Cutting performance and tool wear in laser-assisted grinding of SiCf/SiC ceramic matrix composites

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Abstract
Ceramic matrix composites have high hardness, so their machining requires high grinding forces that cause severe wear of the grinding head. To investigate this problem, the present study investigated the cutting performance of conventional grinding (CG) and laser-assisted grinding (LAG) of SiCf/SiC ceramic matrix composites using electroplated diamond grinding heads. Firstly, a three-dimensional transient heat transfer model based on a Gaussian heat source was developed to observe the surface and internal temperature field distributions of SiCf/SiC ceramic matrix composites subjected to laser irradiation. Secondly, the effects of laser heating temperature on the workpiece surface on the grinding forces were analysed. It was found that the axial and feed grinding forces were more than 40% lower under LAG than CG due to the removal mechanism of the SiC matrix changing from brittle fracture to ductile fracture and the oxidation reactions occurred in the SiCf/SiC ceramic matrix composites.
Thirdly, the material removal mechanism was analysed by observing the morphology of machined surfaces, which showed that ductile removal from the SiC matrix occurs during LAG. Finally, it is also founded that the mean height of exposed abrasive grains from machined surface was reduced by 1.02 μm, 12.52 μm in LAG and CG respectively. The forms of wear caused by abrasive grains were studied. Under CG, the abrasive grains mainly exhibit cleavage fractures; while under LAG, micro-abrasion is the main wear form.

Nomenclature

\( q \) heat flux density
\( r \) radial distance to the laser radiation centre
\( R_a \) radius of the laser
\( P \) laser power
\( n \) laser absorption rate
\( T \) temperature field
\( \rho \) density
\( c_p \) specific heat capacity
\( k \) thermal conductivity
\( t \) time
\( h \) convective heat transfer coefficient
\( \sigma \) Stephen Boltzmann constant
\( \varepsilon \) emissivity
\( d_c \) critical depth
Ceramic matrix composites have many excellent mechanical properties [1], such as high specific modulus, high specific strength, a low thermal expansion coefficient, high-temperature resistance [2], corrosion resistance, and wear resistance. These give them broad application prospects in the fields of aerospace, automobiles [3], high-speed trains, and others [4]. However, fibre-reinforced ceramic matrix composites have high hardness and strength as well as anisotropy and heterogeneity, such that machining of these materials results in high cutting forces, severe tool wear and poor surface integrity. To solve this problem, various conventional machining (CM) and unconventional machining methods have been studied.

Zhang et al [5] carried out drilling experiments on C_f/SiC composites to study tool wear with different machining parameters using polycrystalline diamond (PCD) tools. Usca et al [6] examined the machinability characteristics when milling Cu-B-CrC composites using Al/TiN coated carbide tools. Zhou et al [7] investigated the material removal behavior and abrasive wear of C_f/SiC composites using two types of abrasive belts. Diaz et al [8] reviewed conventional machining techniques for ceramic matrix composites with a focus on the effects of different machining techniques on surface integrity. In addition to conventional machining methods, a series of unconventional methods have been applied to the machining of fibre-reinforced ceramic matrix composites to improve their machinability, such as ultrasonic vibration-assisted grinding (UAG), laser-assisted machining (LAM), high-speed grinding (HSG), and abrasive water-jet machining (AWJ). Hashish et al [9] confirmed that AWJ is suitable for machining holes, slots and through-cuts in SiC_f/SiC ceramic matrix composites. Wang et al [10] carried out ultrasonic vibration-assisted grinding of C_f/SiC ceramic matrix composites, finding that this technique can effectively reduce grinding forces, causes low damage, and is highly efficient.

Compared with conventional machining, many studies have shown the advantages of LAM in reducing cutting forces and improving tool life and machining quality and efficiency. It provides an effective way to machining difficult-to-machine materials [11]. Chen et al [12] explored the feasibility of laser-induced ablation of SiC_f/SiC ceramic matrix composites by numerical simulation and experiment, and analysed the effects of different laser parameters on the ablation zone. Zhou et al [13] proposed a new machining method called laser-induced ablation-assisted grinding and used it in experiments with C_f/SiC ceramic matrix composites. It was found that the abrasive belt grinding force, grinding temperature and average surface roughness were reduced by 47%, 40%, and 26% compared with conventional grinding, respectively, which greatly improved the surface integrity and significantly reduced abrasive wear. Rozziet al [14] conducted laser-assisted edge-milling tests and found a 40% reduction in cutting forces compared with conventional edge-milling, which demonstrated the feasibility of the laser-assisted cutting of ceramic matrix composites. Dong et al [15] carried out laser heating-assisted micro-machining of SiC/HiSiC ceramic matrix composites, which reduced tool wear by 76% and increased tool life by 3.8-fold. Erdenechimeg et al [16] conducted experiments on the laser-assisted machining of carbon fiber-reinforced ceramic matrix composites and found that LAM cutting forces were reduced by 40.7% and roughness was reduced by 33.8% compared with CM Reza et al [17] conducted experiments on the laser-assisted turning of a SiC-Al_2O_3-reinforced aluminum hybrid nanocomposite and found a 26% reduction in laser-assisted cutting forces and a 51% reduction in roughness, which were attributed to softening and plastic deformation of the aluminum matrix. Zhai et al [18] studied the characteristics and mechanism of the LAM of C_f/SiC composites with different fibre orientations (0°, 45°, 90°, 135°). It was found that the fibre orientation had a significant effect on roughness and the surface quality was better with LAM than with (CM). Ma et al [19] conducted experiments on laser-assisted grinding of alumina ceramics and showed that the laser power has the greatest effect on surface roughness. In addition, the removal of alumina ceramics by laser heating alters the fracture type from brittle fracture to plastic fracture. Pu et al [20] performed LAM of Si_3N_4 ceramics and discovered that different material removal modes were obtained by changing the power of the laser.

Laser assisted grinding (LAG) has been studied in numerous metals and ceramic materials [11, 21] but there has been a few study with fibre-reinforced ceramic matrix composites. Especially for laser-assisted grinding of ceramic matrix composites, there is little research literature on the subject. Cutting performance in laser-assisted grinding of SiC_f/HiSiC ceramic matrix composites is not studied. The effects of laser assistance on grinding forces, material removal mechanisms, grading surface morphology and grinding head wear forms remain unclear.

Therefore, both conventional grinding (CG) and LAG experiments of fibre-reinforced ceramic matrix composites were carried out in the present study. The effects of LAG on the grinding forces and wear forms of the
A LAG system was designed to carry out grinding experiments on SiCf3. Experimental work where
where
T
where
q
is equal to room temperature, the initial condition at time

is the laser absorption rate of the SiCf3. To simplify the simulation model, it is assumed that SiCf3/SiC is a monophase material. The thermal properties of SiCf3/SiC are considered to be a function of temperature [22]. Thus, the three-dimensional thermal diffusion equation in Cartesian coordinates is expressed as [23]:

\[
\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + Q(x, y, z, t) = \rho c_T \frac{\partial T}{\partial t}
\]

where \( T \) is the temperature field, \( \rho \) is density, \( c_T \) is specific heat capacity, and \( k_x, k_y, \) and \( k_z \) are the thermal conductivities in the \( x-, y-, \) and \( z-\) directions, respectively. Assuming that the initial temperature of the workpiece is equal to room temperature, the initial condition at time \( t = 0 \) is given as follows:

\[
T(x, y, z, t) = T_0
\]

where \( T_0 = 0 \, ^\circ C \).

The boundary conditions of the problem described in equation (2) can be expressed by:

\[
k \frac{\partial T}{\partial n} - q + h(T - T_0) + \sigma \varepsilon (T^4 - T_0^4) = 0
\]

where \( h \) is the convective heat transfer coefficient (=10 W m\(^{-2}\) K\(^{-1}\)), \( \sigma \) is the Stephen Boltzmann constant (=5.67 \times 10^{-8} W m\(^{-2}\) K\(^{-4}\)) [24], and \( \varepsilon \) is the emissivity (=0.9) [14].

The model was implemented using ABAQUS software and its subroutine Dflux. The dimensions of the model were 35 mm \( \times \) 20 mm \( \times \) 5 mm (length \( \times \) width \( \times \) height) and the minimum mesh size was 2.5e-3 mm. Table 1 lists the physical parameters used in the model [12].

### 3. Experimental work

A LAG system was designed to carry out grinding experiments on SiCf3/SiC ceramic matrix composites. The whole experimental system is shown in figure 1. The system comprised a VMC850B vertical machining centre with a maximum spindle speed of 8000 rpm and a fibre laser with a maximum power output of 4000 W that was controlled by a manipulator arm. A Kistlter dynamometer is used to measure the grinding forces along three directions both in LAG and in CG. The FLIR infrared thermometer was placed in front of the machining center to collect temperature data. The grinding tool is a diamond grinding head with a standard specification of SD-120-100-M. The diameter of the grinding head is 10 mm. The experiment material was a SiCf3/SiC ceramic matrix composite sample with a size of 300 mm \( \times \) 150 mm \( \times \) 5 mm (length \( \times \) width \( \times \) height). During the grinding experiments, the grinding force was recorded using a Kistlter dynamometer and the grinding temperature was measured by a FLIR infrared thermometer. Firstly, a conventional grinding experiment was

| Physical parameter | Index |
|--------------------|-------|
| Density \( \rho \) [kg/m\(^3\)] | 2250 |
| Specific heat capacity \( c \) [J/(kg K)] | 350 |
| Thermal conductivity \( k \) [W/(m K)] | 12 (x-direction) |
| | 12 (y-direction) |
| | 10 (z-direction) |

**Table 1.** Physical parameters of the SiCf3/SiC used in the model.
carried out. The following are the grinding parameters: 5000 rpm for the spindle, 150 mm/min for the feed, 0.05 mm for the depth of grinding, and 10 mm for the grinding width. Then, a LAG experiment was conducted. As shown in figure 2, the position of the laser spot was adjusted using the manipulator arm so that it was in front of the grinding head along the feed direction. The laser spot diameter was 10 mm and the angle between the laser beam and machined surface was 60°. The laser output mode is continuous-wave laser. The other parameters were the same as the conventional grinding parameters to facilitate comparative analysis of the effect of laser assistance. During the grinding experiments, the grinding force was recorded using a Kistlter dynamometer and the grinding temperature was measured by a FLIR infrared thermometer. After the experiments, the cutting forces were exported to an excel file using DynoWare software and the mean value was obtained.

4. Results and discussion

4.1. Grinding force

The grinding force has a significant impact on grinding head wear and surface quality. Examination of fluctuations in grinding forces is crucial in the study of grinding mechanisms, head wear and surface quality. In this study, the grinding forces were divided into axial, feed, and radial forces.

Conventional and laser-assisted grinding forces are compared in figure 3. Compared with conventional grinding, the LAG forces are all lower. Axial and feed forces are more than 40% lower, while the radial force is 5.5% lower. The main reason for this is that the area of radial force generation is less affected by laser heating. This area is located at the edge of the laser spot, where the laser heating effect is poor. There are two main reasons for the lower LAG forces. First, the oxidation reaction between SiC fibres, the SiC matrix and interfacial pyrolytic carbon after high-temperature laser irradiation destroys the material structure, reduces its strength and leads to a reduction in grinding force. Following laser irradiation of SiCf/SiC ceramic matrix composites at high temperatures, a series of oxidation reactions occur in the fibres, matrix and interface materials. The interface of the SiCf/SiC ceramic matrix composite used in this experiment was pyrolytic carbon (PYC), which is oxidized at temperatures >550 °C to produce carbon dioxide or carbon monoxide gas, as shown in equations (5) and (6) [12]. The literature [12, 13] has described in detail the high-temperature oxidation behaviour of SiC fibres with a SiC ceramic matrix under laser irradiation. The oxidation reactions are shown in equation (7–11). Secondly, after high-temperature laser irradiation, the SiC matrix of SiCf/SiC composites is heated and softened, as shown in table 3, which leads to a reduction in grinding force. As can be seen from figure 4, after laser irradiation, the
surface and subsurface temperatures of the workpiece reach \( > 1000 \, ^\circ \text{C} \), which is sufficient for oxidation reaction and softening of the material.

\[
C(s) + O_{2(g)} \rightarrow CO_{2(g)} \\
C(s) + O_{2(g)} \rightarrow CO_{2(g)} \\
SiC(s) + O_{2(g)} \rightarrow SiO_{2(g)} + CO_{2(g)} \\
SiC(s) + O_{2(g)} \rightarrow SiO_{2(g)} + CO_{2(g)} \\
SiC(s) + O_{2(g)} \rightarrow SiO_{2(g)} + CO_{2(g)} \\
SiO_{2(g)} + SiC(s) \rightarrow SiO_{2(g)} + CO_{2(g)}
\]
In this study, LAG not only reduced the grinding force but also its fluctuation. This is related to the removal mechanism of SiCf/SiC ceramic matrix composites which, according to previous studies, is dominated by brittle removal \[8\]. When mainly brittle removal occurs during grinding, the brittle breakage of the material tends to cause tool vibration, resulting in large fluctuations in grinding force.

Figure 5 shows the morphology of the LAG surface where the matrix coating was located, which shows severe plastic deformation of the matrix material. SiC ceramics are typically hard and brittle, so the main material removal mechanism during machining is brittle fracture. However, some scholars have found that the removal mechanism changes from brittle to ductile at a certain depth of cutting. Bifano et al proposed a model for defining the tough-brittle transition of nominally brittle materials based on their characteristics and brittle fracture properties. Based on the Griffith crack extension criterion, a critical depth of cut model was proposed, where ductile removal occurs when the depth of cut is less than the critical depth. The critical depth of cut \( (d_c) \) is formulated as follows \[24\]:

\[
d_c \propto 0.15 \cdot \left( \frac{E}{H} \right) \cdot \left( \frac{K_c}{H} \right)^2
\]

where \( E \) is the modulus of elasticity, \( H \) is the Vickers hardness, and \( K_c \) is the material’s fracture toughness.

From Table 2, it can be seen that the hardness of SiC decreases with increases in temperature. From equation (12), it is known that the critical cut depth is negatively correlated with the material hardness cubic, so a decreased material hardness will lead to an increased critical cut depth. That is to say, ductile removal of hard and brittle materials can be achieved in the ductile region within a large depth range. Therefore, during LAG, the workpiece temperature increases and the hardness of the SiC substrate decreases after laser irradiation. The critical depth of cut of the SiC matrix increases due to the reduction in hardness, leading to a change in the removal mechanism from brittle removal to ductile removal. This is critical for lowering the grinding forces, improving the machined surface quality, and reducing grinding head wear.

| Temperature (°C) | 20  | 300 | 400 | 500 | 600 | 700 | 800 | 1000 | 1100 |
|------------------|-----|-----|-----|-----|-----|-----|-----|-------|-------|
| Hardness (GPa)   | 26  | 22  | 20  | 18  | 16.6| 15  | 14.35| 12.75 | 12    |

Table 2. Relationship between SiC hardness and temperature \[24\].

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4.2. Grinding head wear analysis

The grinding capacity of the grinding head and the form of abrasive wear is directly reflected by the height of the exposed abrasive grains on the grinding head. The morphologies of the abrasive grains under various settings are shown in figure 6. The exposed heights of these grains on were measured using a VHХ-2000С ultra-deep optical microscope (figure 7). The mean height in the initial state was 69.1 \( \mu m \), that after CG was 56.58 \( \mu m \), and that after LAG was 68.08 \( \mu m \) (figure 7). This indicates that grinding head wear is more severe after CG than after LAG.

Figure 7 also shows that the standard deviation of the mean height of exposed abrasive grains after CG is greater than that after LAG, which means that the CG grains are more dispersed in height, forming a rougher surface. This is related to the form of abrasive wear that occurs in the grinding head. Figure 8 shows the form of
abrasive grain wear on the grinding head. Cleavage fractures and micro-abrasions were observed in both CG and LAG abrasive grains. Due to the high grinding force and greater mechanical load on abrasive grains during CG, they are susceptible to cleavage fracture. This result is the same as the results of previous studies [7, 25]. However, under LAG, the abrasive grains can withstand the lower load and are less likely to fracture this way because of the lower grinding force. The abrasive grains mainly exhibit micro-abrasion wear. So, their exposed heights are more evenly distributed. This explains the higher average exposed height and smaller standard deviation of the abrasive grains after LAG. This is extremely beneficial to surface quality and for extending the life of the grinding head.

Figure 6. Abrasive morphologies of the grinding head.

Figure 7. Mean heights of exposed abrasive grains in the initial state and after CG and LAG. Error bars indicate standard deviations.
5. Conclusion

Conventional and laser-assisted grinding tests were carried out on SiCf/SiC ceramic matrix composites to analyse the grinding forces and grinding head wear forms. The following conclusions can be drawn.

(1) Laser heating causes oxidation reactions in SiCf/SiC ceramic matrix composites and softening of the SiC matrix, which reduce the grinding force and change the removal mechanism. Compared with CG, the LAG axial, feed, and radial forces are 43.8%, 40.9% and 7.8% lower, respectively.

(2) During LAG, the hardness of the SiC matrix decreases with an increasing on the temperature due to laser irradiation. The critical depth of cut of the SiC matrix increases due to the reduction in hardness, leading to a change in the removal mechanism from brittle removal to ductile removal. The plastic deformation of SiC matrix also occurs on the machined surface.

(3) In comparison with the 1.02 μm reduction in the mean height of exposed abrasive grains after LAG, that after CG was 12.52 μm lower—a 12.3-fold difference. The standard deviation of the exposed height of abrasive grains after CG is greater than that after LAG. The difference in exposed height is related to the form of wear. After CG, the abrasive grain wear is dominated by cleavage fractures; while after LAG, it is dominated by micro-abrasion.

(4) There are still several challenges that require further research despite the outstanding performance of laser-assisted grinding in reducing cutting forces and grinding head wear. For example, the optimal temperature for reducing cutting forces is not yet clear, the temperature distribution on the laser heating area needs to be further optimized to avoid machined surface burns, and issues such as machined surface integrity and tool life need to be studied in the future.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Competing interests

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Author contributions

All authors contributed to the study conception and design. Xianjun Kong is a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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