Numerical and experimental investigation on the influence of tool rake angle on fused silica in in-situ laser assisted diamond cutting

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Fused silica has been widely applied in various fields such as optical devices, precision instruments, and laser fusion because of its excellent properties. However, it is difficult to achieve high-quality machining of fused silica through conventional diamond cutting owing to severe diamond tool wear caused by the high hardness, brittleness and low fracture toughness of fused silica. In-situ laser assisted diamond cutting (LADC) improves ductile machinability by a focused laser beam passed through a transparent tool, which is considered a viable manufacturing technology to enhance the machinability of fused silica. Besides, large hydrostatic pressure generated during diamond cutting using a tool with a negative rake angle decreases the initiation of brittle fracture, which contributes to the high-quality machining of fused silica. Therefore, laser assistance and using a diamond tool with a negative rake angle are promising methods for machining hard and brittle materials. In this study, a model using smoothed particle hydrodynamics (SPH) method was constructed to simulate the diamond cutting process of fused silica. The distribution of stress is successively investigated to reveal the influence of tool rake angle and laser assistance on the surface generation during diamond cutting of fused silica. Diamond cutting experiments were performed to demonstrate the surface roughness during in-situ LADC using tools with different rake angles. Results show that the shear zone area and the maximum hydrostatic compressive stress increase with the rise of negative rake angle from -15° to -65° during in-situ LADC. With laser assistance, the fracture chips disappear and the continuous chip increase gradually, resulting in a smoother machined surface. The use of a diamond with a large negative rake angle is a practical approach to improve the machined surface quality. Thus, our findings play a role in improving the surface finish of fused silica processed by ultra-precision machining, facilitating the application of fused silica in precision instruments.

NOMENCLATURE

LADC = laser assisted diamond cutting
SPH = smoothed particle hydrodynamics

1. Introduction

The fused silica lens plays a crucial role in aerospace, laser electronics, and various other industries owing to the exceptional attributes it possesses [1]. Enhancing the machining precision of fused silica is becoming progressively significant [2]. However, due to the hard and brittle characteristics of fused silica, it is difficult to machine fused silica with high surface quality through convention diamond cutting [3].

In-situ LADC is regarded as an important way to achieve high quality processing of hard and brittle materials by softening the material treated by laser beam and improving its ductile machinability [4]. Mohammadi et al. [5] examined the shape and surface characteristics of infrared crystals produced through in-situ LADC. Their findings revealed that not only does in-situ LADC preserve the intended shape of the machined materials, but it also prolongs the lifespan of the tools. You et al. [6] demonstrated that laser assistance plays a significant role in enhancing surface quality and reducing tool wear in the diamond cutting of tungsten carbide, achieving a surface roughness of 4.66 nm in Sa. Moreover, our previous work proved that under in-situ LADC, the critical cutting depth of fused silica increases from 82.06 nm to 324.03 nm, and a surface with a Sa of 11.43 nm could be obtained [7-8].

In addition to the modification of materials through laser, the use of negative rake angle tools is also an important way to improve the surface quality of hard and brittle materials [9]. Fang et al. [10] have reported that a large negative rake angle has a significant effect on the ductile-brittle transition and subsurface deformation mechanisms in ductile regime machining of monocrystalline germanium. Guo et al. [11] discovered that the negative rake angle tool proves to be more efficient in facilitating the ductile machining of fused silica compared to the positive rake angle tool, as demonstrated by an SPH simulation model.

According to the above analysis, the laser assistance and the use of negative rake angle tools is conducive to improving the surface quality of fused silica during diamond cutting. Therefore, in this paper, the finite element simulation and experiment are combined to study the influence of different tool rake angles on the surface quality of fused silica during in-situ LADC.

2. SPH cutting simulation and results

2.1 Numerical simulation method

To observe the material removal and stress distribution during in-situ LADC of fused silica with different rake angle diamond tools, SPH simulations were performed in the Abaqus software. The simulated model was shown in Fig. 1. The workpiece was modeled with SPH particles, with the dimensions of $240 \times 40 \times 4\ \mu m^3$. The temperature of the workpiece was set to 873K to simulate the assistance of the laser power of 10 W according to previous research [7]. Three rake angles, including -15°, -35°, and -65°, are considered. The clearance angle of the diamond tool is 10°. Johnson-Cook material constitutive model is utilized in this research to describe the deformation behavior of fused silica [12].

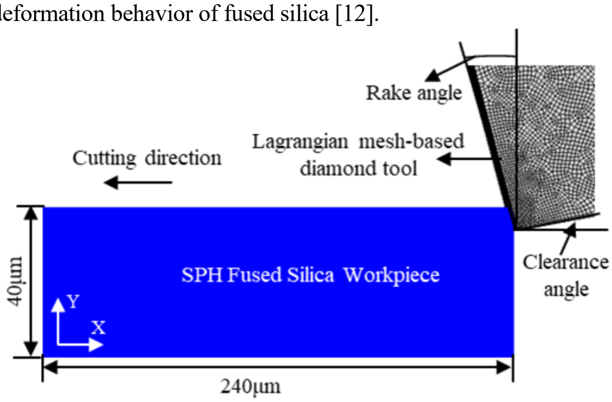

Fig. 1 SPH cutting simulation model of fused silica

2.2 Diamond cutting simulation results

SPH simulation was carried out to explore changes in the machinability of fused silica during diamond cutting with varying tool rake angles and workpiece temperatures. Fig. 2 illustrates snapshots of the cutting process under different conditions, with stress contours coloring the specimen. When the workpiece temperature is 298K, brittle cutting occurs, resulting in discontinuous chips due to the high hardness and brittleness of fused silica (Fig. 2(a) and (c)). However, with increasing temperature, a shift from brittle to plastic cutting is observed (Fig. 2(b) and (d)). The transition is marked by the disappearance of fracture chips and the gradual increase in continuous chip formation, attributed to the heightened plasticity of fused silica at higher temperatures. As shown in Fig. 2(e) and (f), when the tool rake angle is -65°, because there is no chip formation in this state, the impact of laser assistance on the cutting process is not obvious from the chip morphology. Nevertheless, it is noted that cutting stress decreases as temperature rises, as high temperatures reduce the hardness of fused silica, thereby alleviating stress concentration on the workpiece.

Alterations in tool geometry play a crucial role in stress distribution and chip formation during cutting processes. In Fig. 2(b) and (d), when utilizing -15° and -35° tools alongside laser assistance, the continuous chip formation suggests the ductile deformation of fused silica facilitated by the negative rake angle tool. When the rake angle becomes more negative, material ahead of the cutting edge is compressed downwards, impeding chip formation, as depicted in Fig. 2(f). Cutting stress predominantly concentrates in the initial deformation zone near the cutting edge. Von Mises stresses escalate as the tool's rake angle decreases, peaking at -65°. The primary shear zone's extent is governed by the shear plane length and angle. Variations in the diamond tool's rake angle notably impact these dimensions. From -15° to -65°, a reduction in rake angle leads to an elongation of the shear plane and a decrease in its angle. This expansion of the shear zone boosts material strength, consequently elevating deformation energy levels. Therefore, with the increase of the negative rake angle of the tool, the crack suppression ability in the cutting process is enhanced, and the quality of the machined surface will be improved

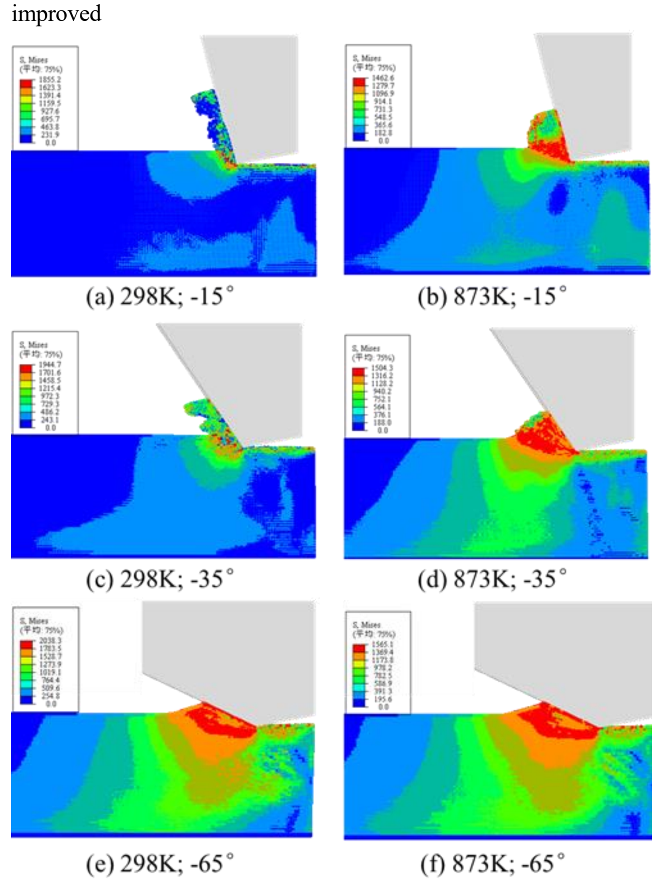

Fig. 2 Material deformation in SPH simulation at different temperatures and tool rake angels

3. Experimental setup and results

3.1 Experimental setup

The in-situ LADC trials were carried out using a laser assisted machining system integrated into an ultra-precision machining tool, as depicted in Fig. 3. Within this system, a laser was collimated via a collimator and focused near the tool edge. Machining parameters were tailored for a cutting depth of 2 μm, a feed rate of 2 mm/min and a spindle speed of 2000 rpm. For the diamond cutting experiments, a laser power of 10 W was employed with the aid of cutting fluid lubrication. Fused silica workpieces measuring 25.4 mm in diameter were paired with diamond tools featuring a nose radius of 0.5 mm and a clearance angle of 10°. To explore the impact of rake angles on cutting mechanisms, tools with rake angles of -15°, -35°, and -65° were utilized. Machined surfaces were examined using a white light interferometer.

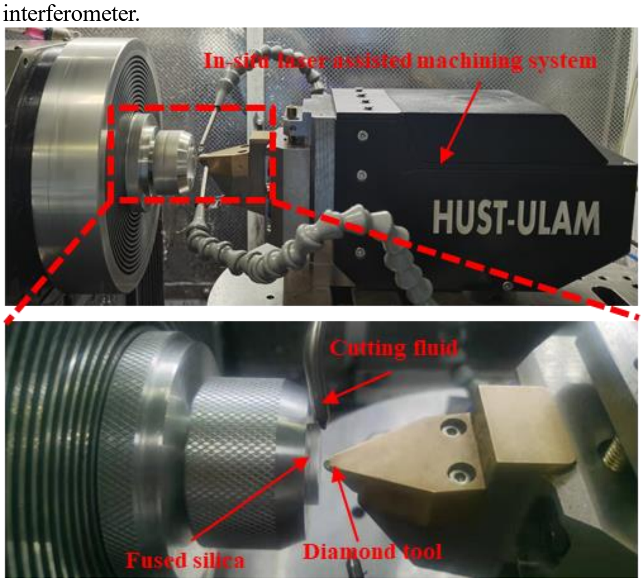

Fig. 3 Experimental setup

3.2 Experimental results

The white light interferometer was utilized to measure the surface roughness produced under various cutting conditions. It can be clearly seen from Fig. 4 that with laser assistance, the surface roughness of fused silica under different tool rake angels decreases. This can be attributed to the fact that the assistance of laser improves the ductile machinability of fused silica. Thus, the surface integrity is significantly improved during in-situ LADC.

Furthermore, Fig. 4 illustrates a clear trend: as the negative rake angle of the tool increases, the surface roughness of in-situ LADC decreases. The rake angle of the tool plays a significant role in determining the extent and depth of the high-stress field. Decreasing the negative rake angle of the tool from -65° to -15° gradually alleviates the extrusion at the tool-workpiece interface, resulting in a reduction of hydrostatic compressive stress ahead of the cutting edge. The absence of this stress inhibition leads to crack formation, indicating poor workpiece surface integrity when using a tool with rake angle of -15°. This observation further validates the accuracy of the SPH simulation. Notably, machining the surface during in-situ LADC with a -65° rake angle tool yields an exemplary surface finish quality of 18.43 nm in Sa, demonstrating that employing a negative rake angle tool enables the ductile machining of fused silica with consistent quality.

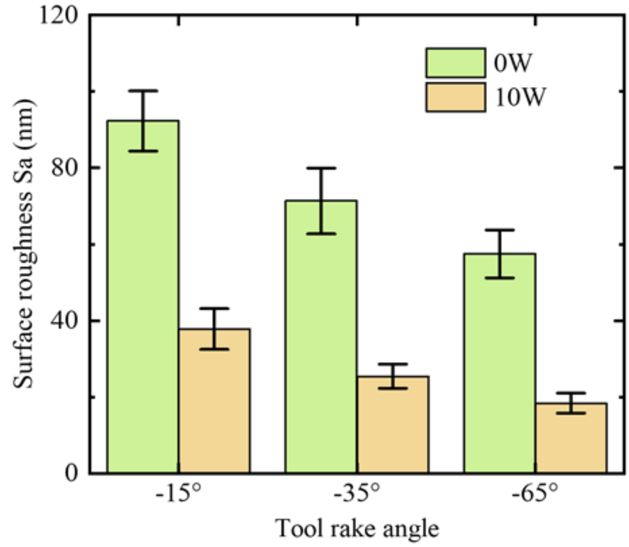

Fig. 4 Surface roughness (Sa) of fused silica under different cutting conditions

4. Conclusions

In order to reveal the underlying mechanism of the laser assistance and the use of a tool with a negative rake angle during diamond cutting of fused silica, a SPH model was develop and the chip formation and the distribution of hydrostatic pressure were analyzed. End face turning experiments were performed to demonstrate the surface roughness during in-situ LADC at different rake angle diamond tools. Simulated and experimental results show that with laser assistance, the fracture chips disappear and the continuous chip increase gradually, resulting in a smoother machined surface. Furthermore, with a decrease of rake angle in the range from -15° to -65°, the shear zone area and the maximum hydrostatic compressive stress increase, which results in the plastic deformation of the material with little or no brittle fracture. Therefore, the laser assistance and the use of a diamond with a large negative rake angle is an effective approach to improve the machined surface quality. The minimum surface roughness of 18.43 nm in Sa is achieved at the tool rake angle of -65° during in-situ LADC.

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