with phase transformation or dislocation activity [3]. This is the result of the non-neglectable edge geometry which induces strong size effect and distinctive cutting mechanism different from the classical shearing theory [4, 5].

However, the BDT depths for most brittle materials are at nanoscale. This restricts the undeformed chip thickness (UCT) within the nanoscale as well, because brittle fracture would happen when UCT becomes larger than BDT depth. As a result, the tool feed is slow and cutting distance is very long in the diamond turning process, in order prevent the machined surface from being damaged [6]. This significantly reduces the efficiency and, for those materials with great hardness, intensifies the tool wear which in turn deteriorates the surface quality. In this paper, a novel method named as nanometric machining of ion-implanted materials (NiIM) is introduced to solve the issue above. As shown in Fig. 1, this method uses ion beam to irradiate the workpiece surface prior to the mechanical process. Then, a modified layer is formed which can reduce the surface brittleness and hardness. NiIM was first reported in 2011 where 10 MeV fluorine

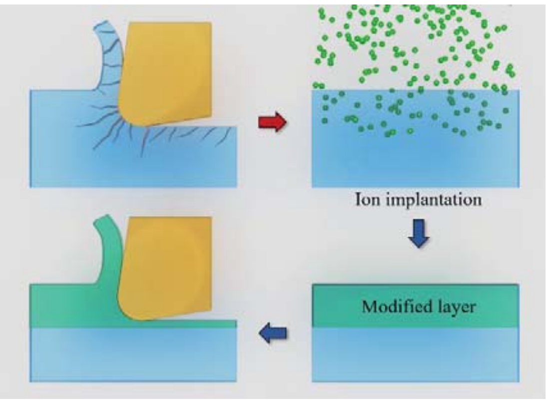

Fig. 1 Schematic illustration of the NiIM principle

ions were implanted into silicon and improvement in the machinability was confirmed [7]. Since then, it has been applied on various brittle materials including optical crystals [**Error! Reference source not found.**-10] and ceramics. In the following sections, the work conducted by the authors will be presented to give a detail illustration of how the NiIM acts from both the molecular dynamics (MD) simulation and experimental results.

2. Theoretical analysis by MD

MD simulation is a widely used method to investigate the nanometric cutting and ion implantation processes from atomic perspectives. As shown in Fig. 2a, after the ion enters the target solid, it successively collides with lattice atoms and loses its energy. When the energy transported during the collision is large enough to displace a lattice atom, material defects (vacancy-interstitial pair) are generated along the trajectory. With the accumulation of implantation dosage, these simple defects evolve into complex and stable damages, and crystalline to amorphous transition occurs at last. This amorphous layer plays a critical role in NiIM. As shown in Fig. 2b and 2c, both the cutting forces and the stress intensity are obviously reduced after the implantation, which indicates an improvement in ductility and tool wear. It is also interesting to note that the subsurface damage could be alleviated, as more energy would be dissipated via plastic deformation enhanced by the amorphous layer.

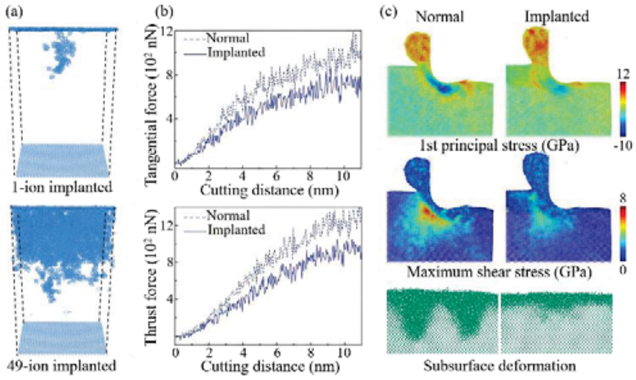

Fig. 2 MD simulation results on silicon [**Error! Reference source not found.**, 12]. (a) Lattice damage induced by 2 keV silicon implantation. (Only amorphous structures are visualized.) (b) Cutting forces. (UCT: 2.5 nm, edge radius: 5 nm, speed: 2 m/s) (c) Stress distribution and subsurface deformation. (UCT: 5 nm, edge radius: 5 nm, speed: 200 m/s)

3. Experimental validations

3.1 Applying NiIM on germanium and tungsten carbide

Two examples are provided in this section to show the effect of surface modification on single crystal and ceramics. The first is 3 MeV, 1×10^{16} cm^{-2} copper ion implantation into the germanium (100) surface. TEM observation reveals the formation of a 2.17 μm thick amorphous layer, which is identified by the electron diffraction pattern and has a clear boundary between the crystalline substrate (Fig. 3a). Taper cutting test shows a significant increase in the BDT depth from ~55 nm of normal germanium to at most 700 nm of implanted germanium, as shown in Fig. 3b. What's more, a strong influence of cutting speed occurs on the modified workpiece, where the BDT depth rapidly decreases when the tool moves faster. It is attributed by the enhanced hardness under high strain rate, which is reported in the study of nanoindentation on amorphous silicon [13]. Therefore, appropriately reducing the cutting speed is beneficial for a better surface quality.

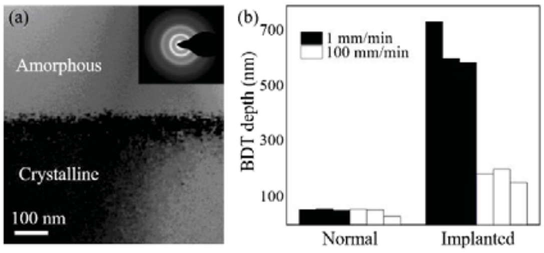

Fig. 3 Copper ion implantation into germanium [**Error! Reference source not found.**]. (a) TEM image of the crystalline-amorphous boundary. (b) BDT depths for two cutting speeds.

The other example is about the binderless tungsten carbide ceramics (RCCFN, Nippon Tungsten Co., Ltd.) with extreme hardness and brittleness. After 7 MeV, 6.4×10^{14} cm^{-2} gold ion implantation, intragranular amorphization happens, which reduces the hardness and elastic modulus from 28.6 GPa to 19.9 GPa and from 715.8 GPa to 535.3 GPa, respectively. As shown in Fig. 4, the seriously fractured surface of the cutting groove becomes much smoother after the implantation. In addition, curled chips covered with shear bands are found, which is the evidence of plastic deformation during the material removal. After 2 m cutting distance, the tool for the normal workpiece has a wear land of 3 μm width on the flank face, while there is no apparent wear on the tool cutting the implanted workpiece except for some chips adhering on the rake face.

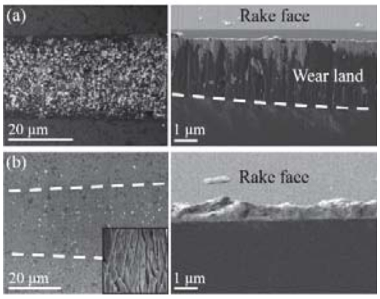

Fig. 4 Surface morphology and tool edge of diamond cutting on (a) normal and (b) implanted tungsten carbide [**Error! Reference source not found.**]. The inserted figure shows the chip surface.

3.2 Multi-implantation for higher efficiency

A thick amorphous layer (up to several microns) is usually expected to fit the depth of cut. However, this is a most time-consuming process as illustrated in Fig. 5a. As discussed before, large enough defect density, vacancy considered here, is necessary to completely disorder the lattice, but this density is not a uniform along the project range. Amorphization would first happen at the vacancy peak under the surface, then extend to the surface as the dosage increases. A uniform modified layer would not be formed until the topmost surface becomes amorphous. In other words, the dosage is determined by the minimum defect density if the implantation is conducted only one time. Therefore, we can use several density peaks locating at different depths to reduce the total dosage, and each of them represents a "sub-implantation". This also increases the flexibility of parameter design.

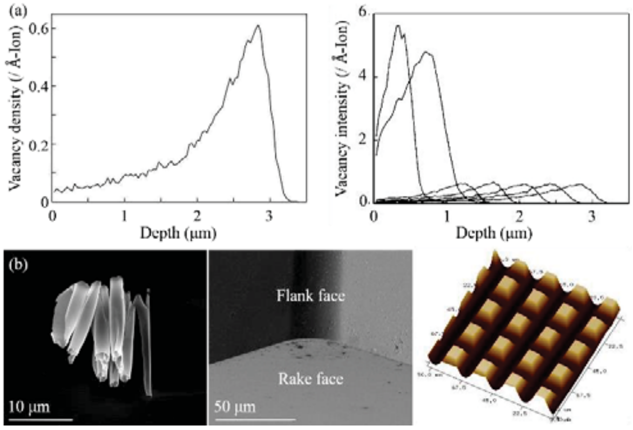

Fig. 5 Principle and experimental result of multi-implantation surface modification [**Error! Reference source not found.**]. (a) Defect distribution obtained by Monte Carlo simulation. (b) Chip morphology, tool edge and micro pillar array machined on modified silicon surface.

Using multi-implantation strategy, a 3 μm modified layer on silicon can be realized by seven-time implantations of silicon and gold ions, and the total dosage (2.9×10^{15} cm^{-2}) is reduced to only one-fifth of that for single implantation (1.47×10^{16} cm^{-2}) only by silicon ions. As in the case of tungsten carbide, the hardness and elastic modulus are reduced, the BDT depth is increased 11 times at most, and the chips exhibit remarkable plastic deformation, as shown in Fig. 5b. A micro structure array consisting of 17956 pillar elements is machined by fly-cutting. Ductile regime cutting is maintained during the process and the tool edge has no serious wear like cutting on normal silicon.

4. Conclusions

A novel method for improving the machinability of brittle materials by ion implantation surface modification is presented in this paper, including simulation study and experimental validation. The key of NiIM is to generate a modified (amorphous) layer which can significantly reduce the surface brittleness and tool wear. An advanced approach to higher efficiency by multi-implantation is also introduced. The results indicate the superiority of NiIM to be an effective way to realizing the high-precision machining of difficult-to-cut materials with nanometric surface finishing.

ACKNOWLEDGEMENT

This work was supported by the National key Research and Development Program of China (No. 91423101, 61635008) and the '111' project by the State Administration of Foreign Experts Affairs and the Ministry of Education of China (Grant No. B07014).

REFERENCES

1. R. F. King, D. Tabor. The strength properties and frictional behaviour of brittle solids, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 1954, 223(1153): 225–238.
2. T. G. Bifano, T. A. Dow, R. O. Scattergood. Ductile-regime grinding: a new technology for machining brittle materials, Journal of Engineering for Industry, 1991, 113(2): 184–189.
3. J. W. Yan, T. Asami, H. Harada, et al. Fundamental investigation of subsurface damage in single crystalline silicon caused by diamond machining, Precision Engineering, 2009, 33(4): 378–386.
4. F. Z. Fang, H. Wu, Y. Liu. Modelling and experimental investigation on nanometric cutting of monocrystalline silicon, International Journal of Machine Tools and Manufacture, 2005, 45(15): 1681–1686.
5. F. Z. Fang, M. Lai, J. S. Wang, et al. Nanometric cutting: mechanisms, practices and future perspectives, International Journal of Machine Tools and Manufacture, 2022, 178: 103905.
6. W. S. Blackley, R. O. Scattergood. Ductile-regime machining model for diamond turning of brittle materials, Precision Engineering, 1991, 13(2): 95–103.
7. F. Z. Fang, Y. Chen, X. Zhang, et al. Nanometric cutting of single crystal silicon surfaces modified by ion implantation, CIRP Annals - Manufacturing Technology, 2011, 60(1): 527–530.
8. S. To, H. Wang, E. V. Jelenkovic. Enhancement of the machinability of silicon by hydrogen ion implantation for ultra-precision micro-cutting, International Journal of Machine Tools and Manufacture, 2013, 74: 50–55.
9. H. Tanaka, S. Shimada. Damage-free machining of monocrystalline silicon carbide, CIRP Annals - Manufacturing Technology, 2013, 62(1): 55–58.
10. Z. W. Xu, L. Liu, Z. D. He, et al. Nanocutting mechanism of 6H-SiC investigated by scanning electron microscope online observation and stress-assisted and ion implant-assisted approaches, The International Journal of Advanced Manufacturing Technology, 2020, 106(9–10): 3869–3880.
11. J. S. Wang, X. Zhang, F. Z. Fang. Molecular dynamics study on

nanometric cutting of ion implanted silicon, Computational Materials Science, 2016, 117: 240–250.

12. J. S. Wang, F. Z. Fang, X. Zhang. Nanometric cutting of silicon with an amorphous-crystalline layered structure: A molecular dynamics study, Nanoscale Research Letters, 2017, 12: 41.
13. D. M. Jarzbek, M. Milczarek, S. Nosewicz, et al. Size effects of hardness and strain rate sensitivity in amorphous silicon measured by nanoindentation, Metallurgical and Materials Transactions A, 2020, 51: 1625–1633.
14. J. S. Wang, F. Z. Fang, X. Zhang. An experimental study of cutting performance on monocrystalline germanium after ion implantation, Precision Engineering, 2015, 39: 220–223.
15. J. S. Wang, F. Z. Fang, G. Yan, et al. Study on diamond cutting of ion implanted tungsten carbide with and without ultrasonic vibration, Nanomanufacturing and Metrology, 2019, 2: 177–185.
16. J. S. Wang, X. D. Zhang, F. Z. Fang, et al. Diamond cutting of micro-structure array on brittle material assisted by multi-ion implantation, International Journal of Machine Tools and Manufacture, 2019, 137: 58–66.